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REVIEW

Robot-assistive minimally invasive surgery: trends and future directions

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Abstract

The evolution of medical technologies—such as surgical devices and imaging techniques—has transformed all aspects of surgery. A key area of development is robot-assisted minimally invasive surgery (MIS). This review paper provides an overview of the evolution of robotic MIS, from its infancy to our days, and envisioned future challenges. It provides an outlook of breakthrough surgical robotic platforms, their clinical applications, and their evolution over the years. It discusses how the integration of robotic, imaging, and sensing technologies has contributed to create novel surgical platforms that can provide the surgeons with enhanced dexterity, precision, and surgical navigation while reducing the invasiveness and efficacy of the intervention. Finally, this review provides an outlook on the future of robotic MIS discussing opportunities and challenges that the scientific community will have to address in the coming decade. We hope that this review serves to provide a quick and accessible way to introduce the readers to this exciting and fast-evolving area of research, and to inspire future research in this field.

Keywords Minimally invasive robotic surgery · Medical robotics · Surgical robots · Image-guided robotic surgery

1 Introduction

Since the early breakthrough with Lister's seminal work on antiseptic surgery (1860s), surgery has been constantly evolving, and surgeons continue to explore new approaches to improve outcomes for patients by making procedures safer, less traumatic and more effective (Vitiello et al. 2013). Moreover, emerging technologies have played crucial roles in aiding and enhancing the abilities of surgeons (Fig. 1). For example, advances in the areas of anaesthesiology, radiology, microbiology, histopathology, immunology, oncology, engineering, imaging, and in particular the digital transformation of the healthcare domain, are today supporting the surgical procedures around the globe, allowing the surgeons to refine, or even redefine, their specialties. And such developments will continue to propel and transform approaches to diagnosis and surgical treatment of diseases, leading to exciting future developments.

The advent of Hopkins' endoscope in the 1960s, technology advancements in the following two decades, and the first laparoscopic cholecystectomy by Mühe in the 1985 (Reynolds 2001), marked the transition to the minimally invasive surgery (MIS) era and its application in many surgical applications over open surgery. The main goal of MIS is to minimize the incisions—both in number and size—thus reducing the damage to soft tissues created by large incisions. In consequence, this minimizes the patient recovery time, postoperative pain or the risk of contracting an infection, while ensuring overall cost-effectiveness (Vitiello et al. 2013). While the advantages of MIS are clear to patients, new surgical technologies require the clinicians to undergo specific training to use such new devices. Traditional surgical curricula have not yet been revised to accommodate advanced or even emerging technologies (Kuhn et al. 2021). Therefore, clinicians must adapt to new surgical workflows and surgical instruments manipulation, thus to new visuo-tactile feedback. In fact, laparoscopic devices (e.g., video camera, rigid surgical instruments) physically separate the surgeon from the patient reducing their perception (e.g., visual or haptic sensing) and manipulation capabilities. For example, in laparoscopic procedures surgeons operate while looking at a screen displaying

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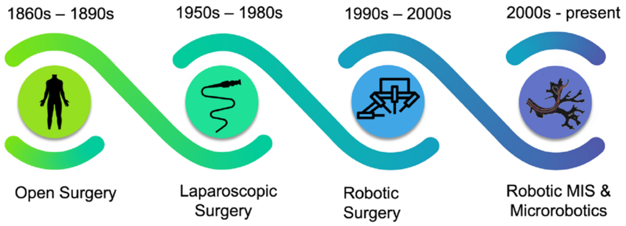


Fig. 1 The evolution of surgery is strictly linked to the evolution of technology. The discovery of anaesthesia and antiseptic in the XIX century paved the way to modern open surgery. The mid of XX century is characterised by the evolution of minimally invasive surgery (MIS), thanks to the discovery of rigid endoscopes followed by flexible fibre optics devices. Imaging techniques such as x-ray and computed tomography (CT) strongly contributed to the evolution of surgery towards a more minimally invasive approach and early diagnosis of diseases. Smaller lesions brought on by early diagnosis necessitate minimally invasive access as well as precision surgery, which frequently calls for surgeons to possess enhanced manipulation, vision, thinking, and decision-making capabilities. The era of robotic surgery started at the end of the XX century when bulky industrial robots were used for the first time to perform clinical tasks. In the following decades, bespoke robots for minimally invasive surgery have been developed and quickly evolved toward smaller and smarted devices that can be used in several surgical applications (sometimes not even requiring an incision in the body, e.g., through natural orifices and lumens). The future of surgery will be directed by technology advances in areas like robotic MIS toward precision intervention and targeted therapy, e.g., micro/nano robots that can navigate the human body to a desired target and perform diagnosis and treatment in one step

2D images provided by the endoscope, with consequent loss of depth perception (Sørensen et al. 2016). Surgeons must manoeuvre the surgical instruments while addressing the so-called 'fulcrum effect' brought on by the constricting incision ports, which limits haptic sensation, causes motion inversion and affects input scaling (Gallagher et al. 1998). Other MIS procedures (e.g., endovascular intervention (Dagnino et al. 2018)), for example use force feedback to safely navigate the human body. However, novel assistive concepts were proposed to manual clinical routines, e.g., in laparoscopy, or the use of laser instrumentation. 3D visualisation has demonstrated superior outcomes in laparoscopic surgery (Wagner et al. 2012) and became a component of European clinical roadmaps (Arezzo et al. 2019). More specifically, rendering of augmented visual feedback has demonstrated a significant improvement on adjustment of the laser focal position in endoscopic laser surgery (Kundrat et al. 2019; Schoob et al. 2016).

Robotic systems have been introduced into clinical practice to mitigate these limitations, bringing solutions such as enhanced dexterity, improved stability, motion accuracy, and the possibility of accessing target anatomies located in previously difficult-to-reach areas of the body using bespoke flexible devices.

In the last 30 years, surgical platforms have been developed for essentially all parts of the human body. In order to overcome the limitations of conventional minimally invasive procedures (challenging to perform due to the limitations described above), surgical robots were first created to address the clinical demand for greater accuracy in manipulation and visualisation (Vitiello et al. 2013). Today, robotic systems are utilized in many specialties, including neurosurgery, ear-nose-throat (ENT), head and neck, orthopaedics, laparoscopy and via human body lumens. According to (Bergeles and Yang 2014), there are four major generations of surgical robots: (i) stereotaxic robotic systems (first generation); (ii) rigid dexterous robots for MIS (second generation); (iii) flexible robots for MIS (third generation); and (iv) untethered microsurgeons (fourth generation). Standard laparoscopy (manual) can be considered the zeroth generation. Alternative classification approaches in medical robotics, for example, consider the level of system autonomy to describe the evolution from teleoperation executed by skilled surgeons to full autonomy (Yang et al. 2017; Fiorini et al. 2022; Attanasio et al. 2021).The evolution of surgical robots over the last decades has shown a constantly growing and stronger integration of image-guidance, sensing, and robotic assistance, which resulted in safer and more effective procedures.

In the next sections, we will provide a perspective on the evolution of surgical robot applications in the last decades, an overview of the available technologies for robot-assistive MIS, as well as open challenges and future directions of this fast-growing area of healthcare technology.

2 Methodology of the study

An extensive examination of pivotal research studies and articles pertaining to robotic Minimally Invasive Surgery (MIS) has been conducted. This study encompassed a survey dedicated to robotic systems and publications that exemplify significant advancements in the field of robotic MIS, while also pinpointing ongoing challenges and prospective research avenues. The search terms employed for this inquiry included "Robotics for Minimally Invasive Surgery" and "Robot-Assisted Surgery." In this review, the authors endeavor—when possible—to encompass systems that have progressed into the realm of commercialization, emphasizing their clinical impact and innovative contributions. The framework adopted in this paper is centered on the interplay between robotics, imaging, and sensing. It is essential to note that this review does not aim to present an exhaustive taxonomy of research publications. This review serves to provide a quick and accessible way to introduce the readers to this exciting and fast-evolving area of research, and to inspire future research in this field. Instead, we direct interested readers to consult existing reviews dedicated to the broader landscape of robotic surgery (Vitiello et al. 2013; Bergeles and Yang 2014; Troccaz et al. 2019; Bergeles et al. 2016; Payne and Yang 2014; Cundy et al. 2013; Marcus et al. 2014; Marcus et al. 2017; Lee et al. 2010; Karimyan et al. 2009).

3 Evolution of robotics for minimally invasive surgery

Figure 2 summarises the evolution of minimally invasive robotic surgery from its beginning in the 1980s to present days. In 1985 a conventional industrial robot, the PUMA 200 (Unimation, Danbury, CT) (Kwoh et al. 1988), was experimentally employed in a surgical procedure of needle insertion, becoming the first example of a surgical robot in history. Since then, an ever-increasing number of platforms from both commercial and research organizations have been developed and successfully used in a wide range of surgical specializations, such as neurosurgery, ear-nose-throat (ENT), orthopaedics, laparoscopy, and endoluminal procedures. For a comprehensive domain-specific review of the literature, we refer the readers to Vitiello et al. (2013); Bergeles and Yang 2014; Troccaz et al. 2019; Bergeles et al. 2016; Payne and Yang 2014; Cundy et al. 2013; Marcus et al. 2014; Lee et al. 2010; Marcus et al. 2017; Karimyan et al. 2009).

The 80 s were characterized by the first generation of surgical robots for stereotaxic interventions in neurosurgery and orthopaedics. Examples include the Neuromate system (Renishaw, UK) for accurate positioning of neurosurgical tools for biopsy, electrode implantation, and neuro-endoscopy (Lavallee et al. 1992); and Robodoc (Curexo Technology, USA), developed at IBM to improve arthroplasty surgeries of the hip (Paul et al. 1992a).

The 90 s' marked the move from stereotaxic robotic systems to a second generation of surgical robots, i.e., rigid dexterous robots for MIS with several arms remotely controlled by the surgeon via a remote operating console. This concept was exploited in the Zeus platform (Computer Motion, USA) first, and then in the da Vinci system after the merger of Computer Motion and Intuitive Surgical in 2003. Since 2003 several versions of the da Vinci system have been developed, including the most advanced multi-arm version (da Vinci Xi), and the single port version for narrow access surgery (da Vinci SP).

The first decade of the new millennium signs the evolution of surgical robots toward miniaturised and smarter devices: this generation of surgical robots includes small and steerable devices (robotic catheters, robotic endoscopes or snake-like robots) which are flexible and can access and operate constrained regions of the human body not previously reachable with rigid laparoscopy. Exemplary applications are endovascular intervention, abdominal surgery, and bronchoscopy. One of the main limitations of such flexible robots is the inability of applying high manipulation forces to the tissues due to structural deficiencies. Concentric tube robots (also denoted as active cannula), introduced around 2005 by research of Furusho et al. (2005); Sears and Dupont 2006; Webster 2007), address such limitation by providing the required higher stiffness. These robots are made of nested groups of pre-curved elastic tubes (e.g., Nitinol) that, when translated and rotated in relation to one another, bend and deform as a result of structural interaction (Vitiello et al. 2013). This fundamental principle has been explored and extended to many different applications (please refer to reviews in Mitros et al. (2021)) and lately miniaturised to submillimetre scale (Nwafor et al. 2023).

The 2000s also signed the development of a novel generation of MIS robots, the untethered microrobots, focusing on improving the intraluminal navigation of human body thus enhancing the minimally invasive diagnosis and therapy of pathologies. As an example, capsule endoscopes can navigate the gastrointestinal tract with the great benefit of removing the pain, risks, and discomfort of traditional flexible endoscopy. The promising results of capsule endoscopy led to commercialization including advancing imaging and 3D tracking capabilities, e.g., the

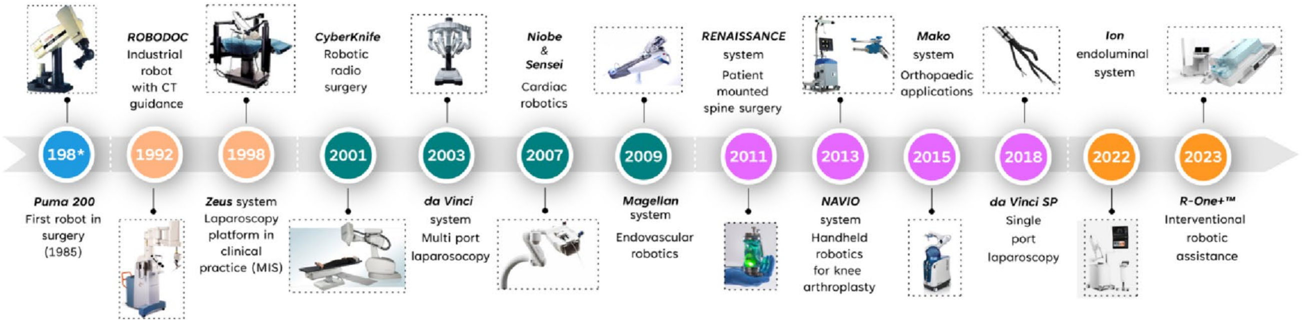


Fig. 2 Timeline of minimally invasive robotic surgery. Image adapted with permission from Troccaz et al. (2019)

ENDOCAPSULE 10 system (Olympus, Tokyo, Japan). Beyond that, several research groups have proposed different designs and locomotion techniques for such devices, including legged (Gorini et al. 2006) and worm-like (Kwon et al. 2007) locomotion systems. Recently, magnetic actuation of endoscopy capsules was demonstrated (Popek et al. 2017). The readers are kindly referred for a general review on capsule endoscopy to Ciuti et al. (2016), for magnetic actuation principles to Chen et al. (2022) and for a review on alternative intra-gastric and intra-intestinal locomotion to Liu et al. (2015).

Jumping at current days, we are entering the era of untethered micro/nano surgical devices (please refer to these review papers (Zhou et al. 2021; Hu et al. 2018)). Surgical platforms that are currently in use in clinical practice still present some major technical difficulties and challenges, such as mechanical parts that are still relatively large and rigid to access and treat small, early lesions or previously inaccessible parts of the human body. The development of miniaturized, adaptable robots with dimensions of a few micrometres and the ability of navigating the whole human body will pave the way for new precise, localized (cellular-level), effective, and patient-tailored procedures.

4 Exemplary applications of robotic MIS platform

This section provides an overview of robotic platforms that have been developed in the last 30 years, categorised by clinical application as summarised in Fig. 3.

4.1 Neurosurgery

As mentioned, the first clinical application of a robot was in stereotaxic neurosurgery in 1985, when the PUMA 200 (Unimation, USA)—an industrial robotic arm—was used to introduce a needle and perform a brain biopsy (Kwoh et al. 1988). Such system evolved into the Neuromate (Renishaw, UK), one of the first robots that received the FDA (Food and Drug Administration) approval. Based on the preoperative planning and intraoperative registration (between pre-operative CT or MRI data and intra-operative ultrasound or x-ray images), this image-guided robot allows accurate positioning of a tool holder along pre-planned trajectories. Due to the clinical advantages compared to frame-based interventions, the device is still used in neurosurgical facilities and has been extensively evaluated in clinical trials (Yasin et al. 2019).

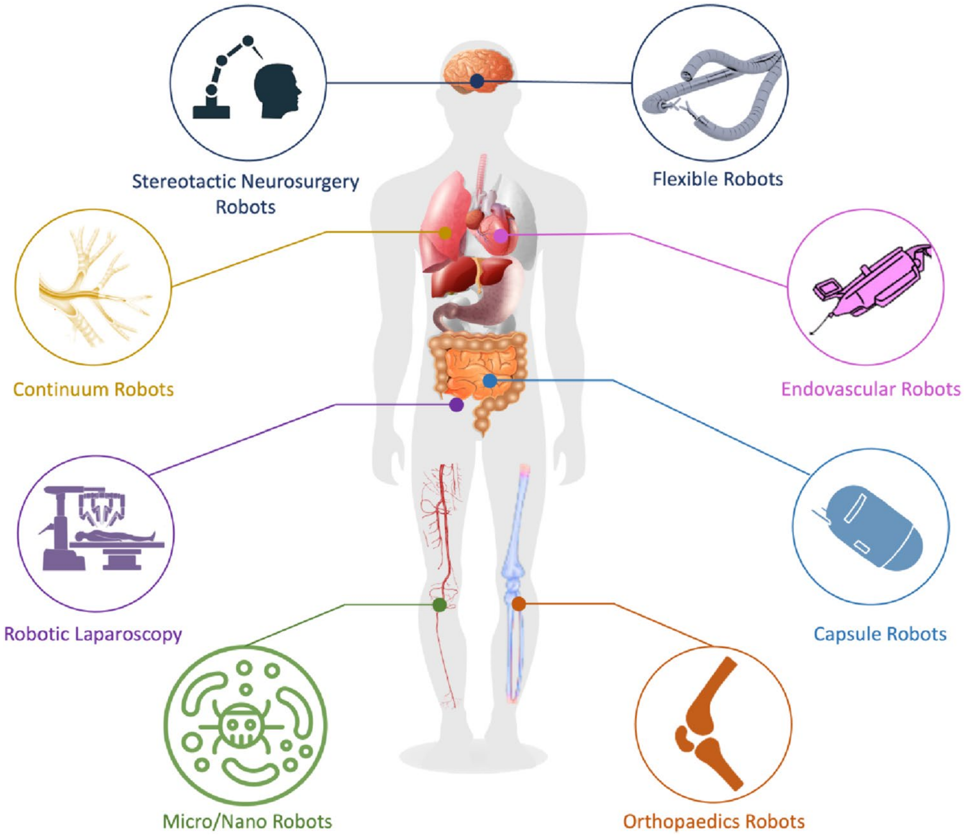


Fig. 3 Examples of robotic MIS applications. Stereotactic neurosurgery is the first application of a robot in surgery quickly followed by orthopedics. Laparoscopy robots started the great commercial success in the early 2000s (with the da Vinci) and are nowadays widely used in many applications such as prostatectomy, cystectomy, rectal cancer, and hysterectomy. Flexible robots for endoluminal intervention are used in varying applications including bronchoscopy, endovascular intervention, colonoscopy and also brain microsurgery. Capsule robots can be swallowed for endoscopic diagnosis and treatment of the gastrointestinal tract. Recent advances in micro/nanorobots are paving the way for precise surgical applications. For example, micro/nanorobotic tools, such as nanodrillers, micrograppers, or microbullets, offer unique capabilities for early and targeted intervention

Since then, the design of surgical robots moved from bulky industrial arms to smaller and bespoke devices with dedicated systems engineering resulting in enhanced clinical usability. Exemplary systems include the neuroArm, which could be used inside an MR scanner (Cossetto et al. 2012) coupling the superior display of soft-tissue contrast provided by MRI with the enhanced manipulation precision and dexterity of the robot. Additionally, robotic platforms were further miniaturized so to be connected directly to the patient. For example, the Renaissance robot (Mazor Robotics, Israel) can be connected directly to the spine of the patient, and, on the basis of preoperative CT planning, it can follow the patient's motion and guide the surgeon to place screws and implants in the spine.

CyberKnife (Accuray Inc., USA) is another interesting system which used to perform radiotherapy to primarily treat brain and spine tumours. The system takes advantage by the integration of imaging and sensing to compensate for motion in an autonomous way, so to deliver an optimized radiation dose directly to the tissues affected by the tumour, while preserving and protecting the healthy structures (Schweikard et al. 2005).

4.2 Orthopedics

Application of robotics to orthopaedics advanced in parallel to stereotactic neurosurgery. As both specialties deal with rigid structures such bones, the registration between the robotic system and the patient's anatomy is simplified and considered constant over the procedure, enabling desired features such as real-time intraoperative navigation, tracking, and vision-based closed-loop control of the robot (Troccaz et al. 2019).

The first robotic platforms for orthopaedics that have been developed focused on arthroplasty applications. ROBODOC (Curexo Technology, USA) was developed in 1986 to improve total hip replacements, and then commercialized in 1994 by Integrated Surgical Systems (Sacramento, USA) (Paul et al. 1992b). ROBODOC integrates patient CT data into the control system of a robotic arm allowing preoperative 3D planning of the procedure and—for the first time–force sensing to precise mill the femur of the patient and receive the replacement implant.

The Imperial College London's system Acrobot, was developed for total knee replacement (Jakopec et al. 2003). A surgical plan is created using a CT scan of the patient, which is then integrated into the robotic system to direct the surgeon during the milling operations. Active constraints ensure that the robot only operates in predetermined and permissible locations. In such configuration, the robot cooperates with the surgeon (active guidance), rather than performing surgical tasks autonomously as in the ROBODOC example.

Similarly to Acrobot, a more recent system for knee arthroplasty—the Mako system (Stryker, USA)—uses CT data of the knee acquired preoperatively to create the surgical plan. The 3D model of the knee is registered to the patient and the surgeon can see it on a screen while manipulating the burr intraoperatively. The Mako system generates no-fly zones to prevent burring the bone outside of predefined and safe areas and offers haptic and auditory feedback (Lang et al. 2011). Clinical benefits include reduced postoperative pain and more accurate implant positioning compared to conventional arthroplasty (Batailler et al. 2021).

A smaller-scale, frameless handheld robotized driller for knee arthroplasty—the Navio system (Smith & Nephew, UK)—does not require intra-operative registration or preoperative CT scans. Instead, Navio uses an infrared camera and optical tools to track the patient's anatomy and the handheld robotic device, and a 3D model of the knee is produced by the creation of a physical map of the anatomy by tactile mapping the tracked optical probe over it (Herry et al. 2017). A comparative study of the latest robotic technologies for arthroplasty—the Mako and Navio systems—and their impact on the 1-year patient outcome showed no differences in terms of radiologic implant position assessment (Leelasestaporn et al. 2020).

Fracture surgery is another growing area of orthopaedics where robotics and image guidance can support the clinical team. Pioneering research from (Dagnino et al. 2017, 2016a, b; Georgilas et al. 2018) proposes a robotic platform to reduce joint fractures. The system, named as RAFS (robot-assisted fracture surgery), can perform minimally invasive (percutaneously) reduction of joint fractures (i.e., in the knee) based on patient-specific CT data. Before surgery, the fracture is manually reduced in the computer (virtual reduction) by the surgeon using CT-generated 3D bone models. The preoperative planning is registered with the patient in the operating room, and the robot completes the physical reduction while the surgeon can make adjustments or take over as necessary. RAFS tracks both the patient's anatomy and the robotic manipulators to offer real-time intraoperative 3D navigation.

4.3 Robotic laparoscopy

Moving from robotic platforms that deal with rigid structures like bones to robots involved in the manipulation of soft tissues, a number of challenges such as manipulation and tracking of deformable anatomies in a constrained (luminal or endoluminal) space must be kept into consideration. These limitations became the focus of surgical robots used in laparoscopy.

In the early 1990s—the development of surgical robotic systems for minimally invasive applications started. The first example is PROBOT—a modified version of the PUMA

560 industrial robot with a safety frame to restrict the arm's workspace—that was designed for prostatectomy (Ng et al. 1993). The concept of using several robotic arms that can be teleoperated from a remote console to perform laparoscopy procedures, resulted in the Zeus platform (Computer Motion, USA) (Butner and Ghodoussi 2003), followed by the da Vinci system. The da Vinci—the most famous surgical robotic platform on the market with almost 7000 units installs to date and 1.5 million procedures completed only in 2021 (see Intuitive Surgical 2021 annual report https://isrg.gcs-web.com)—features stereo vision of the surgical field at the master console, and restore the hand–eye coordination lost in traditional laparoscopy. The surgeon can interact with the anatomy using 7-DOF devices named EndoWrist, which is not achievable with traditional laparoscopy. However, the da Vinci does not offer haptic feedback despite these benefits. Applications include prostatectomy, cholecystectomy, fundoplication, colorectal surgery and many others (Yaxley et al. 2016). Global research activities on the da Vinci platform are supported by the da Vinci Research Kit (dVRK) (Intuitive Foundation, USA) and its academic community which enables participating institutions to develop and test customised design or control applications on retired generations of the platform. For example, integration strategies for haptic feedback have been proposed and evaluated (Saracino et al. 2019). In 2018 Intuitive Surgical announced the da Vinci SP (single port) with the goal of further reducing the invasiveness of robot laparoscopy (Dupont et al. 2021). The system has received FDA clearance in the USA introduced the Hugo RAS System to the market. The system is a portable and modular robot with the aim of improving the clinical workflow while reducing procedure-related costs. It consists of an "open" surgical console featuring a high-definition 3D passive display, a system tower, and four individual arm carts. Each robotic arm is autonomous and can extend, thanks to its six distinct joints. Its configuration allows the patient to experience the advantages of a highly flexible movable arm, made possible by the multitude of joints (Gueli Alletti et al. 2022). The Hugo RAS made its debut in the European market in March 2022, obtaining CE approval for various procedures, including gynecological, urological, and adrenalectomy surgeries (Raffaelli et al. 2023).

Recently, CMR Surgical (Cambridge, UK) launched the Versius surgical system. This a modular system featuring bedside units (BSUs) that are compact enough to fit within a standard operating room and can be easily relocated at the conclusion of a surgical procedure. The novelties of this system include the downsizing of its components, rendering them inconspicuous within the operating room, and the maneuverability of each robotic element, allowing this modular system to be effortlessly transferred from one operating room to another, effectively transforming it into a versatile "instrument" adaptable to the unique needs of patients (Dixon et al. 2021).

While the aforementioned commercial platforms provide enhanced dexterity and improved visual guidance, they are still lacking haptic feedback. Integrating such guidance into robot-assisted laparoscopy is being the objective of many research groups (Patel et al. 2022; Hernandez Sanchez et al. 2023; Chua and Okamura 2023).

4.4 Flexible robot for endoluminal intervention

A promising innovation that could enhance MIS through transluminal and/or endoluminal treatments involves miniaturized flexible robots that don't require the need for skin incisions. Snake-like robots, such as the i-Snake (Shang et al. 2011), have the potential of navigating and exploring the anatomy via natural orifices and body lumens, providing enhanced navigation and manipulation accuracy via integrated sensing and imaging. Although these robots can easily operate in the abdomen or chest of the patient, they are not suitable to navigate constrained anatomical sites such as arteries, veins, or brain, due to their large diameter. Hence, steerable catheters and concentric tube robots can overcome this limitation.

Endovascular procedures involve the navigation of catheters and wires inside the vascular tree, to reach the anatomy of interest, and perform procedures like stent placement, coiling, valve (re-)implantation, and ablation (Lee et al. 2017). These procedures require a high level of manoeuvrability to avoid dangerous injuries to the vasculature, i.e., puncture or rupture, and robotic assistance can improve these challenging manoeuvres by providing enhanced manipulation precision and stability while reducing the ionizing radiation doses—generated by the necessary fluoroscopy guidance—to both the patient and the operator.

Exemplary commercial systems include the Magellan (for endovascular procedures) and Sensei X2 (for electrophysiology procedures) by Hansen Medical (now Auris Health Inc., USA) platforms. These platforms are teleoperated by the clinician—who sits at the master console—and using 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, USA) is used in endovascular electrophysiology applications (Feng et al. 2017). 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 provides 3D intraoperative navigation.

CorPath GRX (Siemens Healthineers, Erlangen, Germany) is an interesting and more recent teleoperated robotic platform for endovascular intervention that features partial procedural automation of guidewire manipulation (e.g., spin to cross lesions) mimicking motion patterns from manual instrument handling (Mahmud et al. 2020). Moreover, the platform has been used for the first-in-human long distance robotic percutaneous coronary intervention (Patel et al. 2019).

In 2023, Robocath (Rouen, France) launched their new product R-One +, a robotic endovascular platform that provides physicians with reliable, precise assistance during procedures and enhance movements creating better interventional conditions, by being totally protected from x-rays (Durand et al. 2023). The system can use third-party endovascular devices, an improvement with respect to other systems that requires proprietary devices.

A novel approach to robot-assisted endovascular intervention is proposed by researchers at Imperial College London (Fig. 4), who developed a robotic platform that features enhanced instruments manoeuvrability, multimodal image guidance (standard fluoroscopy and MRI), and vision-based haptic feedback (Dagnino et al. 2018; Kundrat et al. 2021). The system was successfully tested on in-vivo porcine models (Dagnino et al. 2022).

As mentioned above, one main limitation of the steerable robotic catheters is their limited capability of producing high manipulation forces. As highlighted in Sect. 3, concentric tube robots offer the necessary flexibility to manoeuvre through tortuous anatomy while also having a higher stiffness due to inherent material and structural properties. Concentric tube robots have evolved to enable teleoperated surgery in a number of endoluminal applications (e.g., cardiology, urology and ENT). New platforms for endoluminal interventions like the Ion system by Intuitive Surgical and the Monarch system by Auris Healthcare have recently been launched to the market targeting peripheral lung biopsy with the support of 3D image guidance complemented by robotic assistance.

4.5 Medical capsules and untethered micro/nano robots

In the early 2000s, the possibility of taking a "pill" to capture images from deep inside the human body revolutionised the science of gastrointestinal endoscopy and gave rise to a brand-new area of study: medical capsule robots (Dupont et al. 2021). The latter are small enough to be swallowed by the patient, and while navigating the gastrointestinal tract acquire images of the anatomy similarly to endoscopy cameras (Valdastri et al. 2012). Given Imaging (Yokneam Illit,

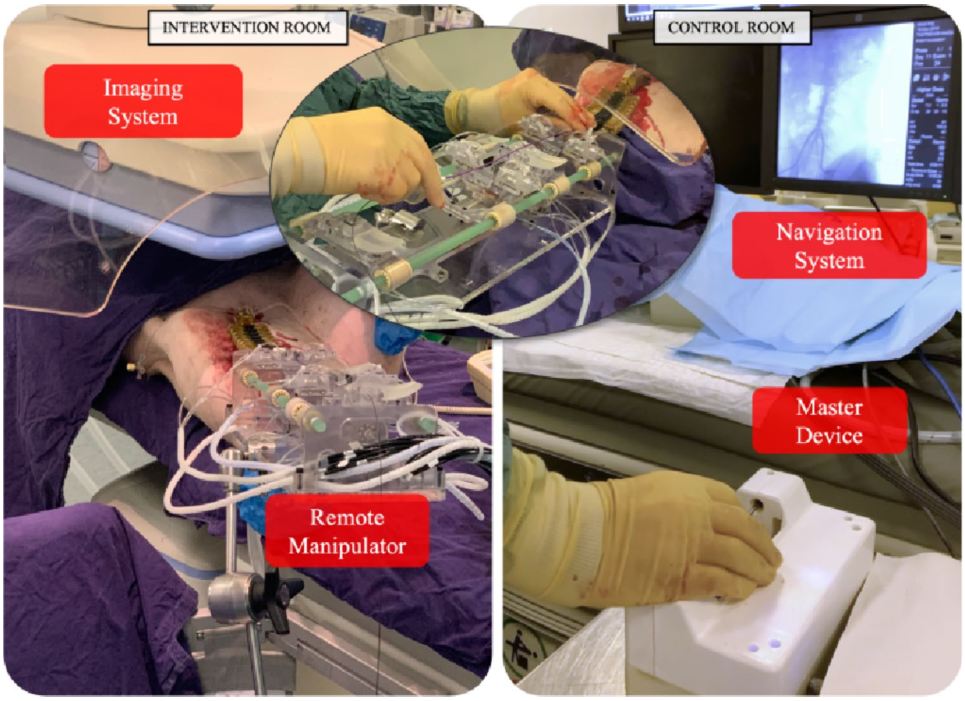


Fig. 4 The CathBot platform developed at Imperial College London during in vivo testing on porcine models. This MR-safe system allows teleoperated manipulation of catheters and guidewires to complete cannulation tasks. The operator interacts with a tailored human–machine interface, i.e., the master device, that incorporates human motion patterns (gripping, displacement, rotation) from conventional endovascular surgery, guided by the navigation system. The master device renders vision-based haptic feedback, providing the operator with haptic guidance. The remote pneumatically actuated and MR-compatible robotic manipulator is placed close to the animal and manipulates the endovascular instrument replicating the surgeon's motion commands captured by the master device. Comprehensive evaluation of the CathBot systems showed that it can potentially improve the execution of endovascular procedures, paving the way for clinical translation. Image adapted with permission from Dagnino et al. (2022)

Israel—now Medtronic) introduced PillCam in 2001—a wireless capsule that can inspect the gastrointestinal tract in a minimally invasive way. Since then, several other devices have been launched, such as the EndoCapsule (Olympus, Japan). Please refer to (Chen et al. 2022; Liu et al. 2015; Valdastri et al. 2012; Ciuti et al. 2010) for a comprehensive review. The suboptimal field of view of the camera and the lack of active control for necessary interaction with tissue (e.g., to take a biopsy) are main limitations. Researchers (Gorini et al. 2006; Kwon et al. 2007) focused on improving the locomotion of the capsules by proposing novel actuation strategies. For example, by means of an external and controllable magnetic field, it is possible to manipulate the capsule inside the patient (Ciuti et al. 2010). Other improvements focused on the possibility of taking biopsies through the actuation of various sampling tools like magnetic-field-actuated blades, razors, and screw-like devices (Popek et al. 2017).

In the coming years, micro/nano robots with embedded advanced imaging and sensing may enhance the clinicians' diagnostic and therapeutic capabilities with great potential for early-stage detection and precision treatment of diseases. However, while promising, these new technology is still challenging to translate into actual clinical therapies due to the safety concerns and the complexity of operating inside the human body (Soto and Chrostowski 2018). Locomotion is once again a challenge, and due to the small scale of the robots, traditional actuation and power supply are not possible. Novel solutions may make use of chemically powered motors or external magnetic and ultrasound energies to drive their motion (Li et al. 2017). Recent advances in micro/nanorobots are paving the way for precise surgical applications. For example, micro/nanorobotic tools, such as nanodrillers, microgrippers, or microbullets, offer unique capabilities for early and targeted intervention. Exemplary application include eye surgery nanorobots developed by Nelson's group (Chatzipirpiridis et al. 2015); the endovascular microrobots proposed by (Park et al. 2010); the robotic drug delivery capsule RoboCap (Srinivasan et al. 2022); or the magnetic helical microrobot for image-guided targeted therapies developed by (Yan et al. 2017).

5 Technologies for robotic MIS

This section is dedicated to the analysis of the state of the art of technologies that support and complement Robotic MIS (Table 1), which we have categorized in two main areas: (1) surgical navigation, and (2) human–robot interaction and artificial intelligence (AI). With surgical navigation we refer to the integration of imaging and sensing technologies into the robot control architecture to provide the surgeon with enhanced visual and haptic guidance as well as to guide the robot to accomplish surgical tasks autonomously or in cooperation with the human operator. Human–Robot Interaction and AI are key technologies to enable the interaction between the human users and the robotic system at different levels of autonomy, e.g., from teleoperated control to cooperative interaction between operators and robot, to AI-driven fully autonomous robotic tasks.

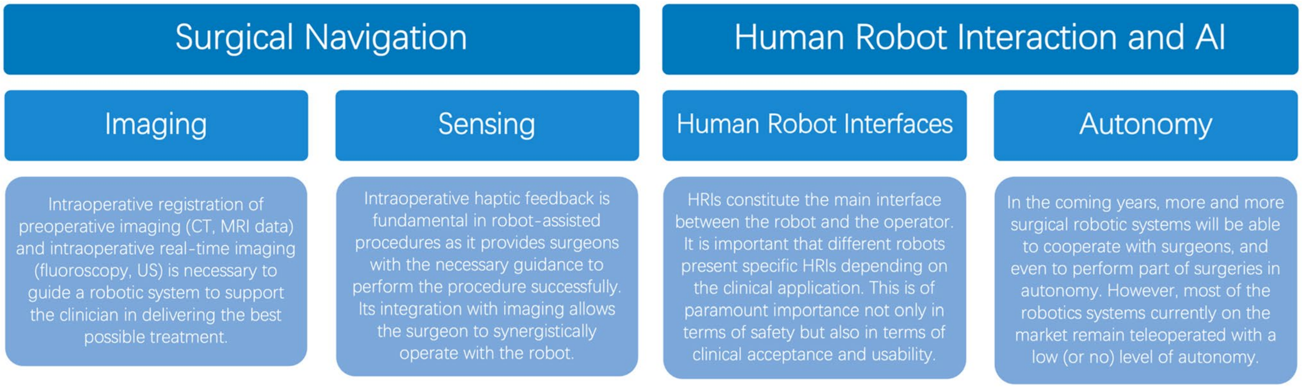
This analysis complements the description of the robotic platforms introduced in the previous section and serves as an input to the discussion of future directions and challenges of Robotic MIS, which will be the topic of the next and final section.

5.1 Surgical navigation for robotic MIS

5.1.1 Imaging

New surgical robotic systems should work alongside surgeons, giving them enhanced dexterity as well as integrated real-time intraoperative image guiding, and sensing. The surgeon will be able to close the system's control loop and collaborate with the robot by using sight and sense data. This will ensure a shorter procedure, less cognitive demands on

Table 1 Technologies that support and complement robotic MIS



Surgical Navigation		Human Robot Interaction and AI	
Imaging	Sensing	Human Robot Interfaces	Autonomy
Intraoperative registration of preoperative imaging (CT, MRI data) and intraoperative real-time imaging (fluoroscopy, US) is necessary to guide a robotic system to support the clinician in delivering the best possible treatment.	Intraoperative haptic feedback is fundamental in robot-assisted procedures as it provides surgeons with the necessary guidance to perform the procedure successfully. Its integration with imaging allows the surgeon to synergistically operate with the robot.	HRIs constitute the main interface between the robot and the operator. It is important that different robots present specific HRIs depending on the clinical application. This is of paramount importance not only in terms of safety but also in terms of clinical acceptance and usability.	In the coming years, more and more surgical robotic systems will be able to cooperate with surgeons, and even to perform part of surgeries in autonomy. However, most of the robotics systems currently on the market remain teleoperated with a low (or no) level of autonomy.

the clinical operator, and a better surgical outcome for the patient.

Patient-specific volumetric data is usually acquired pre-operatively via MRI and CT imaging and represents the basis to preplanning the procedure and developing the optimal surgical strategy. However, these imaging modalities have limited temporal capabilities (i.e., it takes time to acquire the data). This limitation makes such image modalities not yet suited to be directly used intra-operatively where the temporal resolution is very important. Therefore, the effective fusion of preoperative planning with intraoperative data such as real-time imaging and sensing information is essential to support the clinician in delivering the best possible treatment (Troccaz et al. 2019). Ultrasound imaging is routinely utilized to help with guidance and soft tissue identification in MIS. Fluoroscopy is frequently employed for intravascular applications, but soft tissues are not visible to the operator without the use of iodine contrast. Unfortunately, these real-time intraoperative imagining modalities provide only a limited amount of data when compared to CT and MRI. Real-time MRI guidance is able to provide good soft tissue contrast, but the low temporal resolution limits the number of 2D images that can be acquired per second. On top of this, MR-compatible instruments and tools can only be used during MR-guided procedures. A number of novel MR-compatible robotic devices have been developed for clinical applications like endovascular intervention (Dagnino et al. 2022), neurosurgery (Sutherland et al. 2008), prostate interventions (Stoianovici et al. 2007) and breast biopsy (Groenhuis et al. 2020). With more and more expected MR-compatible robotic devices, advances in the field of real-time MR imaging are also happening (Nijsink et al. 2022).

The combination of preoperative models (e.g., from CT or MRI data) and the intraoperative data and scene (e.g., from fluoroscopy or ultrasound) is usually necessary, and requires the registration of such models to the intraoperative workspace. Registration between different imaging modalities has been—and is—widely studied by several researchers (Dagnino et al. 2017; Markelj et al. 2012). While rigid registration of multimodal images is relatively simple to accomplish and maintain during a surgical procedure, tracking soft tissues that deforms intraoperatively is still a challenge (Lee et al. 2010; Schoob et al. 2017). Computer vision can be used to address this challenge, providing techniques to generate 3D surfaces directly from a surgical video during laparoscopy (Pérez-Pachón et al. 2020). For example, with augmented reality, preoperative or intraoperative data can be overlaid onto the exposed surgical view. Combining and integrating in the surgical workflow preoperative and intraoperative images is also focus or research: clinical usability is a challenge here, and clinical operators should always be in control of the scene and of the way preoperative and intraoperative images are fused together and displayed. Intuitiveness and ease of use are also key aspects in terms of clinical usability of this technology. In neurosurgery and orthopaedic surgery the overlay of preoperative data to the intraoperative scene is easily obtainable via rigid registration; however, this is still a challenge when tissues deform during the procedure (e.g., soft tissue manipulation) (Vitiello et al. 2013).

One potential solution is provided by Dynamic Shape Instantiation, a technique that combines preoperative 3D motion models with a few intraoperative images. This modality allows a fast and computationally low generation of proper 3D geometry of deforming anatomy (Zhou et al. 2018).

Regarding Robotic MIS, the intraoperative detection and tracking of robotics end effectors with respect to the anatomy is a fundamental requirement. While the coarse pose (position and orientation) of robotic end effectors in the operational workspace can be calculated via the robot kinematics, robotics platforms make use of external measurement devices—usually mounted on the robot end-effectors—that track their pose in real-time with high accuracy. Tracking technologies commonly used in clinical practice include optical sensors, electromagnetic sensors, and impedance sensors (Glossop 2012).

Optical tracking devices, such as the Polaris (NDI, Canada) use infrared cameras to determine the pose of tracking tools (usually made of reflective markers) placed on desired targets (Dagnino et al. 2016b). Optical tracking systems present a high level of tracking accuracy but suffer from line-of-sight issues (i.e., cameras and tracking tools must be maintained on a continuous unobstructed line).

EM tracking systems—e.g., the Aurora (NDI, Canada)—consist of a field generator and detecting sensor coils. Sensors detect the EM field created by the field generator, and a current is generated in the receiving coil. This current can be used to define the pose (at least 5-DOF: x, y, z, pitch, and yaw) of the sensor based on its phase and intensity. One limitation of EM systems is their susceptibility to metal and EM interferences that distort the magnetic field. A benefit over optical technologies is the lack of line-of-site issues, and the small size of the sensors allows their placement inside small clinical devices such as catheters, guidewires, and needles.

Another family of tracking systems is based on impedance and are mostly used in cardiovascular applications such as electrophysiological mapping and ablation. While these systems do not suffer of the line-of-sight issue and are not affected by ambient metal in the environment, they have a limited attainable accuracy. Biosense Webster for example make use of this technology in their CARTO 3 system (a 3-D mapping system for electrophysiology applications) which is used in combination of robotic catheter platforms, as described above. An alternative impedance-based navigation approach inspired by electric fish is proposed for real-time intravascular navigation and mapping to preoperative models (Sutton et al. 2020).

5.1.2 Sensing

In terms of robotic navigation, robotic platforms should provide haptic feedback to the operators, thus the necessary surgical guidance. To this regard, active constraints and virtual fixtures have been developed to guide the surgeon during the robot-assisted procedure by gradually increasing the stiffness of the robotic handle when the end-effector enters a predefine forbidden region of the anatomy (the aforementioned Acrobot robot is an example). The goal is to enhance the safety of the procedure while reducing the cognitive workload of the clinician.

However, in most robotic MIS applications, direct force sensing at the end-effector would require the integration of force sensors directly on the robot, which is challenging and not always possible or desirable. A potential solution is provided by image-base haptic guidance. Researcher at Imperial College London (Dagnino et al. 2018; Benavente Molinero et al. 2019) have developed a vision-based haptic guidance framework for robot-assisted endovascular intervention. Dynamic active constraints are generated by tracking via image processing the relative position of vascular instruments and the vasculature with the goal of guiding the operator during the procedure while avoiding high-force contacts between the instruments and the vessel walls that may result in dangerous injuries. For the sake of completeness, the readers are kindly referred to the comprehensive survey on virtual fixtures and active constraints in Bowyer et al. (2014).

5.2 Human–robot interaction and AI

One important aspect of robotic MIS is the interaction between clinical operators and the robotic platforms. Human–robot interfaces (HRI) constitute the main operator interface in terms of control input and visual representation of the device state and are an essential component of robotic MIS platforms. Therefore, it is very important that HRIs are designed with end user involvement and clinical application in mind in order to increase clinical acceptance and positive user experience. The implementation of suitable HRIs and related control strategies is fundamental to enhance the users' skills, thus the positive outcome of the surgery.

In the last decade, various HRIs concepts were proposed in MIS robotics. Many research platforms still use conventional joysticks which are mapped to the robot end-effector displacement, feeding, rotation, or bending. However, as mentioned above, it is important that HRIs present task-specific features. As an example, a bespoke HRI for endovascular robotic surgery has been designed to replicate clinical handling and motion pattern of conventional catheters and guidewires (Kundrat et al. 2021). This approach has been well received by senior vascular surgeons due to its transparency. Thanks to the direct mapping of robotic manoeuvres to manual procedures, this design approach can reduce the operator's training for a smooth transition from manual to robotic interventions. Similarly, flexible electronic circuits are proposed for realisation of customised HRIs to enhance user control and feedback for example of soft robots for endoscopy (Gifari et al. 2019).

The interaction between the robot and the operator is linked to the concept of robot autonomy. Currently, most of the robotic platforms are still teleoperated. The actuation of a remote robotic manipulator operated by the clinician via a dedicated HRI is still the clinical gold standard in robotic surgery and represents the lowest autonomy level according to the taxonomy presented in Yang et al. (2017). Here, six independent autonomy levels are defined, ranging from no autonomy (level 0)—with robotic control based on direct operator input—to fully autonomous surgical tasks without human interaction (level 5). Currently, only partial automation of some tasks is realised in commercial MIS devices like the CorPath® GRX platform (Corindus, A Siemens Healthineers Company) for endovascular applications. This system can automate the manipulation of a guidewire mimicking motion patterns from manual instrument handling (e.g., spin to cross lesions). Research on conditional autonomy (level 3) using a robotic platform with generative adversarial imitation learning has demonstrated feasibility is selected cannulation results (Chi et al. 2020). In the future, it is expected that surgical robotic platforms will be able to cooperate with surgeons, and even to perform surgical tasks in autonomy (level 5). On this direction, researchers at Johns Hopkins and at the University of North Carolina Wilmington have recently demonstrated the feasibility of autonomous robotic laparoscopic surgery for intestinal anastomosis on in vivo porcine models using a setup of two robotic arms with embedded suturing device and endoscopic vision (Saeidi et al. 2022). However, the use of fully autonomous robots in clinical practice is still science fiction for both technological and regulatory issues. In terms of technology, a better integration of imaging, sensing, and AI across all levels is necessary to facilitate a robot with the abilities from making clinical decisions to completion of surgical tasks. And this brings in other issues related to regulatory, ethical, and legal challenges, which requires harmonised efforts of engineers, clinicians, regulators, investors, and the business community in order to be addressed (Dupont et al. 2021).

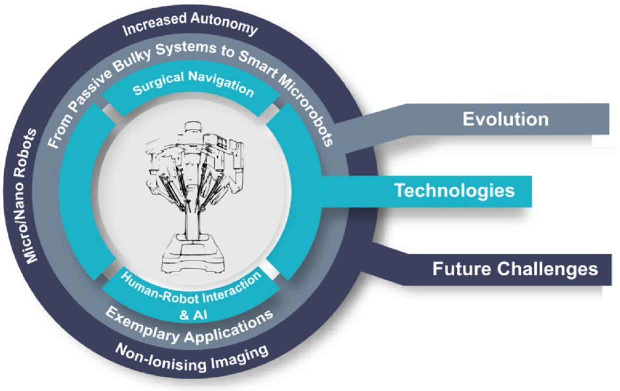


Fig. 5 Evolution, technologies, and future challenges of robotic MIS

6 Conclusion

This paper presented an overview of robotic platforms and related technologies that have contributed to the evolution of robotics MIS (Fig. 5). In the last few decades, the scientific community has addressed a multitude of surgical challenges by proposing novel robotic technologies and introducing novel clinical methodologies and workflows. Recent advances focus on miniaturising robotic devices, better integrating advanced imaging modalities intraoperatively, increasing the level of autonomy and cooperation with the clinical team, and improving the integration within the surgical workflow.

Looking at the future, interdisciplinary efforts are required from engineers, clinicians, and industry to create the next generation of robotic MIS platforms. Major future challenges and opportunities include the combination of AI technologies, the increasing availability of large clinical data sets, and the next generation of robotic devices. It is expected that robots will become smaller and smarter and will be able to navigate the human body with an increased level of autonomy, and interaction of microrobots with pathologies at cellular level will be possible. For example, dexterous and atraumatic endoscopes with compliant manipulators in combination with holistic diagnostic workflows with imaging, online assessment of tissue lesions, decision support, and subsequent autonomous sample dissection may become reality. Integration of AI, novel imaging modalities, and sensing devices will also impact other minimally invasive procedures, such as endovascular intervention. For example, action recognition applied to recordings of clinical imaging data (e.g., non-ionising MRI) may enable trajectory planning, decision making and autonomous robotic real-time navigation of endovascular instrumentation. Talking about autonomy, driven by advances in AI, fundamental research efforts in robotics MIS target increased autonomy levels to support clinical operators and to realise even better clinical outcomes. For example, autonomous cannulation of targets in the vasculature represents a highly relevant clinical use case (Chi et al. 2020). The integration of robotics, computer assistance, and control enables autonomous manipulation and navigation of magnetic endoscopes. Partial autonomy enables cooperation between the surgeon and the robot in certain situations, e.g., navigating challenging anatomy. However, despite many recent technology advances, clinicians will still continue to be in charge and take full control of the procedure, and it is envisioned that partial autonomy will become an important feature of clinical assistance in robotic surgery in the coming years. Last but not least, translational efforts are required to mature technology readiness levels from research to product level involving clinical use cases and working toward commercialization. This huge leap is essential for making novel technologies available to the broader society.

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Declarations

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References

Arezzo, A., et al.: The use of 3D laparoscopic imaging systems in surgery: EAES consensus development conference 2018. Surg. Endosc. **33**(10), 3251–3274 (2019). https://doi.org/10.1007/s00464-018-06612-x

Attanasio, A., Scaglioni, B., De Momi, E., Fiorini, P., Valdastri, P.: Autonomy in surgical robotics. Annu. Rev. Control Robot. Auton. Syst. **4**(1), 651–679 (2021). https://doi.org/10.1146/annurev-control-062420-090543

Batailler, C., et al.: MAKO CT-based robotic arm-assisted system is a reliable procedure for total knee arthroplasty: a systematic review. Knee Surg. Sports Traumatol. Arthrosc. off. J. ESSKA **29**(11), 3585–3598 (2021). https://doi.org/10.1007/s00167-020-06283-z

Benavente Molinero, M., et al.: Haptic guidance for robot-assisted endovascular procedures: implementation and evaluation on surgical simulator, presented at the IROS19, Macau (2019)

Bergeles, C., Yang, G.Z.: From passive tool holders to microsurgeons: safer, smaller, smarter surgical robots. IEEE Trans. Biomed. Eng. **61**(5), 5 (2014). https://doi.org/10.1109/TBME.2013.2293815

Bergeles, C., Vitiello, V., Yang, G.-Z.: Surgical robotics: the next 25 years. Successes, challenges, and the road ahead. UK-RAS White Paper, White paper, (2016). [Online]. Available: http://hamlyn.doc.ic.ac.uk/uk-ras/sites/default/files/UK_RAS_WP_SR25yr_web.pdf. Accessed 27 Oct 2023

Bowyer, S.A., Davies, B.L., Baena, F.R.Y.: Active constraints/virtual fixtures: a survey. IEEE Trans. Robot. **30**(1), 1 (2014). https://doi.org/10.1109/TRO.2013.2283410

Butner, S.E., Ghodoussi, M.: Transforming a surgical robot for human telesurgery. IEEE Trans. Robot. Autom. **19**(5), 5 (2003). https://doi.org/10.1109/TRA.2003.817214

Chatzipirpiridis, G., et al.: Electroforming of implantable tubular magnetic microrobots for wireless ophthalmologic applications. Adv. Healthc. Mater. **4**(2), 209–214 (2015). https://doi.org/10.1002/adhm.201400256

Chen, W., Sui, J., Wang, C.: Magnetically actuated capsule robots: a Review. IEEE Access **10**, 88398–88420 (2022). https://doi.org/10.1109/ACCESS.2022.3197632

Chi, W., et al.: Collaborative robot-assisted endovascular catheterization with generative adversarial imitation learning, presented at the IEEE International conference on robotics and automation (ICRA) (2020)

Chua, Z., Okamura, A.M.: A modular 3-degrees-of-freedom force sensor for robot-assisted minimally invasive surgery research. Sensors **23**(11), 11 (2023). https://doi.org/10.3390/s23115230

Ciuti, G., Valdastri, P., Menciassi, A., Dario, P.: Robotic magnetic steering and locomotion of capsule endoscope for diagnostic and surgical endoluminal procedures. Robotica **28**(2), 2 (2010). https://doi.org/10.1017/S0263574709990361

Ciuti, G., et al.: Frontiers of robotic endoscopic capsules: a review. J. Micro-Bio Robot. **11**(1), 1–18 (2016). https://doi.org/10.1007/s12213-016-0087-x

Cossetto, T.L., Zareinia, K., Sutherland, G.R.: Robotics for neurosurgery. In: Gomes, P. (ed.) Medical Robotics, pp. 59–77. Woodhead Publishing, Sawston (2012). https://doi.org/10.1533/9780857097392.59

Cundy, T.P., et al.: The first decade of robotic surgery in children. J. Pediatr. Surg. **48**(4), 858–865 (2013). https://doi.org/10.1016/j.jpedsurg.2013.01.031

Dagnino, G., Georgilas, I., Köhler, P., Atkins, R., Dogramadzi, S.: Image-based robotic system for enhanced minimally invasive intra-articular fracture surgeries. IEEE Int. Conf. Robot. Autom. (ICRA) **2016**, 696–701 (2016a). https://doi.org/10.1109/ICRA.2016.7487196

Dagnino, G., Georgilas, I., Köhler, P., Morad, S., Atkins, R., Dogramadzi, S.: Navigation system for robot-assisted intra-articular lower-limb fracture surgery. Int. J. Comput. Assist. Radiol. Surg. (2016b). https://doi.org/10.1007/s11548-016-1418-z

Dagnino, G., et al.: Image-guided surgical robotic system for percutaneous reduction of joint fractures. Ann. Biomed. Eng. **45**(11), 11 (2017a). https://doi.org/10.1007/s10439-017-1901-x

Dagnino, G., et al.: Intra-operative fiducial-based CT/fluoroscope image registration framework for image-guided robot-assisted joint fracture surgery. Int. J. Comput. Assist. Radiol. Surg. (2017b). https://doi.org/10.1007/s11548-017-1602-9

Dagnino, G., Liu, J., Abdelaziz, M.E.M.K., Chi, W., Riga, C., Yang, G.Z.: Haptic feedback and dynamic active constraints for robot-assisted endovascular catheterization. In: 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Madrid, Spain, (2018)

Dagnino, G., et al.: In-vivo validation of a novel robotic platform for endovascular intervention. IEEE Trans. Biomed. Eng. (2022). https://doi.org/10.1109/TBME.2022.3227734

Dixon, F., et al.: Initiation and feasibility of a multi-specialty minimally invasive surgical programme using a novel robotic system: a case series. Int. J. Surg. Lond. Engl. **96**, 106182 (2021). https://doi.org/10.1016/j.ijsu.2021.106182

Dupont, P.E., et al.: A decade retrospective of medical robotics research from 2010 to 2020. Sci. Robot. (2021). https://doi.org/10.1126/scirobotics.abi8017

Durand, E., Sabatier, R., Smits, P.C., Verheye, S., Pereira, B., Fajadet, J.: Evaluation of the R-One robotic system for percutaneous coronary intervention: the R-EVOLUTION study, EuroIntervention. [Online]. Available: https://eurointervention.pcronline.com/article/evaluation-of-the-r-one-robotic-system-for-percutaneous-coronary-intervention-the-r-evolution-study. Accessed 28 Sep 2023

Feng, Y., et al.: An efficient cardiac mapping strategy for radiofrequency catheter ablation with active learning. Int. J. Comput. Assist. Radiol. Surg. **12**(7), 7 (2017). https://doi.org/10.1007/s11548-017-1587-4

Fiorini, P., Goldberg, K.Y., Liu, Y., Taylor, R.H.: Concepts and trends n autonomy for robot-assisted surgery. Proc. IEEE Inst. Electr. Electron. Eng. **110**(7), 993–1011 (2022). https://doi.org/10.1109/JPROC.2022.3176828

Furusho, J., Ono, T., Murai, R., Fujimoto, T., Chiba, Y., Horio, H.: Development of a curved multi-tube (CMT) catheter for percutaneous umbilical blood sampling and control methods of CMT catheters for solid organs. In: IEEE International Conference Mechatronics and Automation, 2005, Vol. 1, pp. 410–415 (2005). https://doi.org/10.1109/ICMA.2005.1626582

Gallagher, A.G., McClure, N., McGuigan, J., Ritchie, K., Sheehy, N.P.: An ergonomic analysis of the fulcrum effect in the acquisition of endoscopic skills. Endoscopy **30**(7), 617–620 (1998). https://doi.org/10.1055/s-2007-1001366

Georgilas, I., Dagnino, G., Tarassoli, P., Atkins, R., Dogramadzi, S.: Robot-assisted fracture surgery: surgical requirements and system design. Ann. Biomed. Eng. (2018). https://doi.org/10.1007/s10439-018-2005-y

Gifari, M.W., Naghibi, H., Stramigioli, S., Abayazid, M.: A review on recent advances in soft surgical robots for endoscopic applications. Int. J. Med. Robot. **15**(5), e2010 (2019). https://doi.org/10.1002/rcs.2010

Glossop, N.: Localization and tracking technologies for medical robotics. In: Gomes, P. (ed.) Medical Robotics Minimally Invasive Surgery, pp. 41–58. Elsevier, Amsterdam (2012)

Gorini, S., Quirini, M., Menciassi, A., Pernorio, G., Stefanini, C., Dario, P.: A novel SMA-based actuator for a legged endoscopic capsule. In: The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, 2006. BioRob 2006, pp. 443–449 (2006). https://doi.org/10.1109/BIOROB.2006.1639128

Groenhuis, V., Siepel, F.J., Stramigioli, S.: Sunram 5: a magnetic resonance-safe robotic system for breast biopsy, driven by pneumatic stepper motors. In: Abedin-Nasab, M.H. (ed.) Handbook of Robotic and Image-Guided Surgery, pp. 375–396. Elsevier (2020). https://doi.org/10.1016/B978-0-12-814245-5.00022-0

Gueli Alletti, S., et al.: Introducing the new surgical robot HUGO^{TM} RAS: system description and docking settings for gynecological surgery. Front. Oncol. (2022). https://doi.org/10.3389/fonc.2022.898060

Hernandez Sanchez, J., Amanhoud, W., Billard, A., Bouri, M.: Enabling four-arm laparoscopic surgery by controlling two robotic assistants via haptic foot interfaces. Int. J. Robot. Res. **42**(7), 475–503 (2023). https://doi.org/10.1177/02783649231180366

Herry, Y., Batailler, C., Lording, T., Servien, E., Neyret, P., Lustig, S.: Improved joint-line restitution in unicompartmental knee arthroplasty using a robotic-assisted surgical technique. Int. Orthop. **41**(11), 11 (2017). https://doi.org/10.1007/s00264-017-3633-9

Hu, C., Pané, S., Nelson, B.: Soft micro- and nanorobotics. Annu. Rev. Control Robot. Auton. Syst (2018). https://doi.org/10.1146/annurev-control-060117-104947

Jakopec, M., Baena, F.R.Y., Harris, S.J., Gomes, P., Cobb, J., Davies, B.L.: The hands-on orthopaedic robot 'acrobot': early clinical trials of total knee replacement surgery. IEEE Trans. Robot. Autom. **19**(5), 5 (2003). https://doi.org/10.1109/TRA.2003.817510

Karimyan, V., Sodergren, M., Clark, J., Yang, G.-Z., Darzi, A.: Navigation systems and platforms in natural orifice translumenal endoscopic surgery (NOTES). Int. J. Surg. **7**(4), 297–304 (2009). https://doi.org/10.1016/j.ijsu.2009.05.007

Kuhn, S., Huettl, F., Deutsch, K., Kirchgässner, E., Huber, T., Kneist, W.: Surgical education in the digital age - virtual reality, augmented reality and robotics in the medical school. Zentralbl. Chir. **146**(1), 37–43 (2021). https://doi.org/10.1055/a-1265-7259

Kundrat, D., et al.: Toward assistive technologies for focus adjustment in teleoperated robotic non-contact laser surgery. IEEE Trans. Med. Robot. Bionics **1**(3), 145–157 (2019). https://doi.org/10.1109/TMRB.2019.2931438

Kundrat, D., et al.: An MR-safe endovascular robotic platform: design, control, and ex-vivo evaluation. IEEE Trans. Biomed. Eng. **68**(10), 3110–3121 (2021). https://doi.org/10.1109/TBME.2021.3065146

Kwoh, Y.S., Hou, J., Jonckheere, E.A., Hayati, S.: A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery. IEEE Trans. Biomed. Eng. **35**(2), 153–160 (1988). https://doi.org/10.1109/10.1354

Kwon, J., Park, S., Park, J., Kim, B.: Evaluation of the critical stroke of an earthworm-like robot for capsule endoscopes. Proc. Inst. Mech. Eng. [h] **221**(4), 4 (2007). https://doi.org/10.1243/09544119JEIM134

Lang, J.E., et al.: Robotic systems in orthopaedic surgery. J. Bone Joint Surg. Br. **93-B**(10), 10 (2011). https://doi.org/10.1302/0301-620X.93B10.27418

Lavallee, S., Troccaz, J., Gaborit, L., Cinquin, P., Benabid, A.L., Hoffmann, D.: Image guided operating robot: a clinical application in stereotactic neurosurgery. In: Proceedings 1992 IEEE International Conference on Robotics and Automation, vol. 1, pp. 618–624 (1992). https://doi.org/10.1109/ROBOT.1992.220223

Lee, S.-L., et al.: From medical images to minimally invasive intervention: computer assistance for robotic surgery. Comput. Med. Imaging Graph. **34**(1), 33–45 (2010). https://doi.org/10.1016/j.compmedimag.2009.07.007

Lee, S.-L., Constantinescu, M., Chi, W., Yang, G.-Z.: Devices for endovascular interventions: technical advances and translational challenges. National Institute for Health Research and Clinical Research Network, UK, White Paper, White paper, Dec. (2017). [Online]. Available: https://www.nihr.ac.uk/news-and-events/documents/cardio_report_2017.pdf. Accessed 27 Oct 2023

Leelasestaporn, C., Tarnpichprasert, T., Arirachakaran, A., Kongtharvonskul, J.: Comparison of 1-year outcomes between MAKO versus NAVIO robot-assisted medial UKA: nonrandomized, prospective, comparative study. Knee Surg. Relat. Res. **32**(1), 13 (2020). https://doi.org/10.1186/s43019-020-00030-x

Li, J., Esteban-Fernández de Ávila, B., Gao, W., Zhang, L., Wang, J.: Micro/nanorobots for biomedicine: delivery, surgery, sensing, and detoxification. Sci. Robot. **2**(4), eaam6431 (2017). https://doi.org/10.1126/scirobotics.aam6431

Liu, L., Towfighian, S., Hila, A.: A review of locomotion systems for capsule endoscopy. IEEE Rev. Biomed. Eng. **8**, 138–151 (2015). https://doi.org/10.1109/RBME.2015.2451031

Mahmud, E., et al.: Robotic peripheral vascular intervention with drug-coated balloons is feasible and reduces operator radiation exposure: results of the robotic-assisted peripheral intervention for peripheral artery disease (RAPID) Study II. J. Invasive Cardiol. **32**(10), 380–384 (2020)

Marcus, H.J., Cundy, T.P., Nandi, D., Yang, G.-Z., Darzi, A.: Robot-assisted and fluoroscopy-guided pedicle screw placement: a systematic review. Eur. Spine J. off. Publ. Eur. Spine Soc. Eur. Spinal Deform. Soc. Eur. Sect. Cerv. Spine Res. Soc. **23**(2), 291–297 (2014). https://doi.org/10.1007/s00586-013-2879-1

Marcus, H.J., et al.: Trends in the diffusion of robotic surgery: a retrospective observational study. Int. J. Med. Robot. **13**(4), e1870 (2017). https://doi.org/10.1002/rcs.1870

Markelj, P., Tomaževič, D., Likar, B., Pernuš, F.: A review of 3D/2D registration methods for image-guided interventions. Med. Image Anal. **16**(3), 3 (2012). https://doi.org/10.1016/j.media.2010.03.005

Mitros, Z., Sadati, S.M.H., Henry, R., Cruz, L., Bergeles, C.: From theoretical work to clinical translation: progress in concentric tube robots. Annu. Rev. Control Robot. Auton. Syst. (2021). https://doi.org/10.1146/annurev-control-042920-014147

Ng, W.S., Davies, B.L., Hibberd, R.D., Timoney, A.G.: Robotic surgery: a first-hand experience in transurethral resection of the prostate. IEEE Eng. Med. Biol. Mag. **12**(1), 1 (1993). https://doi.org/10.1109/51.195948

Nijsink, H., Overduin, C.G., Willems, L.H., Warlé, M.C., Fütterer, J.J.: Current state of MRI-guided endovascular arterial interventions: a systematic review of preclinical and clinical studies. J. Magn. Reson. Imaging **56**(5), 1322–1342 (2022). https://doi.org/10.1002/jmri.28205

Nwafor, C.J., Laurent, G.J., Rougeot, P., Rabenorosoa, K.: The caturo: a submillimeter diameter glass concentric tube robot with high curvature. Adv. Intell. Syst. **5**(2), 2200308 (2023). https://doi.org/10.1002/aisy.202200308

Park, S., Cha, K., Park, J.: Development of biomedical microrobot for intravascular therapy. Int. J. Adv. Robot. Syst. **7**(1), 1 (2010). https://doi.org/10.5772/7260

Patel, T., Shah, S., Pancholy, S.: Long distance tele-robotic-assisted percutaneous coronary intervention: a report of first-in-human experience. EClinicalMedicine (2019). https://doi.org/10.1016/j.eclinm.2019.07.017

Patel, R.V., Atashzar, S.F., Tavakoli, M.: Haptic feedback and force-based teleoperation in surgical robotics. Proc. IEEE **110**(7), 1012–1027 (2022). https://doi.org/10.1109/JPROC.2022.3180052

Paul, H.A., et al.: Development of a surgical robot for cementless total hip arthroplasty. Clin. Orthop. (1992a). https://doi.org/10.1097/00003086-199212000-00010

Paul, H., et al.: A surgical robot for total hip replacement surgery. In: Proceedings 1992 IEEE International Conference on Robotics and Automation, (1992b), pp. 606–611.

Payne, C.J., Yang, G.-Z.: Hand-held medical robots. Ann. Biomed. Eng. **42**(8), 8 (2014). https://doi.org/10.1007/s10439-014-1042-4

Pérez-Pachón, L., Poyade, M., Lowe, T., Gröning, F.: Image overlay surgery based on augmented reality: a systematic review. In: Rea, P.M. (ed.) Biomedical Visualisation, vol. 8, pp. 175–195. Springer International Publishing, Cham (2020). https://doi.org/10.1007/978-3-030-47483-6_10

Popek, K.M., Hermans, T., Abbott, J.J.: First demonstration of simultaneous localization and propulsion of a magnetic capsule in a lumen using a single rotating magnet. In: 2017 IEEE International Conference on Robotics and Automation (ICRA), pp. 1154–1160 (2017). https://doi.org/10.1109/ICRA.2017.7989138

Raffaelli, M., et al.: The new robotic platform Hugo™ RAS for lateral transabdominal adrenalectomy: a first world report of a series of five cases. Updates. Surg. **75**(1), 217–225 (2023). https://doi.org/10.1007/s13304-022-01410-6

Reynolds, W.: The first laparoscopic cholecystectomy. JSLS **5**(1), 89–94 (2001)

Saeidi, H., et al.: Autonomous robotic laparoscopic surgery for intestinal anastomosis. Sci. Robot. (2022). https://doi.org/10.1126/scirobotics.abj2908

Saracino, A., et al.: Haptic feedback in the da Vinci Research Kit (dVRK): a user study based on grasping, palpation, and incision tasks. Int. J. Med. Robot. **15**(4), e1999 (2019). https://doi.org/10.1002/rcs.1999

Schoob, A., Kundrat, D., Lekon, S., Kahrs, L.A., Ortmaier, T.: Color-encoded distance for interactive focus positioning in laser microsurgery. Opt. Lasers Eng. **83**, 71–79 (2016). https://doi.org/10.1016/j.optlaseng.2016.03.002

Schoob, A., Kundrat, D., Kahrs, L.A., Ortmaier, T.: Stereo vision-based tracking of soft tissue motion with application to online ablation control in laser microsurgery. Med. Image Anal. **40**, 80–95 (2017). https://doi.org/10.1016/j.media.2017.06.004

Schweikard, A., Shiomi, H., Adler, J.: Respiration tracking in radiosurgery without fiducials. Int. J. Med. Robot. Comput. Assist. Surg. MRCAS **1**(2), 19–27 (2005). https://doi.org/10.1002/rcs.38

Sears, P., Dupont, P.: A steerable needle technology using curved concentric tubes. In: 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2850–2856 2006 (2006). https://doi.org/10.1109/IROS.2006.282072

Shang, J., et al.: An articulated universal joint based flexible access robot for minimally invasive surgery. In: 2011 IEEE International Conference on Robotics and Automation, pp. 1147–1152 (2011). https://doi.org/10.1109/ICRA.2011.5980261

Sørensen, S.M.D., Savran, M.M., Konge, L., Bjerrum, F.: Three-dimensional versus two-dimensional vision in laparoscopy: a systematic review. Surg. Endosc. **30**(1), 11–23 (2016). https://doi.org/10.1007/s00464-015-4189-7

Soto, F., Chrostowski, R.: Frontiers of medical micro/nanorobotics: in vivo applications and commercialization perspectives toward clinical uses. Front. Bioeng. Biotechnol. (2018). https://doi.org/10.3389/fbioe.2018.00170

Srinivasan, S.S., et al.: RoboCap: robotic mucus-clearing capsule for enhanced drug delivery in the gastrointestinal tract. Sci. Robot. **7**(70), eabq9066 (2022). https://doi.org/10.1126/scirobotics.abp9066

Stoianovici, D., et al.: 'MRI Stealth' robot for prostate interventions. Minim. Invasive. Ther. Allied Technol. MITAT off. J. Soc. Minim. Invasive Ther. **16**(4), 241–248 (2007). https://doi.org/10.1080/13645700701520735

Sutherland, G.R., Latour, I., Greer, A.D., Fielding, T., Feil, G., Newhook, P.: An image-guided magnetic resonance-compatible surgical robot. Neurosurgery **62**(2), 286–292 (2008). https://doi.org/10.1227/01.neu.0000315996.73269.18

Sutton, E.E., Fuerst, B., Ghotbi, R., Cowan, N.J., Navab, N.: Biologically inspired catheter for endovascular sensing and navigation. Sci. Rep. **10**(1), 1 (2020). https://doi.org/10.1038/s41598-020-62360-w

Troccaz, J., Dagnino, G., Yang, G.-Z.: Frontiers of medical robotics: from concept to systems to clinical translation. Annu. Rev. Biomed. Eng. (2019). https://doi.org/10.1146/annurev-bioeng-060418-052502

Valdastri, P., Simi, M., Webster, R.J.: Advanced technologies for gastrointestinal endoscopy. Annu. Rev. Biomed. Eng. **14**, 397–429 (2012). https://doi.org/10.1146/annurev-bioeng-071811-150006

Vitiello, V., Lee, S.L., Cundy, T.P., Yang, G.Z.: Emerging robotic platforms for minimally invasive surgery. IEEE Rev. Biomed. Eng. **6**, 111–126 (2013). https://doi.org/10.1109/RBME.2012.2236311

Wagner, O.J., Hagen, M., Kurmann, A., Horgan, S., Candinas, D., Vorburger, S.A.: Three-dimensional vision enhances task performance independently of the surgical method. Surg. Endosc. **26**(10), 2961–2968 (2012). https://doi.org/10.1007/s00464-012-2295-3

Webster, R.J.: Design and mechanics of continuum robots for surgery, PhD, (2007)

Yan, X., et al.: Multifunctional biohybrid magnetite microrobots for imaging-guided therapy. Sci. Robot. **2**(12), eaaq1155 (2017). https://doi.org/10.1126/scirobotics.aaq1155

Yang, G.-Z., et al.: Medical robotics—regulatory, ethical, and legal considerations for increasing levels of autonomy. Sci. Robot. **2**(4), 4 (2017). https://doi.org/10.1126/scirobotics.aam8638

Yasin, H., Hoff, H.-J., Blümcke, I., Simon, M.: Experience with 102 frameless stereotactic biopsies using the neuromate robotic device. World Neurosurg. **123**, e450–e456 (2019). https://doi.org/10.1016/j.wneu.2018.11.187

Yaxley, J.W., et al.: Robot-assisted laparoscopic prostatectomy versus open radical retropubic prostatectomy: early outcomes from a randomised controlled phase 3 study. Lancet **388**(10049), 10049 (2016). https://doi.org/10.1016/S0140-6736(16)30592-X

Zhou, X.-Y., Lin, J., Riga, C., Yang, G.-Z., Lee, S.-L.: Real-time 3-D shape instantiation from single fluoroscopy projection for fenestrated stent graft deployment. IEEE Robot. Autom. Lett. **3**(2), 1314–1321 (2018). https://doi.org/10.1109/LRA.2018.2798286

Zhou, H., Mayorga-Martinez, C.C., Pané, S., Zhang, L., Pumera, M.: Magnetically driven micro and nanorobots. Chem. Rev. **121**(8), 4999–5041 (2021). https://doi.org/10.1021/acs.chemrev.0c01234

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