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Endovascular robotics: technical advances and future directions

Matteo Pescio[a,b], Dennis Kundrat[c] and Giulio Dagnino[b,d]

[a]Bioengineering, Polytechnic University of Turin, Turin, Italy; [b]University of Turin, Turin, Italy; [c]Individualized Therapy, Fraunhofer Research Institution for Individualized and Cell-Based Medical Engineering (IMTE), Lübeck, Germany; [d]Robotics and Mechatronics, University of Twente, Enschede, The Netherlands

ABSTRACT

Endovascular interventions excel in treating cardiovascular diseases in a minimally invasive manner, showing improved outcomes over open techniques. However, challenges related to precise navigation – still relying on 2D fluoroscopy – persist. This review examines the role of robotics, highlighting commercial and research platforms, while exploring emerging trends like MRI compatibility, enhanced navigation, and autonomy. MRI-compatible systems offer radiation-free 3D imaging. Human-robot interaction evolves with task-specific interfaces, while autonomy ranges from partial to full, aiding clinical operators. Challenges include complexity and cost, emphasizing compatibility and navigation advancements. Integrating MRI-compatible robots, refining human-robot interaction, and enhancing autonomy promise advancements in endovascular surgery, fueled by AI and innovative imaging.

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1. Introduction

Cardiovascular disease is the leading cause of death in many Western countries [1], amounting to about 18 million deaths each year [2]. Vascular diseases are a main contributing factor. For example, disorders affecting coronary or peripheral vessels can cause myocardial infarction or stroke [3]: atherosclerosis and plaques on the vessel walls can result in blockage within the arterial system, which in turn can lead to ischemia and cause a number of serious conditions including heart attack and stroke; aneurysm is another serious condition which can lead to severe hemorrhaging and potentially death in the case of rupture. Cardiac arrhythmias represent another common cardiovascular disease that can become life-threatening [1].

Endovascular interventions have become the gold standard to treat such conditions in a minimally invasive way providing improved clinical outcomes over open techniques such as faster recovery times and reduced risk of infections [4–6]. Current endovascular procedure involves guiding special shaped catheters and guidewires to a specific target in the vascular tree, such as the aorta and auxiliary arterial vessels, combined with different treatment options including angioplasty, stenting, embolization, and ablation. Angioplasty is a procedure used to widen narrowed or obstructed arteries or veins (e.g., vascular opening in the case of narrowing or occlusion as in stroke or cardiac arrest). Stenting involves the placement of a stent (a tube usually constructed of a metallic alloy or a polymer) which is inserted into the lumen of a vessel to keep the passageway open. Occluding procedures like endovascular embolization fill or close blood vessels to prevent bleeding and rupturing: a catheter is maneuvered through the blood vessel up to the area being treated, and small plastic particles, glue, metal coils, foam, or a balloon are placed through it to seal off the faulty blood vessel. The procedure is most often used to treat aneurysms in the brain. Finally, cardiac ablation is an electrophysiology procedure to treat arrhythmia. The procedure involves the placement of several catheters through blood vessels to the heart to map and treat (ablate) the area that is causing the abnormal heart rhythm. Ablation techniques make use of radiofrequency heat energy or very cold temperatures (cryoablation) to eliminate the targeted area [1].

CONTACT Giulio Dagnino g.dagnino@utwente.nl Department of Robotics and Mechatronics, University of Twente, Drienerlolaan 5, 7522 NB Enschede, The Netherlands

These procedures are made possible through the use of medical imaging, most commonly X-Ray-based fluoroscopy, to allow for real-time procedural visualization and safe manipulation of the catheters and guidewires in the vasculature.

Vascular navigation is challenging and requires excellent endovascular skills to avoid unintentional (yet frequent) contact between the manipulated instruments and the vessel walls, with the potential for perforation and injuries [7]. For navigating these instruments through the delicate vascular tree, the operator has to rely on visual and haptic cues obtained mostly from 2D fluoroscopy guidance and the small axial forces and torques sensed at the fingertips [1]. Intra-operative 2D fluoroscopy guidance exposes both the patient and (partially) the operator to ionizing radiation and requires contrast injection and static 2D roadmaps, hence significant information on the 3D vascular anatomy is lost. Large doses of contrast agent can also result in nephrotoxicity and complications including renal failure, therefore it is used sparingly at critical points during the procedure [1]. However, specific procedures may need higher doses due to tedious anatomical pathologies.

Presently, there is a growing interest in robotic technology for the accurate maneuver of catheters and guidewires. Benefits include improved stability and precision (e.g., clamping one device more easily), simple access to difficult-to-reach anatomy, reduced radiation doses (both for patients and clinical staff), and improved patient comfort [8].

This mini-review addresses the role of robotics in endovascular intervention, presenting an up-to-date analysis of the latest advancements in commercial and research platforms, as well as emerging technologies, with a focus on translational challenges and opportunities for future technical developments.

A review of key research studies and articles related to robot-assisted endovascular interventions was carried out. This review included an examination and overview of robotic systems and significant publications that highlight major advancements in endovascular robotics, while also addressing current challenges and potential research directions. The search terms used in this review were 'Endovascular Robotic Platforms', 'Endovascular Robots', and 'Endovascular Surgical Robots'. It is important to note that this mini-review does not aim to provide a comprehensive taxonomy of research publications. Instead, it offers a concise and accessible introduction to this dynamic and rapidly advancing field, with the goal of inspiring future research directions.

2. Robot-assisted endovascular intervention

Current technologies for robot-assisted endovascular intervention involve the use of remotely controlled endovascular devices, i.e., catheters and guidewires. Over the past two decades, there has been a growing interest in robotic steerable catheter technology, offering advantages such as enhanced precision and stability, reduced radiation doses, improved comfort, and better access to challenging and tortuous anatomy [9]. However, these commercially available platforms often disregard the operator's natural bedside manipulation skills, resulting in the underutilization of their manually acquired experience and dexterity, while still relying on 2D fluoroscopy guidance. Unmet clinical needs in the development of robotic endovascular intervention include improved 3D navigation, integrated force feedback, and enhanced ergonomics [10].

2.1. Commercial platforms

Figure 1 shows the timeline of commercial endovascular robotic platforms. Current commercial platforms are designed in a teleoperated configuration, with the operator using either a 3D joystick or navigation buttons to manipulate endovascular devices *via* a remote workstation under fluoroscopy guidance. In the teleoperated configuration, the change of catheters and guidewires is performed manually by an additional operator located at the patient side unit of the robot. Table 1 reports representative examples of commercial robotic platforms for endovascular procedures. It is worth noting that we differentiate between platforms used for electrophysiology and those used for broader endovascular applications. Electrophysiology refers to procedures that focus on diagnosing and treating electrical abnormalities in the heart, such as cardiac arrhythmias, often requiring precise navigation of catheters to specific locations within the heart for ablation or mapping. In contrast, endovascular applications refer to a wider range of minimally invasive procedures within the blood vessels, including interventions for conditions like aneurysms, stenosis, and thrombosis, which typically involve catheterization of arteries or veins. While 'endovascular' is used as an umbrella term throughout the manuscript to refer to procedures involving navigation through the vasculature, the distinction between these specific applications helps highlight the different technical requirements and challenges in each domain.

Commercial platforms available on the market include Genesis [11] and Niobe [12] from Stereotaxis (St. Louis, MO, USA), which use magnetic navigation of the catheters during electrophysiology (EP)

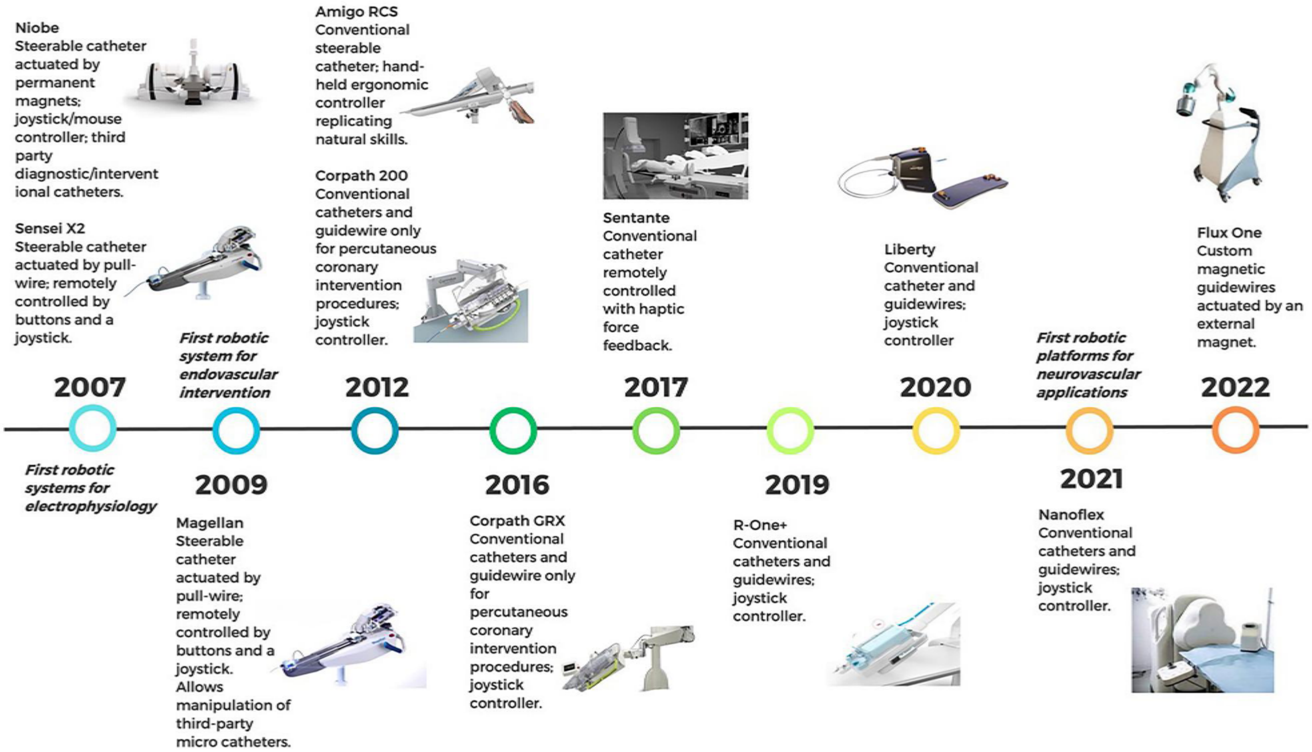

Figure 1. Timeline of exemplary endovascular robotic platforms that reached the market, including key features and milestones. "Niobe" © Stereotaxis; "Sensei X2" and "Magellan" © Johnson & Johnson MedTech; "Amigo RCS" © Catheter Precision; "Corpath 200" and "Corpath GRX" © Siemens Healthineers; "Sentante" © Inovatyvi Medicina; "R-One+" © Robocath; "Liberty" © Microbot Medical; "Nanoflex" © Nanoflex robotics; "Flux One" © Flux Robotics.

procedures. These platforms consist of two permanent magnets to generate a magnetic field for controlling the tip deflection of the catheters. Genesis is an evolution of Niobe, bringing the same benefits but with a smaller, lighter, faster, and more flexible system architecture.

Other exemplary commercial systems include the Magellan (for endovascular procedures) [13–16] and Sensei X2 (for electrophysiology procedures) [17–21] by Hansen Medical. (Mountain View, CA, USA). These platforms are teleoperated by the clinician – who sits at the operator console – *via* a joystick or buttons. The Magellan system makes use of 2D fluoroscopy for intraoperative guidance, while the Sensei X2 integrates 3D guidance provided by third-party software. Niobe (Stereotaxis) is used in endovascular electrophysiology applications. Catheters and guidewires are remotely manipulated (therefore the operator is not exposed to ionizing radiations) using a magnetic field produced by two permanent magnets, while the CARTO 3 System (Biosense Webster, Inc., Irvine, CA, USA) provides 3D intraoperative navigation. This kind of system creates detailed 3D maps of the heart's electrical activity and anatomy and precisely tracks catheters inside the heart using magnetic and current-based localization.

Hansen Medical was acquired by Auris Health Inc. (Redwood City, CA, USA) in 2016, later incorporated into Johnson & Johnson MedTech (New Brunswick, NJ, USA) and both Magellan and Sensei X2 are no longer available on the market.

Corindus Inc. (Waltham, MA, USA), now part of Siemens Healthineers (Enlargen, Germany), developed CorPath 200 and CorPath GRX [22–27]. The GRX is the improved model of the CorPath 200 version. These robotic systems are designed to mechanically drive standard instruments during percutaneous coronary interventions under fluoroscopy guidance. The GRX features partial procedural autonomy of guidewire manipulation (e.g., spin to cross lesions) mimicking motion patterns from manual instrument handling. Nonetheless, in May 2023, Siemens Healthineers announced that CorPath GRX for cardiac and peripheral interventions would be discontinued due to its failure to meet the anticipated adoption rate, leading the company to shift its focus exclusively to neurovascular interventions and withdraw from the robotic-assisted endovascular cardiology sector [28]. The commercial shortcomings of these robotic systems may be attributed to an unfavorable cost-benefit ratio, as well as to the combination of complicated integration, prolonged duration of intervention,

Table 1. Exemplary commercial robotic platforms for endovascular procedures.

Commercial platforms						
System (company)	Application	Endovascular instruments	Controller setup	Haptic feedback	3D navigation	Description
Genesis (Stereotaxis) [11]	EP	Steerable catheter actuated by permanent magnets	Manually advanced catheter	No	No	Joystick/mouse controller. Third party diagnostic/interventional catheters.
Niobe (Stereotaxis) [12]	EP	Steerable catheter actuated by permanent magnets	Manually advanced catheter	No	No	Joystick/mouse controller. Third party diagnostic/interventional catheters.
Sensei X2 (Hansen Medical) [17]	EP	Steerable catheter actuated by pull-wire	Remote workstation	Yes	Yes	Remotely controlled by buttons and a joystick.
Magellan (Hansen Medical) [13]	EV	Steerable catheter actuated by pull-wire	Remote workstation	No	No	Remotely controlled by buttons and a joystick. Allows manipulation of third-party micro catheters.
CorPath GRX (Siemens Healthineers) [22]	EV	Conventional Instruments Electro – Mechanical	Remote workstation	No	No	Conventional catheters and guidewire only for percutaneous coronary intervention procedures. Joystick controller.
CorPath 200 (Siemens Healthineers) [23]	EV	Conventional Instruments Electro – Mechanical	Remote workstation	No	No	Conventional catheters and guidewire only for percutaneous coronary intervention procedures. Joystick controller.
R-One+ (Robocath) [30]	EV	Conventional Instruments Electro – Mechanical	Remote workstation	No	No	Conventional catheters and guidewires. Joystick controller.
Amigo RCS (Catheter Precision) [31]	EP	Conventional Steerable Electro – Mechanical	Remote workstation	No	No	Conventional steerable catheter. Hand-held ergonomic controller replicating natural skills.
Nanoflex (Nanoflex Robotics) [36]	EV	Steerable catheter actuated by permanent magnets	Remote workstation	No	No	Teleoperated AI-based software
Flux One (Flux Robotics) [35]	EV	Custom Guidewire Magnetic	Manually advanced catheter	No	Yes	Custom magnetic guidewires actuated by an external magnet.
Sentante (Inovatyvi Medicina) [37]	EV	Conventional Catheter Electro - Mechanical	Remote workstation	Yes	No	Conventional catheter remotely controlled with haptic force feedback.
Liberty (Microbot Medical) [38]	EV	Conventional Instruments Electro – Mechanical	Remote workstation	No	No	Conventional catheter and guidewires. Joystick controller

EP: electrophysiology; EV: endovascular.

reduced set of tools available for intervention (e.g., catheters and wires), time-consuming instrument exchanges and lack of dexterous control, i.e., non-adequate human-machine interfaces. Expenses incurred throughout the care cycle, encompassing initial investments, surgical costs, and post-surgical expenditures, might not justify the use of such robotic technology over conventional manual procedures. Thus, a strategic emphasis on applications with the potential for realistic socioeconomic impact, such as Siemens Healthineers' focus on neurovascular applications, appears prudent. However, quantifying a reliable cost-benefit analysis concerning improved postoperative outcomes remains challenging [29].

Another contributing factor may be the clinical usability and integration of robotic platforms within the healthcare workflow. The Magellan and Sensei X2 systems faced limitations as they were cumbersome and relied on proprietary instruments. In contrast, recent commercial robotic platforms like Robocath's R-One+ (Rouen, France) [30] and Catheter Precision's Amigo RCS (Mount Olive, NJ, USA) [31–34] exhibit seamless integration into clinical protocols, being compatible with leading market devices (guidewires, stent/balloons, imaging systems, etc.) [10]. Their quick setup time allows them to seamlessly integrate with the intervention protocol, avoiding additional steps – a crucial attribute for enhanced clinical usability and acceptance.

Other interesting devices are the Flux One [35] from Flux Robotics (Enschede, The Netherlands), a spin-off from the University of Twente (Enschede, The Netherlands); Nanoflex [36] from Nanoflex Robotics (Zurich, Switzerland), a spin-off from the

Swiss Federal Institute of Technology Zurich (ETH, Zurich, Switzerland), the Sentante robotic platform [37] from Inovatyvi Medicina (Kaunas, Lithuania) and the Liberty Robotic System [38] from Microbot Medical (Braintree, MA, USA). These platforms are not yet commercially available and are still facing or will soon face the clinical trial phase. Flux One and Nanoflex use a magnetic navigation system, which in the case of Flux One is also enriched by a three-dimensional system derived from preoperatively acquired images. However, those platforms also require specific instrumentation for compliance with magnetic actuation principles. The Sentante platform introduces haptic force feedback on the remote controller. The Liberty system is a disposable robot designed to use off-the-shelf instruments. According to the company, it features remote manipulation of instruments with a quick learning curve, ensuring both predictability and accuracy in performance.

As concluded by Condino et al. [39], the main limitations of current commercial systems include technical complexity, high (running) costs, limited usability, and, in most cases, use of expensive proprietary catheters and wires. It would be highly desirable to ensure the compatibility of robotic platforms with a wide range of off-the-shelf equipment, easy interchangeability, and an improvement in navigation technologies. Beyond that, versatile device applicability to different anatomical scenarios, e.g., thoracic, coronary, and peripheral scenarios, may improve the clinical value of robotic technologies significantly. Last but not least, seamless integration of platforms to existing interventional workflows for elective cases would result in a game-changing system with high clinical adoption potential.

2.2. Emerging research platforms and technologies

Parallel to commercial robotic platforms, research centers, and universities are proposing novel technologies and strategies to overcome the limitations of current platforms, focusing particularly on enhancing instrument navigation (precision, steerability), guidance (visual and haptic), and autonomy levels (cooperation, full autonomy). More in detail, research trends on future endovascular platforms primarily focus on:

- Development of MRI-compatible platforms that can benefit from real-time MR-guidance, e.g., providing dynamic 3D images with no x-ray exposure during guidance for endovascular interventions [3,40,41];
- Improvement of the human-robot interface, through the development of controllers that move away from the joystick concept and render more fidelity to instruments used manually by surgeons, i.e., mimicking endovascular maneuvers [42];
- Increasing robot autonomy to perform some tasks in collaboration with the surgeon, or even in full autonomy (e.g., simple repetitive tasks).

Table 2 reports a list of promising research robotic platforms for endovascular intervention. We encourage the readers to refer to the suggested references for a detailed description of the robotic systems.

In the next three sub-sections, emerging technologies, which we believe will play a key role in improving robot-assisted endovascular intervention in the coming years, are discussed.

2.2.1. MRI compatibility in endovascular robotics

MRI offers several potential advantages in the context of endovascular interventions, particularly due to its ability to provide radiation-free imaging. MRI is potentially an excellent alternative to fluoroscopy as it can provide radiation-free, 3D and functional (blood flow, tissue oxygenation, diffusion, perfusion and temperature change) guidance [3,40,41]. This is especially important for certain patient populations, such as pregnant women and pediatric patients, where minimizing exposure to ionizing radiation is critical. MR-safe robotic platforms can play a crucial role in endovascular interventions for several reasons, primarily related to the unique benefits of combining MRI with robotic-assisted procedures. MRI's excellent soft tissue contrast allows for more detailed visualization of vascular structures and surrounding tissues, potentially aiding in precise navigation and decision-making during complex procedures. However, while these benefits are compelling, MRI-compatible robotic platforms are still largely in the experimental phase, and practical challenges limit their widespread clinical adoption.

2.2.1.1. MRI applications and patient populations.

MRI is particularly advantageous for cases where radiation exposure must be minimized, but its utility remains focused on specific procedures. For example, it has been explored in guiding interventions like aneurysm repair near critical brain structures, where the high soft tissue contrast provided by MRI allows for safer navigation in delicate anatomical regions [40]. However, such cases represent a relatively small

Table 2. Research robotic platforms for endovascular procedures

Platform (year)	Application	Endovascular instruments	Controller setup	Haptic feedback	3D navigation	Description
Research platforms						
Jayender et al. (2008) [56]	EV	Steerable catheter	Remote workstation	Yes	Yes	SMA actuated catheter.
Ganji et al. (2009) [57]	EP	Steerable EP catheter	Remote workstation	Yes	No	EM sensor and haptic controller.
Srimathveeravalli et al. (2010) [58]	EV	Standard catheter and guidewire	Remote workstation	Yes	No	Friction drive mechanism.
Wang at al. (2010) [59]	EV	Standard catheter	Remote workstation	Yes	Yes	Haptic interface.
Park et al. (2010) [60]	EP	Steerable EP catheter	Remote workstation	Yes	No	Controller replicating catheter handling.
Fu et al. (2011) [61]	EV	Steerable pull-wire catheter	Remote workstation	Yes	Yes	EM sensors and haptic controller.
Payne et al. (2012) [62]	EV	Standard catheter	Manually advanced catheter	Yes	No	User interface mimicking manual manipulation.
Zakaria et al. (2013) [63]	EV	Standard catheter	Remote workstation	Yes	No	User interface mimicking manual manipulation.
Tavallaei et al. (2016) [43]	EV	Steerable catheter	Remote workstation	No	No	MR-compatible. User interface mimicking manual manipulation.
Ataollahi et al. (2016) [44]	EP	Steerable catheter	Remote workstation	No	No	MR-compatible.
Cha et al. (2016) [65]	EV	Steerable catheter	Remote workstation	Yes	No	User interface mimicking manual manipulation.
Cercenelli et al. (2017) [64]	EP	Steerable catheter	Remote workstation	Yes	No	Joystick controller.
Sankaran et al. (2018) [66]	EV	Standard catheter	Remote workstation	Yes	No	Bidimensional maneuverability of vascular devices.
Omisore et al. (2018) [67]	EV	Standard catheter	Remote workstation	Yes	Yes	No teleoperation. Backlash correction system.
He et al. (2018) [68]	EV	Steerable catheter	Remote workstation	Yes	No	Variable stiffness steerable catheter.
Guo et al. (2019) [69]	EV	Standard catheter	Remote workstation	Yes	No	Ergonomic user interface.
Dagnino et al. (2022) [8]	EV	Standard catheter	Remote workstation	Yes	Yes	MR-compatible. User interface mimicking manual manipulation.

EP: electrophysiology; EV: endovascular.

subset of patients yet, and the high costs associated with MRI-compatible robotic systems may not be justified for more routine interventions, where fluoroscopy or angiography suffice.

2.2.1.2. Technical limitations and resolution challenges. While MRI excels in providing soft tissue contrast, it faces limitations in terms of spatial and temporal resolution. For instance, its ability to visualize smaller vessels with the same precision as fluoroscopy is restricted by physical factors, including specific absorption rate (SAR) limits and the strength of magnetic gradients. These limitations are particularly pronounced when high temporal resolution is required, such as in dynamic vascular procedures. In contrast, traditional X-ray-based modalities like fluoroscopy are better suited for imaging fast-moving structures, as they offer higher spatial resolution in real time [41].

2.2.1.3. Procedural constraints. For MRI-guided interventions, SAR limits are a potential concern, especially in long or complex procedures. The amount of energy absorbed by the body during MRI restricts the duration and intensity of certain sequences, which is particularly problematic for pediatric and pregnant patients. These constraints limit the sequences available for real-time imaging and reduce the resolution and speed at which interventions can be conducted. Additionally, obtaining regulatory approval for certain MRI sequences in these patient groups can be a complex and time-consuming process. MRI-guided procedures are currently limited in their ability to fully exploit advanced MRI techniques during time-critical interventions. Advanced MRI techniques like diffusion-weighted imaging (DWI), perfusion-weighted imaging (PWI), and tissue oxygenation mapping can provide invaluable information about the extent of damage, ischemia, and tissue viability, but they are time-consuming. These imaging processes can take several minutes, which is a substantial delay in an acute setting. The trade-off between imaging detail and procedural speed is a key challenge. Current prototypic platforms focus primarily on incorporation of real-time MR imaging to the procedural workflow which is challenging due to the continuous adaption of scan planes.

2.2.1.4. Future outlook.

Although MRI holds great promise for specific endovascular applications, particularly in reducing radiation exposure, its current limitations in terms of speed, resolution, and procedural complexity make it unlikely to fully replace fluoroscopy in most cases. The development of MRI-compatible robotic platforms is a promising avenue, but significant advances in MRI scanner technology, such as improving real-time imaging capabilities, will be needed before MRI-guided interventions can become more widely applicable.

Research continues to explore the integration of MRI with robotic systems, with the aim of achieving safer, radiation-free interventions in highly specialized cases. Researchers at Imperial College London have created an MR-safe robotic platform for endovascular intervention [3]. The robotic platform, named CathBot, features enhanced instrument maneuverability, multimodal image guidance (standard fluoroscopy and MRI), and vision-based haptic feedback [7]. The system was successfully tested on in-vivo porcine models [8].

Few other MRI-compatible endovascular robotics are reported in the literature, namely those of Tavallaei et al. [43], Ataollahi et al. [44], and Lee et al. [45]. However, development of fully MRI-compatible robots remains challenging due to constraining design, sensing, and actuation components resulting from operating in MR-safe areas.

For now, the focus remains on balancing the advantages of MRI with the practical limitations of current technology.

2.2.2. Human-robot interaction

Human-machine interfaces (HMI) constitute the main operator interface in terms of control input and visual representation of the device state.

The majority of academic endovascular platforms and commercial devices continue to rely on traditional joysticks (with one to multiple degrees of freedom). These joysticks are typically mapped to control instrument displacement, feeding, rotation, or bending.

Researchers have tackled this limitation through various approaches in their studies, mainly by creating task-specific HMI, and introducing novel concepts and feedback cues by abstracting the input layer. In this scenario, the operators can swiftly familiarize themselves with the robot's operation and even replicate their established surgical habits or experiences gained from manual interventional procedures. It's worth noting that the operators' expertise is derived from manual instrument manipulation, which may not always align seamlessly with the requirements of robotic systems. To prevent this loss of skill, HMI mimicking a real vascular instrument manipulation could be a solution. Such devices are being developed but are still far from being implemented in clinical practice. For example, a tailored HMI has been presented for endovascular surgery thus replicating clinical handling and motion pattern of conventional catheters and guidewires [3]. Guo et al. [46] developed an endovascular catheter robot presenting a magnetically controlled HMI based on hydrogel and solid magnetorheological fluid that offers a sense of haptic feedback to operators and tremor reduction. *In vitro* experiments demonstrated that haptic feedback has the advantage of reducing workload and shortening surgery completion time.

2.2.3. Autonomy

In 2017, Yang et al. defined a taxonomy of level of autonomy for surgical robots [47]. They introduced the distinction between six levels of autonomy, starting from no autonomy with robotic control based on direct operator input to fully autonomous execution and completion of the robotic task without human interaction.

In addition, a technical report (IEC/TR 60601-4-1) [48] published by the International Organization for Standardization (ISO) in collaboration with the International Electrotechnical Commission (IEC) proposed initial standardization on autonomy levels of medical robots. Haidegger et al. [49] provided a top-down classification of Levels of Autonomy (LoA) for general robot-assisted MIS. Their classification considers four robot cognitive functions (i.e., generate, execute, select, and monitor options).

For the practice of minimally invasive endoluminal surgeries Pore et al. propose five levels of robot autonomy, based on the assistance provided while navigating instruments such as catheters or steerable guide wires [50]. They identify the three specific cognitive functions for an endoluminal navigation task:

target localization, motion planning, and execution and replanning.

As of now, commercial endovascular platforms have achieved only partial autonomy, meaning that certain workflow phases with fully predictable device behaviors are implemented. In other words, sequences of motion primitives are executed autonomously to facilitate teleoperation.

Utilizing artificial intelligence (AI) techniques alongside robotic platforms is an emerging approach to enhance the autonomy of robots in endovascular procedures. Machine learning (ML), a subset of AI, has experienced notable advancements in recent years, particularly in data analysis and learning applications. Within healthcare, various domains already leverage ML for tasks such as disease prediction and diagnosis. ML algorithms can be categorized into three primary groups: supervised, unsupervised, and reinforcement learning. The most prevalent form, supervised learning, entails constructing a model trained on a labeled dataset, where the model learns patterns to accurately predict labels for new, unknown instances based on the acquired knowledge from the training data.

The clinical need for autonomous task execution in endovascular procedures is driven by several factors related to the complexity, precision, efficiency, and safety of these interventions. As the field of endovascular therapy evolves, the demand for more sophisticated techniques that can improve outcomes while reducing risks is increasing. For example, autonomous systems can enhance precision by executing tasks with millimeter accuracy, reducing the risk of human error. These systems can follow pre-programmed paths, clamp individual instruments in a cooperative setting, or adjust movements based on real-time imaging data, ensuring consistent and precise execution, which is especially critical in complex or high-risk procedures.

Autonomic task execution can streamline procedures by automating repetitive or time-consuming steps, such as wire manipulation, catheter advancement, or device deployment. This not only speeds up the procedure but also allows the interventionalist to focus on decision-making and more complex tasks, thus improving overall efficiency.

Autonomous systems can standardize the execution of critical tasks, ensuring consistent performance regardless of operator experience or fatigue. This standardization can lead to more predictable outcomes, reducing the learning curve for new practitioners and enhancing the overall quality of care.

Autonomously executed tasks can be performed with minimal direct human intervention, potentially reducing the time spent under fluoroscopy or allowing procedures to be performed in MRI suites where radiation exposure is not an issue. This can greatly enhance safety for both patients and clinicians.

Autonomous systems could democratize access to complex endovascular care by allowing less experienced practitioners to perform procedures with support from AI-driven autonomy. This could extend the reach of advanced care to regions where specialized expertise is not available, such as remote areas without interventional radiology centers.

For a detailed analysis of the role of AI in the autonomous robotic navigation of endovascular intervention, we refer the readers to these recent reviews [50–52].

Taking the CorPath GRX platform as an example, it incorporates partial procedural autonomy for guidewire manipulation, such as spinning to navigate through lesions, replicating motion patterns observed in manual instrument handling. Fueled by significant advancements in vision and AI, ongoing research endeavors in endovascular robotics aim to elevate autonomy levels, providing enhanced support to clinical operators and ultimately improving clinical outcomes. A particularly relevant clinical application is the autonomous cannulation of targets within the vasculature. Achieving this involves extensive training for interventionists to avoid damage to delicate vessels and to precisely reach the intended target using both guidewire and catheter instrumentation. Studies employing conditional approaches (autonomy Level 3) through a robotic platform, coupled with generative adversarial imitation learning, have demonstrated feasibility and shown improvements in cannulation results. Chi et al. [53] explored the acquisition of catheterization skills for the brachycephalic artery through expert demonstration coupled with a generative adversarial imitation learning agent. Following this, a proximal policy optimization agent is trained to perform catheterization on the left common carotid artery. The training and evaluation of both agents take place in a Type I aortic arch, with subsequent assessments conducted in both Type I and Type II aortic arch phantoms, utilizing electromagnetic tracking for feedback. Karstensen et al. [54] developed a learning-based system for autonomous navigation of vascular guidewire without human demonstration. A neural network-based controller *via* deep reinforcement learning in a finite element simulation was trained to navigate the venous system. The system achieved a 100% success rate in a simulated environment, proving the feasibility of learning-based approaches. However, the success rate dropped to 30% in *ex vivo* experiments on porcine liver showing limitation on translating the approach to real-world applications (domain transfer problem).

Attanasio et al. [55], considering the work of Yang et al. [47], include platforms that provide active assistance by providing real-time haptic feedback on the user manipulator at the Level 1 of autonomy, i.e., robot-assistance. This is the case with the work of Jayender et al. [56], Ganji et al. [57], Srimathveeravalli et al. [58], Wang et al. [59], Park et al. [60], Fu et al. [61], Payne et al. [62], Zakaria et al. [63], Cercenelli et al. [64], Cha et al. [65], Sankaran et al. [66], Omisore et al. [67], He et al. [68] Guo et al. [69], and Dagnino et al. [7].

Some of the newly introduced platforms, like the one from Kundrat et al. [3] also feature a computer-assisted system for navigating instruments during surgery. This technology allows for a system of interactive control and security of the intervention procedure. They propose a control architecture composed by the catheter tracker, the vessels tracker, and dynamic active constraints [7]. According to the classification introduced by Pore et al. such navigation system would be labeled as LoA 1, as the human operator maintains the control intraoperatively but it is assisted by the execution of the motion [50].

3. Discussion

Navigating through the vascular system presents challenges, demanding exceptional endovascular skills to prevent inadvertent contact that may lead to perforations and injuries [70,71]. The reliance on 2D fluoroscopy exposes both patients and operators to ionizing radiation, with associated risks and limitations. Robotic technology has garnered increasing interest due to its potential to enhance catheter and guidewire maneuverability, offering benefits such as improved stability, precision, reduced radiation doses, and enhanced patient comfort. For example, robotic systems such as the CorPath GRX have been shown to improve precision in coronary neurovascular interventions [72,73] by offering sub-millimeter accuracy in catheter positioning, reducing the risk of human error, and enhancing procedural outcomes. Mahmud et al. [74] reported a significant reduction in radiation exposure for operators using the CorPath robotic system in percutaneous coronary interventions (PCI). The study found that operators experienced a 95% reduction in radiation exposure compared to traditional methods. A pilot study by Patel et al. [75] demonstrated the feasibility of remote-controlled robotic PCI, successfully performing the procedure over a significant distance without compromising patient safety. However, further clinical studies are required to substantiate the benefits of robotic systems. These studies should assess cost-effectiveness, demonstrate improved patient outcomes, and compare various competing solutions. The clinical value of such devices might be evident through enhanced efficiency (e.g., improved functional outcomes, longer survival), reduced adverse effects (e.g., less blood loss, minimized radiation exposure), or improved operational aspects (e.g., fewer personnel needed, shorter procedure times, faster recovery). Given that these clinical trials can span several years, the anticipated improvements may not always be immediately apparent [29].

Commercial platforms, generally teleoperated, can enhance maneuverability of vascular instruments but often modify operators' natural manipulation skills, necessitating a focus on improving 3D navigation, integrated force feedback, and overall ergonomics.

However, due to the time-consuming and complex workflows currently required by available robotic systems in particular due installation and instrument exchanges, as well as challenges in their implementation and limited versatility, these devices are not yet suitable for emergency interventions. The need for rapid decision-making and swift action in emergencies like strokes or acute hemorrhages makes the use of these systems impractical in their current form.

However, there are specific procedures that, while time-intensive and highly standardized, could benefit from robotic assistance. One such procedure is trans-arterial chemoembolization (TACE), which is used to treat liver tumors. TACE is both time-consuming and involves prolonged exposure to radiation for medical staff. Robotic systems could reduce radiation exposure by allowing operators to control the procedure remotely, thus minimizing the need for direct involvement near the radiation source.

Additionally, these systems could improve the precision and reproducibility of TACE, which relies on accurate catheter navigation and embolization. While further advancements are needed to make robotic systems viable for emergency interventions, their potential to enhance safety and efficiency in complex but non-emergent procedures like TACE is promising and warrants further discussion and exploration.

Emerging technologies such as the CathBot system [8], aim to address such limitations by enhancing robots' usability and integration within the clinical workflow, versatility, and reducing the setup time.

MRI-compatible platforms can potentially provide radiation-free 3D imaging during endovascular interventions. Human-robot interaction is evolving, with efforts to develop controllers that mimic manual instrument handling. Additionally, autonomy levels in robotic endovascular interventions are advancing, with studies exploring varying degrees of assistance. Some robotic platforms (please refer to Tables 1 and 2) integrate available pre-procedure imaging data, such as CT or MRI scans, in a manner that enhances precision and control during interventions. In conventional angiography suites, pre-procedure CT or MRI data is co-registered with live 2D angiographic images to create 3D guidance models. Robotic systems leverage similar approaches by incorporating this imaging data into their software platforms [76,77]. The pre-procedural imaging data is used to create a detailed 3D map of the vascular anatomy, which the robotic system can reference in real-time during the procedure. However, current registration methodologies are rigid, and a dynamic approach to track anatomical deformations in real-time, such as those caused by instrument-tissue interactions or physiological activities like breathing and heartbeat, would be highly desirable for intraprocedural monitoring and guidance [78]. Integrating such a dynamic registration system would enable the robotic system to navigate with sub-millimeter precision using a 3D roadmap generated from continuously updated images. This would allow the system to automatically align the catheter or guidewire along the optimal path, accommodating anatomical variations and minimizing the risk of vessel injury [79].

Similarly, tracking endovascular devices is crucial for achieving precision and enhancing the safety of procedures. One promising technology in this area is shape sensing using fiber optics. For instance, Philips (Eindhoven, The Netherlands) has developed Fiber Optic RealShape (FORS) technology, which provides real-time 3D visualization of the complete shape of devices within the body, eliminating the need for fluoroscopy. FORS operates by sending pulses of light through hair-thin optical fibers embedded in minimally invasive devices. By directing laser light into the fiber and analyzing the reflected light, it's possible to reconstruct and visualize the entire shape of the devices in real-time, in 3D, with distinctive colors, and from any angle.

Despite current technological advancements, challenges persist, including technical complexity, high costs, limited usability, and the need for specialized equipment. As research continues to push the boundaries of robotic endovascular interventions, addressing these challenges will be essential for widespread adoption and improved patient outcomes. Future developments should aim for compatibility with off-the-shelf equipment, ease of interchangeability, and advancements in navigation technologies. In particular, the integration of MRI-compatible robotic platforms, enhanced human-robot interaction, and increased autonomy hold promise for the future of robot-assisted endovascular interventions. The transformative impact of AI and novel imaging modalities is poised to influence endovascular surgery. For instance, the application of action recognition to clinical imaging data recordings, including non-ionizing MRI, holds the potential to enable trajectory planning, decision-making, and real-time autonomous robotic navigation of endovascular instrumentation. While recent technological strides have been significant, clinicians are expected to retain control over procedures in the coming decades. Partial autonomy is anticipated to play a crucial role in providing clinical assistance in medical robotics. Beyond that, current training procedures require physical robot set-ups due to absence of simulator environments. Here, clinical training could be greatly enhanced by providing VR-based training for general installation and preparation of the system; additionally, interaction with dedicated robotic simulators could enhance the procedural training in analogy to robotic platforms in laparoscopy.

4. Conclusion

This review has provided an overview of the current advancements and challenges in the field of endovascular robotics. Robotic platforms for endovascular interventions offer significant benefits, including enhanced precision, improved operator ergonomics, and the potential to reduce radiation exposure. Both commercially available systems and emerging research platforms show promise in improving the outcomes of minimally invasive procedures, particularly through improved navigation and control of instruments within the vascular system.

However, significant barriers to widespread clinical adoption remain, such as high costs, technical complexity, and the need for seamless integration into existing clinical workflows. Moreover, ongoing research is needed to address limitations in autonomy, real-time imaging capabilities, and the development of MR-compatible systems.

Moving forward, advances in human-robot interaction, imaging modalities, and artificial intelligence are likely to drive the next generation of robotic platforms. These technologies have the potential to improve the accuracy, safety, and efficiency of endovascular procedures, ultimately enhancing patient outcomes and expanding the reach of these innovative systems. Continued collaboration between engineers, clinicians, and researchers will be essential to overcoming current challenges and realizing the full potential of robotics in this field.

Author contributions

Conception and design: GD; Data acquisition: all authors; Analysis and interpretation: all authors; Drafting the manuscript: MP, GD; Critical revision: all authors.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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