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REVIEW

Clinical applications of robotic surgery platforms: a comprehensive review

Ahmed Gamal[1] · Marcio Covas Moschovas[1,2] · Abdel Rahman Jaber[1] · Shady Saikali[1] · Roshane Perera[1] · Chris Headley[1] · Ela Patel[3] · Travis Rogers[1] · Martin W. Roche[4] · Raymond J. Leveillee[5] · David Albala[6] · Vipul Patel[1,2]

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Abstract

Robotic surgery has expanded globally across various medical specialties since its inception more than 20 years ago. Accompanying this expansion were significant technological improvements, providing tremendous benefits to patients and allowing the surgeon to perform with more precision and accuracy. This review lists some of the different types of platforms available for use in various clinical applications. We performed a literature review of PubMed and Web of Science databases in May 2023, searching for all available articles describing surgical robotic platforms from January 2000 (the year of the first approved surgical robot, da Vinci® System, by Intuitive Surgical) until May 1st, 2023. All retrieved robotic platforms were then divided according to their clinical application into four distinct groups: soft tissue robotic platforms, orthopedic robotic platforms, neurosurgery and spine platforms, and endoluminal robotic platforms. Robotic surgical technology has undergone a rapid expansion over the last few years. Currently, multiple robotic platforms with specialty-specific applications are entering the market. Many of the fields of surgery are now embracing robotic surgical technology. We review some of the most important systems in clinical practice at this time.

Keywords Robotic platforms · Surgical robotics · Laparoscopy · Endoscopy · Robotic-assisted surgery

Introduction

Surgery is increasingly adopting less invasive techniques to improve patient outcomes. Minimally invasive methods such as laparoscopic and robotic surgery have resulted in reduced pain, blood loss, scarring, and shortened hospital stays for patients [1]. Laparoscopy, however, is limited by its 2-dimensional (2D) vision, ergonomics, limited range of motion, and steep learning curve [2].This makes operations in narrow fields and complex reconstructions very challenging with a significant learning curve. In this scenario, robotic surgery evolved to enhance laparoscopic surgery while improving practicality and sustainability.

The concept of robotic-assisted surgery was conceived in the 1960s. Still, it wasn't until the 1990s that the US Defense Department (DARPA) teamed up with multiple start-up companies to carry out the first successful project, this collaboration laid the foundation for groundbreaking progress. Following several years of technological advancement, the first robotic-assisted surgery, a cholecystectomy, was performed in 1997 in Belgium using a platform known as "Mona" (the da Vinci system precursor) [3, 4]. The concept of 3D viewing of surgical procedures was game-changing. While the da Vinci robot received clearance from the FDA in 1997, it was initially only approved for visualizing and retracting tissues. However, in 2000, the da Vinci robot was finally cleared for general surgery use.

Initially designed for cardiac surgery, the da Vinci robot has become the most popular robotic platform worldwide after receiving approval for several other procedures in various surgical specialties, such as gynecological, colorectal,

✉ Ahmed Gamal
Dr.ahmedgamal88@gmail.com

[1] Adventhealth Global Robotics Institute, 380 Celebration Place, Orlando, FL 34747, USA

[2] University of Central Florida (UCF), Orlando, FL, USA

[3] Stanford University, Palo Alto, CA, USA

[4] Department of Arthroplasty, Hospital for Special Surgery Florida, West Palm Beach, FL, USA

[5] Baptist Health Physicians Group, Boynton Beach, FL, USA

[6] Associated Medical Professionals, Urology, Syracuse, NY, USA

head and neck, and urological surgeries [5, 6]. At the end of 2022, the worldwide count of robotic surgeries conducted with Intuitive Da Vinci robots has exceeded 11 million, utilizing a network of more than 7500 installed platforms globally [7].

Recently, partly due to patent issues, new robotic platforms have rapidly expanded for various surgical specialties from different surgical companies. The increased competition to improve the current system is expected to promote innovation and advancements in robotic technology [2, 6]. It is also hoped to provide access to robotic surgery in third-world countries and remote areas, improving costs and affordability. The market size of robotic surgery has responded positively to these developments, experiencing substantial growth in recent years. The increased awareness among healthcare professionals and patients regarding the benefits of robotic-assisted surgery contributes to the broader acceptance of these technologies. Market dynamics are shaped by factors such as the rise in surgical automation, the widening application of robotic systems across various surgical specialties, and a notable surge in the number of procedures performed with robotic assistance [7, 8]. Given the state of the field, this review aims to explore the current surgical robotic platforms, delineate their uses in several surgical specialties, and highlight their benefits and limitations.

Methodology

In this review, we employed a qualitative approach to systematically gather and analyze the existing literature on surgical robotic platforms. The purpose of this review was to provide an overview of the current state of surgical robotics, focusing on the various platforms that have been developed and their applications within the field of surgery.

Literature search strategy

We conducted a comprehensive literature search across multiple electronic databases, including PubMed, IEEE Xplore, ScienceDirect, and Google Scholar. The search was conducted using relevant keywords such as "surgical robotics, " "robotic surgical systems, " "robotic platforms, " and variations thereof. In addition, we reviewed references within identified articles to ensure inclusiveness. The search was limited to articles published from January 2000 to May 2023 to ensure the relevance of the information.

Inclusion and exclusion criteria

We included published articles written in English describing the currently available surgical robotic platforms and provided detailed information about the robotic platforms' technical specifications, capabilities, and applications. Studies describing non-surgical robotic platforms or primarily theoretical ones without practical implementation were excluded.

Data extraction and analysis

After the initial search, duplicates were removed, and titles and abstracts were screened to identify potentially relevant articles. Full-text articles were then retrieved and thoroughly reviewed. Information related to each robotic platform's technical features, surgical applications, clinical outcomes, advantages, and limitations was extracted. The extracted data were qualitatively analyzed. Similarities and differences among the platforms were identified, and recurring themes related to their functionality and applications were noted.

Data synthesis and interpretation

The narrative synthesis approach was used to weave together the findings from the selected studies. We categorized the robotic platforms based on their intended surgical specialties (e.g., urology, general surgery, orthopedics) and discussed their unique advantages and challenges. We also explored how technological advancements have influenced the development and adoption of surgical robotic platforms. We divided the robotic platforms based on their surgical applications: abdominal, orthopedic, spine and brain, and endoluminal.

Results

Soft tissue robotic platforms

Platforms used for abdominal and pelvic surgeries, including general surgery, gynecology, and urology, are illustrated in Table 1. These platforms are intended to augment laparoscopic surgery with better dexterity and improved ergonomics for the surgeon.

da Vinci surgical system (USA)

Developed and manufactured by Intuitive Surgical Inc. (Sunnyvale, CA, USA). It was approved by the Food and Drug Administration (FDA) in 2000 for general surgery use as an approach to Nissen fundoplication and cholecystectomy [9]. Over the past 2 decades, the system has undergone modifications and several da Vinci® robotic models have been released, each with continued technological improvements in ergonomics, instruments, high-definition scopes, EndoWrist™ technology, and single-port surgery. Currently, this platform is involved in adult cardiac, general surgery,

Table 1 Soft tissue robotic platforms for abdominal and pelvic surgery (urological, gynecological and general surgery)

Platforms	Manufacturer	Approval agency	Year of release	No of arms	Other features	Uses
da Vinci SI	Intuitive	FDA	2009	4	Earlier version of the system still widely used	– General surgery – Urology – Gynecology – Cardiothoracic – Head and Neck
da Vinci XI	Intuitive	FDA CE Mark	2014	4	8 mm camera port Closed console No haptic feedback	
da Vinci SP	Intuitive	FDA	2018	1	Single robotic arm through a 2.5 cm cannula with 360° of rotation 12 mm articulating camera	– General surgery – Urology – Gynecology – Head and Neck
Senhance	Asenus	FDA CE Mark	2012	2–4	10 mm camera Infrared eye-tracking for camera Haptic feedback	– General surgery – Urology – Gynecology
Revo-I	Meere	KMFDS	2017	4	10 mm camera Excessive force use warning	– General surgery – Urology – Gynecology
Versius	CMR Surgical	CE Mark	2019	2–3	Haptic feedback Portable independent arms Surgeon sitting or standing	– General surgery – Urology – Gynecology – Thoracic surgery
Avatera	Avateramedical	CE Mark	2019	4	10 mm camera with 5 mm instruments	– Urology – Gynecology
Hinotori	Medicaroid	JMHLW	2020	4	Dock free design Surgical console semi closed	– General surgery – Urology – Gynecology
Symani	Medical Microinstruments(MMI)	CE Mark	2020	2	Micro instrument Tremor reduction and motion scaling (7-20x)	– Microsurgery – Lymphatic surgery – Trauma reconstruction
HUGO™RAS	Medtronic	FDA CE Mark	2021	4	Haptic feedback Intelligent motion and collision avoidance capabilities	– General surgery – Urology – Gynecology
Dexter	Distalmotion SA	CE Mark	2021	3–5	Hybrid platform provides transition between a robot and laparoscopic setup	– General surgery – Urology – Gynecology
MicroHand S/SII	Wego Pharmaceutical	N/A	N/A	3	Compact design Low production cost	– General surgery
Toumai	MicroPortMedBot	NMPA (China)	2022	4	Integration of mechanical electronics, AI, and software algorithms	– General surgery – Urology
SHURUI SP	Beijing Shurui	NMPA (China)	N/A	1	Single Port has snake-like maneuver called dual continuum mechanism	– Urology – Gynecology
SSI Mantra	SS Innovations International	CDSCO (India)	2022	3–5	Modular multi-arm system Open-faced Surgeon Command Centre	– General surgery – Urology – Gynecology – Cardiothoracic
KANGDUO	Suzhou Kangduo Robot	NMPA (China)	2022	3–4	Open surgeon console Good ergonomics decreasing surgeon fatigue	– Urology

Table 1 (continued)

Platforms	Manufacturer	Approval agency	Year of release	No of arms	Other features	Uses
MP1000	Shenzhen Edge Medical	NMPA (China)	N/A	2–3	Multiport Surgical system	– Urology
Vicarious	Vicarious Surgical	N/A	N/A	1	Single port with 1.5 cm port size	N/A

gynecologic, head and neck, urological surgery, and pediatric surgery [8, 10].This platform consists of a surgeon's console system used to control robotic arms at the patient-side cart. The robotic arms have a proprietary "EndoWrist" technology and seven degrees of freedom [8–10]. The initial da Vinci® platform had some limitations, with only 3 robotic arms and lack of bipolar instruments, which limited hemostasis and range of motion. In 2006, the da Vinci® S was introduced, featuring a fourth arm, longer arms, bipolar hemostasis, and the introduction of high-definition (HD) scopes [11].

da Vinci. ® Si (USA) The da Vinci® Si was introduced in 2009, incorporating various modifications and upgrades to enhance its functionality. This included the introduction of finger-based clutching, the integration of Firefly™ technology (utilizing indocyanine green fluorescence dye along with the infrared vision for better visualization of blood flow and bile ducts), and other optics improvements. In addition, the system introduced dual-console capabilities, offering the enhanced opportunity of training and teaching surgeons on this novel technology [12].

da Vinci. ® Xi (USA) The release of the da Vinci Xi system in 2014 brought about significant improvements in arm design and trocar placement. This platform featured thinner arms with modified articulations, reducing external clashes of the arms. Furthermore, all ports were standardized to 8 mm in diameter, and the camera could be placed at any of the four locations. This provides dynamic visualization for procedures, allowing access to different abdominal quadrants when needed, such as in nephroureterectomies or partial nephrectomies. Laser guidance technology and simplified coupling were also introduced for docking, ensuring optimal procedure-specific positioning to maximize internal and external space during surgery [8].

da Vinci® SP (USA) This platform received clearance from the FDA in 2018, featuring a single trocar that accommodates three biarticulated instruments and one flexible scope. The SP boasts the ability to encompass all required instruments for most surgical procedures within one trocar, minimizing the number of entry points into the abdomen. Since the first clinical report of this robot, several authors have described outcomes using the SP in various surgical procedures. More recently, the SP robot has undergone updates, including changes in the number of foot pedals and improvements in scope definition [13, 14] (Fig. 1).

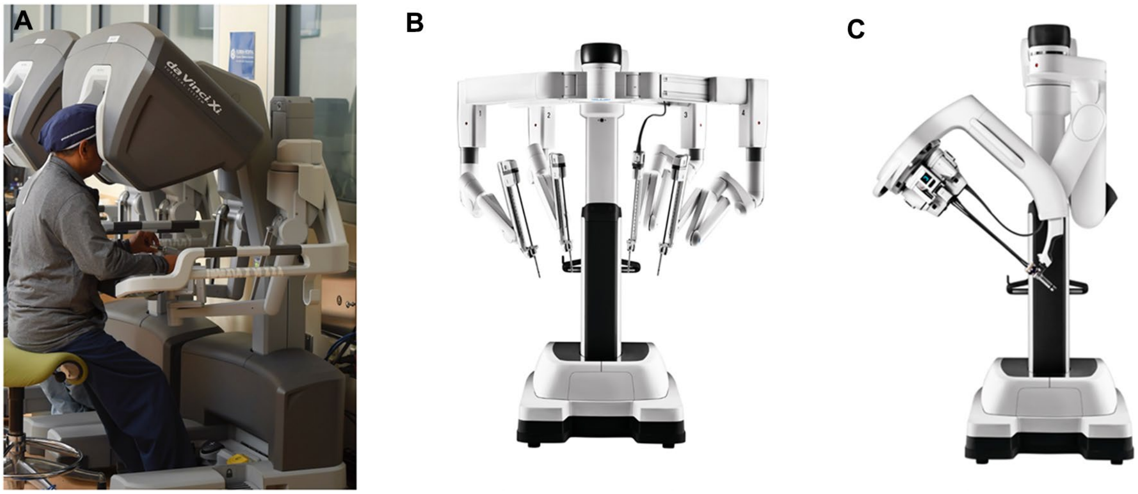

Fig. 1 Illustration of the soft tissue robotic platforms. (**A**) da Vinci Xi surgeon console, (**B**) da Vinci Xi multi-arm system, (**C**) da Vinci SP

Senhance (USA)

What was originally known as the TELELAP ALF-X advanced robotic system (developed in Italy by the company Sofar), obtained CE Mark certification in 2016 for abdominal surgeries. After being acquired by TransEnterix Surgical Inc. in October 2017, it became the first robotic system to receive FDA clearance since the da Vinci system's approval in 2000 [15]. The Senhance system is a multi-port robotic system that integrates new technologies, such as infrared eye-tracking, to control camera manipulation with the surgeon's eye movements and haptic feedback from instruments, which enables a seamless transition for laparoscopic surgeons [14–16]. The system is comprised of up to four independent robotic arms on separate carts, allowing customized positioning and orientation of the surgical instruments. The surgeon operates using an open console, seated ergonomically, and using polarized glasses to operate on a 3D high-definition monitor. The modularity of the Senhance system added a beneficial aspect to the OR setup by providing flexibility in changing positions. However, it's essential to acknowledge that one of the main drawbacks of this platform is that it takes up a significant amount of physical space in the operating room due to its large equipment size, the relatively large size of each patient cart may pose a challenge as it could impact the available space in the operating room [8].

Revo-I (Korea)

Revo-I was developed in 2007 by Meere Company Inc, a Korean manufacturer of advanced equipment. After undergoing preclinical tests and trials, the 5th version of Revo-I was approved in 2015. Subsequently, in August 2017, the platform received approval from the Korean Ministry of Food and Medicine Safety for use in human surgeries [16]. This platform is a master–slave surgical system that shares many similarities with the da Vinci Si platform. It consists of a patient cart with four articulated arms, a surgeon's console featuring a binocular 3D HD closed vision system, and a control cart. The endoscope of the Revo-I system has a diameter of 10 mm and provides 3D HD imaging. The system's instruments have a diameter of 7.4 mm, can be reused up to 20 times, and provide seven degrees of freedom, similar to the da Vinci model. According to porcine studies, the Revo-I system has demonstrated a high level of safety with comparable perioperative results to other robotic systems [16, 17]. In 2018, the first human study using Revo-I was published, which reported robot-assisted retzius-sparing radical prostatectomies performed on a total of 17 patients with encouraging perioperative outcomes [18]. The system is currently only used in S. Korea.

Versius Robot (UK)

This system was manufactured by Cambridge Medical Robotics Ltd (Cambridge, UK) and was approved with the European CE Mark in March 2019 [19]. It comprises modular, wristed robotic arms and an open-design operator console. The surgeon controls the robotic arms through joystick controllers connected to the console while wearing 3D glasses and viewing a monitor. Haptic feedback is provided through the controller, allowing them to feel the force the instruments apply. The operator may sit or stand while operating, allowing them to adjust their ergonomics. Different types of robotic arms have been developed to use 5 mm instruments, which help to reduce further the size of incisions required for surgery as well the ability to maneuver and suture in smaller cavities [20]. This robotic platform is designed for colorectal, upper GI, gynecological, and urological surgery [19, 20]. Its application across various specialties is yet to be seen to be able to compare its feasibility to existing well-established robotic systems. Over 1000 robotic surgical cases have now been performed globally with this system.

Avatera platform (Germany)

Established in 2011 as the first German robotic surgery system, this platform shares similarities with the da Vinci Robotic system and consists of two components: a separate console control unit for the surgeon and a cart with four robotic arms. This design allows for easy integration into most surgical theaters. The system features a high-definition camera for clear visuals and utilizes 5 mm fully articulated working instruments with a wide range of movements in seven degrees of freedom [21].The open-console control unit of Avatera features an eyepiece reminiscent of a microscope, a flexible and integrated seat, user-friendly haptic input devices and footswitches for easy handling. One unique feature of this platform is that all instruments used are disposable, eliminating the need for sterilization procedures [22]. One study performed 6 radical nephrectomies on porcine models and found the system to be technically feasible in terms of maneuverability [23].

Hinotori platform (Japan)

The Hinotori system, developed by Medicaroid Corporation in Kobe, Japan, has received approval for use in Japan. This robotic surgical system features a semi-open console with a 3D HD view provided by a microscope-like eyepiece. The console includes loop-like handles allowing surgeons to control the wristed robotic arms, which are multi-faceted and capable of movement in eight axes. This platform is currently used for urological and gynecological procedures and is expected to be approved in gastrointestinal and thoracic surgery in the future [24, 25]. A prospective study was performed on 30 consecutive patients with small renal tumors using the retro and intraperitoneal approach to robotic-assisted partial nephrectomies. The perioperative outcomes were favorable regarding margins, ischemia, and complications, suggesting the platform may be utilized in small renal tumors [26]. The system is currently only available in Japan.

Symani (Italy)

Developed by Medical Microinstruments (MMI) company, the platform consists of 2 robotic arms that can be adjusted to accommodate surgical procedures across diverse anatomical regions. The system is designed to work with a microscope or surgical loupes instead of a surgeon console. Symani's NanoWrist instruments stand as the smallest wristed surgical tools globally, designed to enhance a surgeon's dexterity and extend their range of motion. It also features a motion scaling range of 7–20 times and an integrated tremor filtration mechanism, which meets the intricacies and challenges posed by microsurgery and supermicrosurgery [27]. It consists of a 3 mm wrist as well as the 7 degrees of freedom we have become accustomed to in other robotic platforms. This specific platform is designed to be utilized in procedures that would be performed using the traditional open approach. The system has been tested in diverse surgical procedures, including free flap reconstruction, lymphovenous anastomosis, microsurgical vessel repair, and ophthalmology procedures. The device possesses potential in microscopic reconstructive surgery [28].

HUGO™ RAS (UK)

Medtronic developed this platform with modular surgical arms mounted on wheeled carts. It was conceived to address the cost and utilization barriers affecting the adoption of robotic surgery in previous decades. This modularity allows for easy configuration of the robot to suit various surgical procedures and environments. The system enhances precision and control during minimally invasive procedures, while the surgeon console offers a 3D HD view of the surgical field. Medtronic's range of systems is globally connected to a patient registry that monitors and records outcomes [29]. The data collected from this registry is then integrated back into the platform, aiding in analysis and improvement. Since the platform was first utilized in a minimally invasive prostatectomy procedure in Chile in June 2021, it has been widely adopted internationally for diverse surgical procedures, including urological, gynecological, and gastrointestinal surgeries [30]. The system is currently available in Europe, Latin America, India, and Australia.

Dexter (Switzerland)

Developed by Distalmotion SA in Switzerland, the platform is approved for a wide range of medical procedures, including gynecologic, general surgery, and urology. This on-demand robotic framework offers the flexibility to selectively utilize advanced laparoscopic instruments for specific surgical stages where the heightened precision of a robotic platform may not be necessary. This enables a swift transition to a laparoscopic approach right at the patient's bedside [31]. Thillou et al. conducted the first case series of robot-assisted radical prostatectomy (RARP) on ten patients using the Dexter system and reported on the safety and feasibility of the platform without intraprocedural complications or major technical failure [32]. Another prospective study by Hotz et al. included a series of 25 patients undergoing general visceral surgery (14 hernias and 11 cholecystectomies), and the Dexter platform was considered a safe and efficient interface to undergo these procedures [33] (Fig. 2).

MicroHand S/SII (China)

Developed by a collaborative effort between Tianjin University and the WEGO Company, the MicroHand surgical robot performed its first clinical cases in 2014 (robotic repair of gastric perforation as well as appendectomies) [34]. MicroHand has a compact design and a low production cost compared to the da Vinci robot. Since its production, it has been employed to perform multiple surgeries ranging from intraabdominal oncological resections to benign repairs of abdominal organs in general surgery. A consecutive case series published by Yao et al. confirmed the safety and reliability of the platform in performing general surgery cases [35]. A direct head-to-head comparison between Microhand S and the da Vinci Si robot in a total mesorectal excision was conducted using a propensity score matched analysis of short-term outcomes [36]. No statistically significant differences were observed in postoperative outcomes, including total operation time, robotic operation time, blood loss, time to first liquid diet, time of getting out of bed, and hospital stay however, they did note longer docking time using the Microhand S. The authors however distinctly note technical differences between the Microhand S and da Vinci Si which include open console, multiple motion scaling options as well as the ability to use energized instruments in both arms simultaneously. Microhand has also been successfully used in remote surgery on swine models at a distance of 3000 km over 5G networks within China [37].

Toumai (China)

Developed by MicroPort MedBot (Group) Co., Ltd. It was the first four-arm surgical robot system in China. The

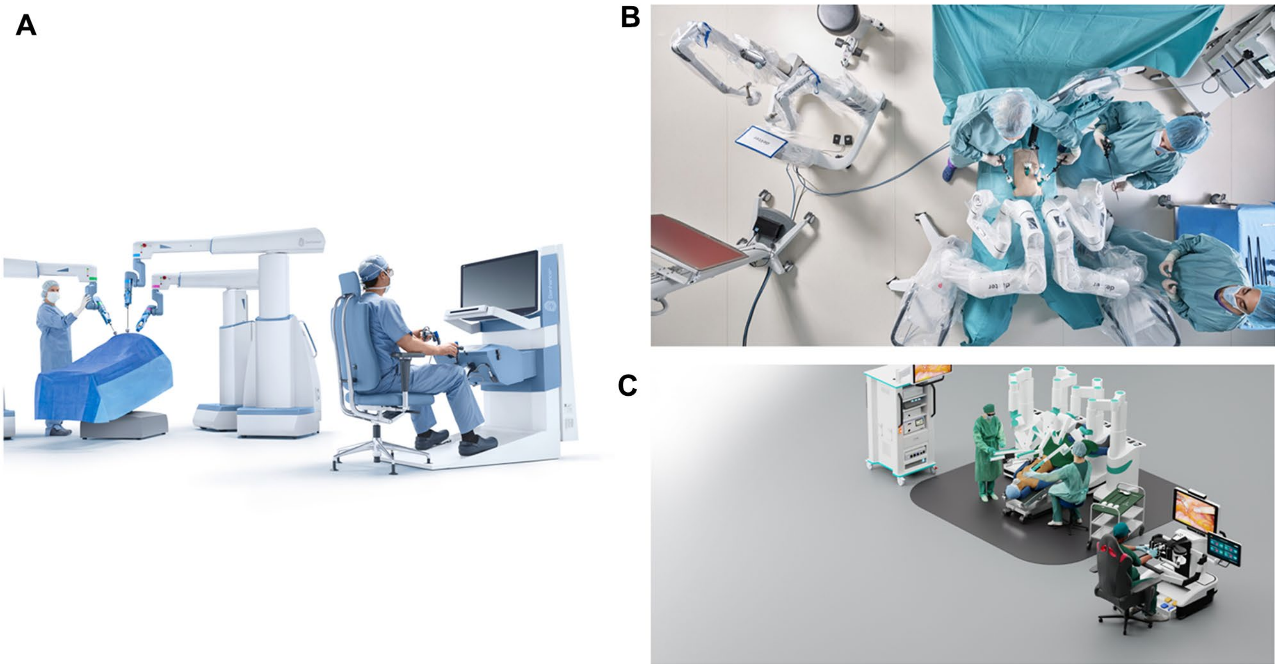

Fig. 2 Illustration of the soft tissue robotic platforms. (**A**) Senhance surgical platform with modular design and open surgeon console, (**B**) Dexter surgical platform enables a swift transition to a laparoscopic approach, (**C**) SSI Mantra modular multi-arm system

platform's technical features include 3D surgical field, fine manipulation of micro-instruments, and high dexterity in narrow spaces. It integrates several technologies such as mechanical electronics, artificial intelligence, and software algorithms. The platform completed a registered clinical trial for application in urologic surgery in January 2021. The trial enrolled 44 cases for robotic radical prostatectomy divided into tw0 groups: the experimental group using the Toumai system and the control group using da Vinci robotic system. Toumai system showed insignificant differences regarding safety, efficacy and short-term outcomes compared to the da Vinci system; however, the long-term oncological and functional outcomes need further studies [38].

SHURUI SP (China)

Developed by Beijing Surgerii Robotics Company Limited. It is the first single-port robotic platform in China. The system achieves motion through the continuous deformation of an elastic structure, allowing a snake-like maneuver (dual continuum mechanism) to permits enhanced payload capability, as opposed to the da Vinci SP platform composed of joints and rigid links. The first robotic ovarian cystectomy using a single-port platform performed in China was reported in 2022 using the SHURUI SP [39]. In a study by Peng et al., 13 cases of partial nephrectomy were done using SHURUI SP, showing the safety and efficacy of the platform with no device-related adverse events [40]. The system is currently approved for urology applications in China.

SSI Mantra (India)

Developed by SS Innovations International, Inc. The platform is India's first robotic surgical system. It has a modular multi-arm system with 3–5 robotic arms, an open-faced ergonomic surgeon command center, a 32-inch large 3D HD monitor, and a 23-inch 2D touch panel monitor for patient-related information. It uses reusable instruments. However, they do opt for a dedicated trocar use [7]. They address the issue of the high cost of other robotic platforms, reporting production at one-third of the price [41]. The system received Indian Medical Device regulatory approval (CDSCO) and is clinically validated in India in more than 35 different surgical procedures, such as cardiothoracic, head and neck, gynecology, urology, and general surgery. They have completed 100 successful surgeries this year and are expanding geographically [41]. The system is currently only in India.

Kangduo (China)

Developed by Suzhou Kangduo Robot Co., Ltd. The KangDuo Surgical Robot-01 (KD-SR-01) system, recently developed in China, features a 3D open display surgeon console and a 3-arm robotic system suspended from a beam, allowing for effective triangulation during the procedure. It has shown promising results for partial nephrectomy and pyeloplasty procedures as well as radical prostatectomies [42]. A direct comparison between KangDuo and da Vinci Si robots was conducted to compare their safety and efficacy in robotic-assisted partial nephrectomies [43]. A double center prospective randomized non inferiority study was conducted between September 2020 and March 2021 on 99 participants divided evenly between both robots. Both groups completed all surgeries successfully with similar eGFR and adverse events. However, the docking and suture time using the KangDuo robot were longer than the da Vinci robot. A prospective single-center, single-arm clinical study was conducted from May 2021 to August 2021. Sixteen RARP procedures with the KD-SR-01 system were performed by 1 surgeon. All procedures were completed successfully with no conversion to traditional, open or laparoscopic RARP. The perioperative, oncological and functional outcomes were well within acceptable limits for RARP which emphasizes the safety, efficacy and feasibility of using the KangDuo in surgically managing localized prostate cancer [44]. Kang Duo is currently only in China (Fig. 3).

MP1000 (China)

Developed by Shenzhen Edge Medical, the MP1000 is a multi-port laparoscopic surgical robot that successfully concluded a registered clinical trial in urological surgery in December 2021. Just a month later, the Chinese National Medical Products Administration (NMPA) accepted its registration application. The platform has demonstrated its efficacy and safety in clinical trials, achieving results comparable to those of the da Vinci surgical system. Shenzhen started clinical trials on a single-port platform as well (SP1000) [45]. The system is being used in China for multi-specialty robotic surgery.

Robotic platforms for orthopedic surgery

Robotic platforms in orthopedic surgeries have been around for over 30 years, providing a precise and accurate means to prepare the bone and alignment of the joints in orthopedic arthroplasty [46]. Table 2 highlights the various methods and robotic systems in orthopedic surgery.

Mako (USA)

Developed by Stryker Corporation, Mako is a robotics-assisted surgical system used primarily in orthopedic procedures, including total hip replacement and partial knee replacement surgeries [47]. This platform incorporates three essential components. First, it utilizes preoperative 3D CT-based planning and image-guided intraoperative navigation to aid in surgical precision. Second, it integrates alignment, implant position, and gap data for pre-resection implant modifications. Finally, the system employs a semi-constrained robotic arm to execute accurate bone resection within defined "haptic" boundaries, facilitating the subsequent placement of cemented implants [48]. Most of the literature evaluating this platform demonstrates improved radiological and clinical outcomes, surgical efficiency, and cost-effectiveness [49].

Fig. 3 Illustration of the soft tissue robotic platforms. (**A**) Kangduo Robot surgical platform, (**B**) Shurui SP surgical platform, (**C**) Medbot Toumai surgical platform

Table 2 Platforms for orthopedic surgery

Platforms	Manufacturer	Approval agency	Year of release	Other features
Mako	Stryker Surgical	FDA	2006	3D imaging technology Haptic feedback Real-time monitoring
NAVIO/CORI	Smith & Nephew	FDA CE Marks	2013	Real-time imaging and mapping NAVIO handpiece that the surgeon uses to position the robot's cutting tools
Rosa	Zimmer Biomet	FDA	2016	Versatile can be used for a range of surgical procedures including stereotactic neurosurgery procedures
VELYS™	Johnson & Johnson	FDA	2020	Advanced imaging technology allows for a more detailed pre-operative assessment of the patient's joint
Honghu	MicroPort® OrthoBot	NMPA FDA	2022	Successfully completed remote arthroplasty with 5G technology NDI camera

The NAVIO/ CORI (UK/USA)

Manufactured by Smith & Nephew, Inc., Memphis, TN, USA, the NAVO is a robotic-assisted platform designed for orthopedic surgeries, specifically total and partial knee replacement procedures. It combines state-of-the-art robotics technology with a surgeon-controlled handheld instrument to enhance precision and improve patient outcomes [50]. A key feature of the NAVIO system is its image-guided capabilities, which rely on preoperative CT scans or MRIs to generate a 3D model of the patient's knee joint. This model serves as a guide for the surgeon, enabling precise surgical planning and personalized implant positioning [51].

ROSA (France)

Developed by Zimmer Biomet, ROSA is an advanced robotics-assisted platform that can be used in a variety of procedures, including orthopedic, neurosurgical, and spine procedures [52, 53]. The spine version of the robot, cleared by the FDA in 2016, is utilized mainly for performing minimally invasive circumferential arthrodesis, with issues like spondylolisthesis or recurrent herniated disc. Its design focuses on assisting surgeons in reducing instances of incorrect screw positioning during arthrodesis, minimizing ionizing radiation exposure for the surgical team, and decreasing surgery-related complications such as infections and postoperative pain by reducing damage to surrounding tissues [54]. The ROSA knee system was officially launched in 2019 and was developed based on the accuracy of the ROSA brain system. It can be considered a semi-active surgical robotic system, where the surgeon remains in charge of the procedure while the robotic assistance provides the capability to position instruments optimally, enabling surgeons to perform surgeries with high accuracy and reproducibility [55].

VELYS™ (USA)

DePuy Synthes developed this platform, a recently-released technology specifically designed for total knee arthroplasty (TKA) [56].This system comprises an optical tracking system featuring bone-mounted arrays and a bed-mounted robotic arm responsible for positioning a surgical saw for bony resections [56, 57]. Notably, one distinguishing feature of the VELYS system is that it does not necessitate pre-operative imaging. Surgery is planned in real-time using the robot's planning software to assess the anatomy of the patient's natural joint. This advancement streamlines the surgical workflow by eliminating the need for pre-operative imaging while still providing the benefits of robotic assistance during TKA procedures [57].

Honghu/Skywalker (China)

The Honghu orthopedic surgical robot, also known as Skywalker, is developed by Suzhou MicroPort® OrthoBot Co., Ltd., a subsidiary of Shanghai MicroPort® MedBot. The platform is the first surgical robot produced in China to successfully acquire certifications and market approval from the NMPA, FDA, and CE Mark. It consists of a robotic console with NDI camera to track the targets during the operation and a robotic arm with six motion joints connected to a cutting jig [58]. The Skywalker has recently completed a remote arthroplasty with the help of 5G technology. The first 5G remote joint replacement surgery was conducted using a Chinese-developed surgical robot [59] (Fig. 4).

Surgical robots for spine and neurosurgery procedures

The first application of robotics in surgery is credited to neurosurgery, with the use of the PUMA 560 robotic system to improve neurosurgical biopsy accuracy [60]. Most robotic

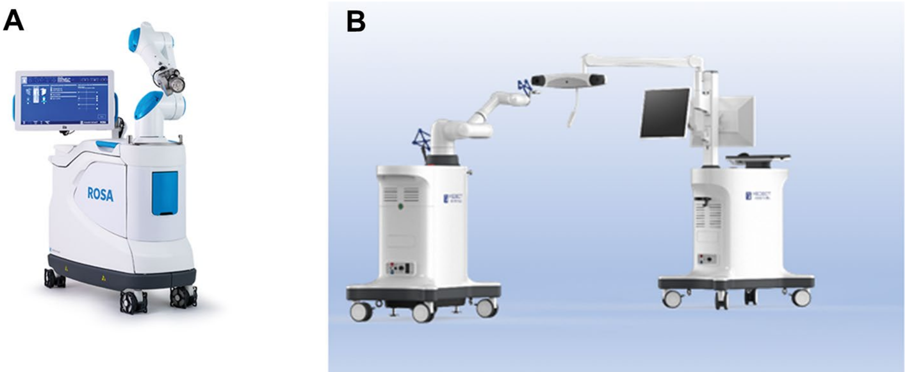

Fig. 4 Illustration of the orthopedic surgery robotic platforms. (**A**) Zimmer Biomet ROSA platform, (**B**), Suzhou MicroPort SkyWalker platform

systems in neurosurgery/spine procedures are designed to assist in anatomical planning and localization, minimizing surgeon hand tremors as well as pedicle screw placement [61]. Platforms used to carry out spine surgeries and different neurosurgical procedures can be seen in Table 3.

Excelsius GPS (USA)

Developed by Globus Medical Inc, Excelsius GPS was approved by the FDA in 2017 [62]. Its main application is providing navigation capabilities in spinal surgery. This novel robot features a sturdy, precise robotic arm with 6 degrees of freedom, securely mounted to a floor unit. It offers trajectory planning capabilities using pre-operative or intraoperative imaging, such as fluoroscopy and CT scans. This allows for real-time intraoperative navigation, enabling accurate instrument placement and enhancing imaging versatility. The system eliminates the need for patient-mounted frames and K-wires by directly deploying screws through its rigid tubular robotic arm. This eliminates a drawback commonly associated with the Mazor and ROSA systems [63, 64].

Mazor X (Israel)

The first robot approved by the FDA to guide the placement of pedicle screws in 2004 was Mazor SpineAssist by Mazor robotics [65]. Soon after Medtronic acquired Mazor Robotics in 2018, they launched the Mazor X Stealth Edition for spine surgery, which is one of the newest generations of robotic-assisted spine surgeries [66]. It consists of a workstation equipped with a computer interface for surgical planning and operating the detachable surgical arm. The arm attaches to the Jackson table bedframe via a custom mount near the foot of the bed. The platform has two different methods available for surgeons to plan the surgery: scan-and-plan and the pre-operative computed tomography (CT) scan. Both planning methods use the same registration method, which requires recognition of a 4-tantalum beaded star marker [67, 68].

Robotic platforms for endovascular and endoluminal uses

These robotic platforms offer enhanced precision and control during complex procedures such as angioplasty, stent placement, and embolization. By providing surgeons with teleoperated tools and advanced imaging guidance, robotics systems enable more accurate navigation through intricate blood vessels and anatomical structures. They have proven their utility in a variety of endovascular procedures as well as peripheral vascular procedures [69]. This results in reduced radiation exposure for both patients and medical staff, shorter procedure times, and improved patient outcomes. In endoscopic procedures, it provides similar benefits to those seen in laparoscopic procedures: increased dexterity, enhanced visualization and better access to narrow spaces. A wide range of robotic platforms used for endovascular and endoluminal procedures, including PCI, bronchoscopy, and GI endoscopy, are illustrated in Table 4.

Table 3 Platforms for spine and neurosurgery procedures

Platforms	Manufacturer	Approval agency	Year of release	No of arms	Other features
Excelsius GPS	Globus Medical	FDA CE Mark	2017	1	K-wires not required Real-time 3D navigation allow instrument tracking
Mazor	Medtronic	FDA	2020	1	Many generation Advanced imaging technology to create a detailed 3D map of the patient's spine

Table 4 Platforms for endoscopic and endovascular procedures

Platforms	Manufacturer	Approval agency	Year of release	Uses	Other features
CorPath	Corindus Robotics	FDA	2012	Cardiology (Endovascular)	Includes joysticks and touch-screen interface
Avicenna Roboflex	ELMED	CE Mark	2013	Urinary tract (Transurethral)	Compatible with different types of flexible ureteroscopy
Flex®Robotic	Medrobotics	FDA	2015	Trans oral and Colonoscopy	Capability of reaching difficult anatomic areas
Invendoscopy E200	Invendo Medical	FDA	2016	Gastrointestinal endoscopy	Colonoscopies without sedation Easy to transport
Monarch	Auris (J&J)	FDA	2018	Pulmonology (Bronchoscopy)	Joystick-like controller Navigate the narrow pathways of the lung
ION	Intuitive	FDA	2019	Pulmonology (Bronchoscopy)	Ultra-thin robotic catheter with advanced maneuverability
Anovo	Momentis Surgical	FDA	2021	Gynecologic (Transvaginal)	Arm Controllers (Joysticks) PC with Touch Screen

CorPath system (USA)

Robotic-assisted PCI was developed to decrease occupational and procedural risks to cardiologists and medical staff performing fluoroscopically guided cardiac procedures [70]. The first-generation CorPath 200 (Corindus) robotic-assisted system for PCI is associated with lower radiation exposure for the operator when compared to conventional PCI [71]. However, the first-generation system was limited by its lack of robotic guide-catheter control [72]. The CorPath GRX (Corindus), a second-generation robotic-assisted system, obtained approval from the FDA in 2016 [73]. Compared to its first generation, this device offers enhanced functional control, including faster guidewire rotation, simplified device exchanges, and a third joystick for guide-catheter manipulation. Smitson et al. showed that high rates of clinical procedural success and technical success of 97.5 and 90.0%, respectively, were achieved using this platform [74].

Avicenna Roboflex (Turkey)

Avicenna Roboflex™ (Elmed, Ankara, Turkey) obtained its CE mark in 2014 and is currently undergoing preparations for FDA approval [75]. The system is specially designed for flexible ureterorenoscopy (FURS). It features an open console, allowing the surgeon to sit and utilize a standard flexible ureteroscope with HD video technology. The handpiece of the scope is connected to a robotic manipulator, enabling the surgeon to control rotation, insertion, and deflection of the scope using joysticks. Functions such as irrigation, activation of the laser fiber, and fluoroscopy control are accessible through touch-screen features and foot pedals [75, 76]. Geavlete et al. compared Avicenna robotic flexible ureteroscopies to classic flexible ureteroscopies and the result showed the superiority of the robotic over the classic FURS with a stone-free rate of 92.4 vs. 89.4% for the classic FURS [77].

Flex® robotic system (USA)

The Flex® robotic system, developed by Medrobotics Corp. based in Raynham, MA, was designed for minimally invasive transoral surgery in the oropharynx, hypopharynx, and larynx. This system features a single-port, operator-controlled flexible endoscope [78]. Its unique design enables the surgeon to navigate around anatomical structures by manipulating a robotic outer mechanism, which guides the movement of an inner mechanism. The operational tower console includes a touch-screen interface and provides high-definition (HD) visualization with magnification and a joystick controller [79]. The system has working channels that accommodate instruments such as scissors, needle drivers, graspers, and dissectors. It can articulate at nearly 180° and allows articulating instruments to be operated via joystick [80]. Clinical implementation of the system in patients who have undergone head and neck surgery has established its safety and feasibility [79, 81].

Invendoscopy E200 system (Germany)

Developed by Invendo Medical GmbH (based in Germany), Invendoscopy E200 is a single-use sterile colonoscope with a reusable handheld controller and processing unit [82]. It is used for visualization, diagnostics, and therapeutic endoscopic surgery. The robotically assisted system has a 170 cm insertion length, and its tip can be deflected 180° in all directions. With a bending radius of 35 mm, it enables retroflection and provides comprehensive visualization of the colon. The Invendo Scope Controller is a lightweight joystick that can be detached from the colonoscope. The controller minimizes the musculoskeletal strain on the operator while retaining the functionality of a conventional colonoscope [83, 84]. Groth et al. ran a feasibility study in 2011 that evaluated the use of Invendo Medical technologies for computer-assisted robotic colonoscopy. The study reported a high intubation success rate at 98.4%, with 95.1% of the procedures being completed without the need for sedation. Importantly, no complications related to the device were encountered during the study [82].

Monarch (USA)

Developed by Auris Health, a subsidiary of Johnson & Johnson. The platform is designed for use in diagnostic and therapeutic procedures in minimally invasive endoluminal interventions, specifically in the lungs [85]. It combines robotics, imaging, and data management to enable precise navigation and control during procedures such as bronchoscopy. The system has a flexible robotic bronchoscope that can be navigated through the pulmonary airways. The bronchoscope is equipped with a high-resolution camera and various instruments for sample collection and treatment. The system also includes a workstation that allows the physician to control the robot and visualize the procedure in real-time using advanced imaging technology [86]. In the 2018 REACH study, the Monarch system underwent initial evaluation using cadavers. The study compared the Monarch system to conventional flexible bronchoscopy of similar diameter (4.2 mm). The findings indicated that the Monarch system could advance further into distal airways compared to conventional bronchoscopy, both in terms of depth and airway generation (9th vs. 6th generations). The enhanced maneuverability of the Monarch system allowed for better navigation of acute angulations within the airways [87] (Fig. 5).

ION (USA)

The Ion robotic bronchoscope can be used for diagnostic and therapeutic interventions within the pulmonary landscape. It is a shape-sensing robotic-assisted bronchoscopy system. The system provides 3D mapping and visualization of the airways, a flexible and fully articulating 3.5-mm (outer diameter) catheter, a peripheral vision probe, and system-specific biopsy needle. It was evaluated in an ongoing prospective trial involving 241 patients and a total of 270 peripheral pulmonary nodules, demonstrating an acceptable safety profile with a low rate of pneumothorax (3.3% asymptomatic, 0.4% requiring intervention) [88, 89].

Anovo (Israel)

Developed by Momentis Surgical Ltd, this robot-assisted system is specifically designed to facilitate vNOTES (vaginal natural orifice transluminal endoscopic surgery) procedures while providing a natural and intuitive surgical experience. It features highly articulated arms that closely mimic the movements of the surgeon's upper extremities the shoulder, elbow, and wrist joints. Each arm is specifically designed to correspond to the respective hand of the surgeon and is controlled using left and right joysticks for accuracy and user-friendly operation. The arms consist of a rigid section (shaft) and a flexible section, with the flexible portion comprising three joints that allow for rotation and flexion in the arms. The platform has been successfully demonstrated in vNOTES procedures, including vaginal bilateral salpingo-oophorectomy (BSO) for non-malignant conditions [90].

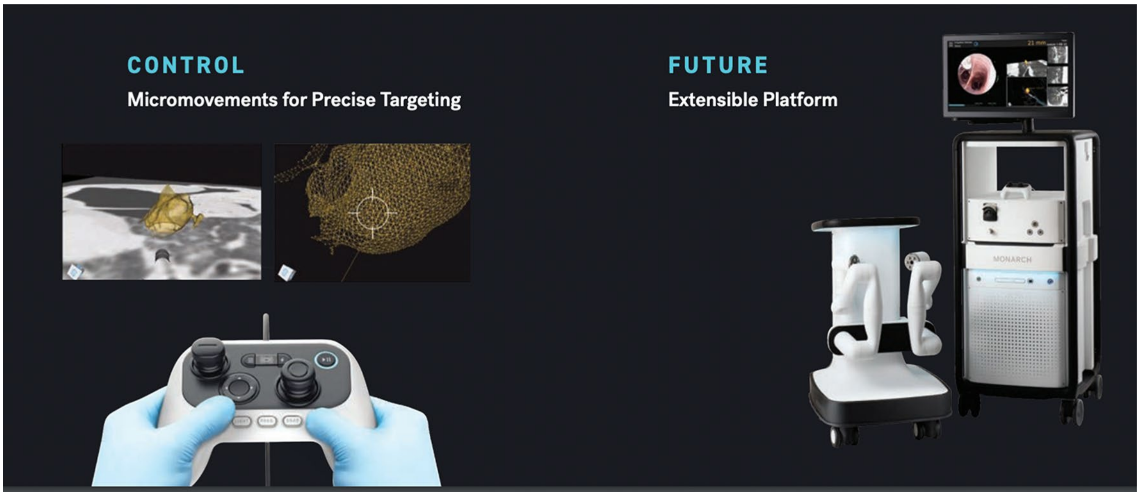

Fig. 5 Illustration of the endoluminal robotic platforms. Auris Health Monarch endoluminal surgical platform for diagnostic and therapeutic procedures within the lung

Discussion

With the numerous robotic platforms released for soft tissue-related operations, it is evident that for the most part, each further development builds on top of recent platforms' beneficial innovations. The year-over-year rate of these advancements has also increased with increasing levels of competition within the market. The initial relative lack of competition within this market is demonstrated by da Vinci's ability to produce a variety of robots for various procedures. Some of the fundamental innovations in the state of robotic platforms at present occurred during this period in the early 2000s: longer arms, bipolar hemostasis, and HD scopes were pioneered by da Vinci S in 2006, solving many of the issues present with the original da Vinci [11]. In 2009, finger-based clutching, scope improvements, and indocyanine green fluorescence were introduced in the da Vinci Si. This model also accounted for the limited teaching and training capabilities present in previous models via dual-console technology, setting a precedent that would go on to rationalize the use of robotic platforms in surgical training settings [12]. The Senhance platform in 2012 introduced two innovations: haptic feedback and modularity. Haptic feedback allows surgeons to perceive different types of tissue and the amount of force exerted by their instruments. Modularity, on the other hand, makes platforms portable, versatile, and compatible with a variety of operating environments, saving space when not all components are required [25, 65]. Senhance also introduced other features that are not the industry standard: infrared eye-tracking for camera control and magnet-attached instruments for ease of replacement during surgery. Certain limitations with this robot including its large size, lack of articulated instruments, and its requirement for polarized glasses, could have contributed to its minimal dissemination in the robotics platform market [91, 92].

In 2014, new technology showcased by the da Vinci Xi (twin high resolution, high frame rate eyepieces), which also featured wristed instruments with motion scaling as well as additional degrees of freedom compared to the Si and tremor-reducing capabilities, propelled da Vinci's market prominence. Further robotic surgical platforms would follow suit by adopting all three new modifications widely. These three traits largely account for high conversion rates between 2003 and 2015 from open to robot-assisted soft-tissue operations, with a 25.5% increase in robotic surgery occurrence during this period [93, 94].

The Versius platform from CMR was released in 2019 to continue Senhance's usage of haptics and modularity but remain relatively large in size compared to both da Vinci and Senhance [25]. Also, in 2019, the Avatera robot solved the issue of lengthy instrument sterilization procedures, making all the instruments disposable. It is very easy to integrate into surgical theaters as it consist only of two components, and is compatible with a diverse range of instruments [21, 22]. Hinotori (2020) has a smaller footprint than other robots, making it well-suited for smaller operating rooms. Its hand control also has four levels of adjustable weight that can be changed mid-surgery for improved ergonomics, and it has a dock-free design [25].

The HUGO RAS platform combines many fundamental da Vinci features with the haptic feedback and modularity pioneered by Senhance and Versius. It builds on top of these capabilities by coupling its haptic feedback with intelligent motion and collision avoidance functionality, and its modularity uses compact rolling carts for easy transportation between operating rooms, as well as rapid setup and takedown between procedures [30].

The emergence of multiple robotic platforms from China has brought a remarkable shift in the landscape of surgical technology. Notably, these platforms have demonstrated efficacy and safety non-inferior to established counterparts. Such innovations have the main feature of addressing a key limitation of adopting robotic platforms worldwide: cost-effectiveness, by providing advanced capabilities at a more accessible price point [25, 36].

Robotic platforms available for orthopedics can carry out a wide range of orthopedic procedures. One of the most common procedures is the robotic total knee arthroplasties (TKA). Robotic arthroplasties have gained significant traction by enhancing the precision of implant positioning and reducing deviations in limb alignment in contrast to conventional TKA [95, 96]. In robotic TKA, computer software transforms anatomical data into a virtual, patient-specific three-dimensional reconstruction of the knee joint [97]. Sodhi et al. investigated the learning curve associated with robotic TKA in two different surgeons. The study revealed that for the initial 20 cases of robotic TKA, operative times were longer than conventional manual TKA. However, after this initial period, the operative times for robotic TKA became comparable to those of conventional manual TKA for both surgeons [98]. Kayani et al. conducted a prospective cohort study comparing early functional outcomes between 40 traditional manual TKA and 40 cases of robotic TKA. The study demonstrated that robotic TKA was associated with several advantages, including reduced postoperative pain, decreased need for analgesics, a shorter time to achieve straight leg raise, and increased knee flexion at discharge [95].

The limitations of robotic technology in this field are initial and maintenance costs. Additional expenses also arise in robotic cases due to various factors, such as the requirement for extra pre-operative imaging, longer operating times during the learning phase, training of the surgical team, software updates, and servicing contracts.

Robotic applications also involved spine surgeries, with significant interest in its potential to improve the precision of instrument implantation. The Mazor robotic system, initially known as SpineAssist, was the pioneering robotic system developed specifically for spinal surgery, which then gained FDA approval in 2004. It remains one of this field's most extensively studied and investigated systems. Presently, there are three robotic systems currently in use for spine surgery: Mazor X Stealth Edition (including previous models such as Mazor X, SpineAssist, and Renaissance) by Mazor Robotics, ExcelsiusGPS by Globus Medical, and ROSA by Zimmer Biomet [99, 100].

These robotic platforms employ shared-control models, allowing the surgeon and the robot to control movements during the procedure simultaneously. By incorporating computer-assisted trajectory planning and guidance through a robotic arm, these systems enable highly accurate placement of screws during spinal surgery. Recent studies have shown comparable or even more precise screw placement with robotic systems compared to fluoroscopy-guided freehand screw placement [99, 101]. A three-arm randomized controlled trial study conducted by Roser et al. was performed to compare screw placement techniques in spinal surgery. The study included patients who underwent SpineAssist screw placement, fluoroscopy-guided placement, and freehand screw placement. The accuracy rates were reported as 99.0% for robot-assisted placement, 92.0% for fluoroscopy-guided placement, and 97.5% for freehand placement [102]. A higher accuracy rate was also observed and was noted in the prospective study by Lonjon et al. using the ROSA platform. The accuracy rate in the robotic group was 97.3%, compared to the 92.0% accuracy of the freehand group [103]. While the initial acquisition cost of robotic systems in spine surgery is substantial, there is a need for additional data to assess the long-term financial implications of these advanced technologies. Incorporating robotic systems in spine surgery has the potential to be cost-effective by reducing the need for revision surgeries and shortening both hospital stays and operative times [104, 105].

Additional examples of promising innovations are in endoluminal and endovascular platforms, which are very specific in their applications, unlike most of the discussed soft tissue and orthopedic platforms. Their applications include endovascular, urinary, upper GI, lower GI, bronchoscopy, and vNOTES procedures, with the devices specifically designed for each type of procedure. Notably, all of these platforms demonstrated high measured levels of procedural and/or technical success and, in many cases, have shown superiority over their analog counterparts [106]. The CorPath endovascular platform demonstrates the constant evolution that pervades this field. Its second iteration showed far superior performance compared to its first (97.5 vs. 80.0% procedural success rates) mainly due to its increased levels of control, which allowed this device to gain FDA approval to begin with [72–74].

Avicenna Roboflex is unique among endoscopic platforms. Being a Turkish, CE-approved machine, it highlights the global scope of the robotic endoscopy market. Interestingly, it is the only endoscopy platform to implement a robotic interface that controls a traditional instrument, a standard flexible ureteroscope. It explores the possibility of hybridization of robotic platforms without the need to purchase expensive specialized instruments [76, 77].

In endoscopy (particularly lower GI), the development of flexible robotic systems quickly addressed concerns about robotic platforms being too rigid for this type of procedure. The Flex robotic system's flexibility seems promising in complex procedures, navigating around tight spaces and extremely acute angles while remaining safe and feasible [78, 80].

The integration of surgical robotic systems has transformed surgical training by necessitating specialized skills, simulation-based learning, and standardized protocols. Robotic surgery introduced a more advanced way of dry lab and simulators not available in open and laparoscopic surgery. Surgeons now undergo structured training programs that incorporate simulation platforms, enabling them to practice and refine their skills before performing actual procedures. By performing several tasks before operating on patients, the surgeon achieves proficiency-based training and skills to proceed to human surgery. The standardization of robotic procedures facilitates competency assessment, while connectivity features allow for remote mentoring and continuous skill enhancement. The impact includes a potentially reduced learning curve for complex surgeries and the evolution of a more structured and adaptable training paradigm [107, 108].

Future prospects

With the advancement of current technology and the integration of artificial intelligence in multiple aspects of the medical field, it is crucial to utilize its full potential in robotic surgery. The road to autonomy of surgical robots starts with the use of deep learning models and artificial neural networks for the robot to be able to learn tasks and perform them independently [109]. However, the ability to autonomously operate is still lacking. Many hurdles exist in terms of patient rights, availability of big data sets for learning, and questions about autonomous surgery's commercial value. All of these issues need to be addressed before allowing the dissemination of this technology [110, 111]. While there have been advancements in robotic surgery, including integration of AI, increased precision, improved imaging, and enhanced capabilities, the idea of fully autonomous robotic systems conducting surgery without direct human intervention is a complex and challenging goal that has not yet been achieved [109].

Another ambition for the future of robotic surgery is the implementation of telesurgical capabilities. Professor Jacques Marescaux's transatlantic robotic cholecystectomy (Lindbergh operation) revealed a potential for surgery that was never deemed possible before the advent of robotic surgery [112]. The obstacles that have prevented its common utility in today's digital surgical world are of an ethical nature as well as technical. Optimization of visual display, latency time, and haptic feedback technology are the main technical aspects that need to be addressed in newer, advanced robotic platforms.

Conclusion

Over the last two decades, robotic surgery has witnessed remarkable technological advancements, significantly improving surgical precision, ergonomics, and operative field magnification. Our comprehensive review emphasizes. Robotic surgery's robust and rapid development is in several surgical areas. In recent years, there has been a surge in the design and release of new robotic platforms, reflecting the continuous efforts to refine and perfect this cutting-edge technology. The integration of these advanced platforms into clinical practice has been driven by the numerous benefits of robotic surgery compared to traditional open and laparoscopic techniques.

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Data availability The authors confirm that the data supporting the findings of this study are available within the article. Raw data that support the findings are available from the corresponding author (AG) upon reasonable request.

Declarations

Conflict of interest The authors declare that no funds, grants, or other support were received during the preparation of this manuscript. The authors have no relevant financial or non-financial interests to disclose.

References

1. Kumar A, Yadav N, Singh S et al (2016) Minimally invasive (endoscopic-computer assisted) surgery: technique and review. Ann Maxillofac Surg 6(2):159. https://doi.org/10.4103/2231-0746.200348
2. Walker AS, Steele SR (2016) The future of robotic instruments in colon and rectal surgery. Semin Colon Rectal Surg 27(3):144–149. https://doi.org/10.1053/j.scrs.2016.04.006
3. Himpens J, Leman G, Cadiere GB (1998) Telesurgical laparoscopic cholecystectomy. Surg Endosc 12(8):1091–1091. https://doi.org/10.1007/s004649900788
4. George EI, Brand TC, LaPorta A et al (2018) Origins of robotic surgery: from skepticism to standard of care. JSLS 22(4):e2018. https://doi.org/10.4293/JSLS.2018.00039
5. Simorov A, Otte RS, Kopietz CM et al (2012) Review of surgical robotics user interface: what is the best way to control robotic surgery? Surg Endosc 26(8):2117–2125. https://doi.org/10.1007/s00464-012-2182-y
6. Oleynikov D (2008) Robotic surgery. Surg Clin North Am 88(5):1121–1130. https://doi.org/10.1016/j.suc.2008.05.012
7. Marchegiani F, Siragusa L, Zadoroznyj A et al (2023) New robotic platforms in general surgery: what's the current clinical scenario? Medicina (Mex) 59(7):1264. https://doi.org/10.3390/medicina59071264
8. Rassweiler JJ, Autorino R, Klein J et al (2017) Future of robotic surgery in urology. BJU Int 120(6):822–841. https://doi.org/10.1111/bju.13851
9. Anonymous (n.d.) Robotic surgical systems | Da Vinci | Ion | Intuitive. https://www.intuitive.com/en-us. Accessed 7 June 2023
10. Bhat KRS, Moschovas MC, Onol FF et al (2021) Evidence-based evolution of our robot-assisted laparoscopic prostatectomy (RALP) technique through 13,000 cases. J Robot Surg 15(4):651–660. https://doi.org/10.1007/s11701-020-01157-5
11. Shin HR, Lee K, Yu HW et al (2021) Comparison of perioperative outcomes using the da vinci S, Si, X, and Xi robotic platforms for BABA robotic thyroidectomy. Medicina (Mex) 57(10):1130. https://doi.org/10.3390/medicina57101130
12. Crusco S, Jackson T, Advincula A (2014) Comparing the da Vinci si single console and dual console in teaching novice surgeons suturing techniques. JSLS 18(3):e2014. https://doi.org/10.4293/JSLS-D-13-0021
13. Covas Moschovas M, Bhat S, Rogers T et al (2021) Applications of the da Vinci single port (SP) robotic platform in urology: a systematic literature review. Minerva Urol Nephrol 73(1). https://doi.org/10.23736/S2724-6051.20.03899-0.
14. Moschovas MC, Seetharam Bhat KR, Onol FF et al (2021) Single-port technique evolution and current practice in urologic procedures. Asian J Urol 8(1):100–104. https://doi.org/10.1016/j.ajur.2020.05.003
15. Samalavicius NE, Janusonis V, Siaulys R et al (2020) Robotic surgery using Senhance® robotic platform: single center experience with first 100 cases. J Robot Surg 14(2):371–376. https://doi.org/10.1007/s11701-019-01000-6
16. Lim JH, Lee WJ, Park DW et al (2017) Robotic cholecystectomy using Revo-i Model MSR-5000, the newly developed Korean robotic surgical system: a preclinical study. Surg Endosc 31(8):3391–3397. https://doi.org/10.1007/s00464-016-5357-0
17. Kim DK, Park DW, Rha KH (2016) Robot-assisted partial nephrectomy with the REVO-I robot platform in porcine models. Eur Urol 69(3):541–542. https://doi.org/10.1016/j.eururo.2015.11.024
18. Chang KD, Abdel Raheem A, Choi YD et al (2018) Retzius-sparing robot-assisted radical prostatectomy using the Revo-i

robotic surgical system: surgical technique and results of the first human trial. BJU Int 122(3):441–448. https://doi.org/10.1111/bju.14245

19. Dixon F, Khanna A, Vitish-Sharma P et al (2021) Initiation and feasibility of a multi-specialty minimally invasive surgical programme using a novel robotic system: a case series. Int J Surg 96:106182. https://doi.org/10.1016/j.ijsu.2021.106182
20. Thomas BC, Slack M, Hussain M et al (2021) Preclinical evaluation of the versius surgical system, a new robot-assisted surgical device for use in minimal access renal and prostate surgery. Eur Urol Focus 7(2):444–452. https://doi.org/10.1016/j.euf.2020.01.011
21. Kinross JM, Mason SE, Mylonas G et al (2020) Next-generation robotics in gastrointestinal surgery. Nat Rev Gastroenterol Hepatol 17(7):430–440. https://doi.org/10.1038/s41575-020-0290-z
22 Rao PP (2018) Robotic surgery: new robots and finally some real competition! World J Urol 36(4):537–541. https://doi.org/10.1007/s00345-018-2213-y
23. Gkeka K, Tsaturyan A, Faitatziadis S et al (2023) Robot-assisted radical nephrectomy using the novel avatera robotic surgical system: a feasibility study in a porcine model. J Endourol 37(3):273–278. https://doi.org/10.1089/end.2022.0596
24. Anonymous (n.d.) SYSTEM | hinotori robotic assisted surgery system | PRODUCT | medicaroid. https://www.medicaroid.com/en/product/hinotori/. Accessed 4 June 2023
25. Suzuki Y, Sato H, Nakazawa N (2023) Current status of robotic surgery in Japan gynecologic field. Intell Surg 6:25–30. https://doi.org/10.1016/j.isurg.2023.03.001
26. Miyake H, Motoyama D, Matsushita Y et al (2023) Initial Experience of robot-assisted partial nephrectomy using hinotori surgical robot system: single institutional prospective assessment of perioperative outcomes in 30 cases. J Endourol 37(5):531–534. https://doi.org/10.1089/end.2022.0775
27. Anonymous (n.d.) Symani system overview. https://www.mmimicro.com/symani-system-overview. Accessed 17 Aug 2023
28. Barbon C, Grünherz L, Uyulmaz S et al (2022) Exploring the learning curve of a new robotic microsurgical system for microsurgery. JPRAS Open 34:126–133. https://doi.org/10.1016/j.jpra.2022.09.002
29. Anonymous (n.d.) Hugo$^{\mathrm{TM}}$ RAS System | Medtronic (UK). https://www.medtronic.com/covidien/en-gb/robotic-assisted-surgery/hugo-ras-system.html. Accessed 4 April 2023
30. ParkJun 22 A (2021) 11:35am. Meet hugo: medtronic's robotic-assisted surgery system makes global debut in chilean clinic. https://www.fiercebiotech.com/medtech/meet-hugo-medtronic-s-robotic-assisted-surgery-system-makes-global-debut-chilean-clinic. Accessed 6 April 2023
31. Anonymous (n.d.) Distalmotion. https://www.distalmotion.com/. Accessed 13 Aug 2023
32. Thillou D, Robin H, Ricolleau C et al (2023) Robot-assisted radical prostatectomy with the Dexter robotic system: initial experience and insights into on-demand robotics. Eur Urol:S0302283823028804.https://doi.org/10.1016/j.eururo.2023.05.034
33. Hotz AS, Breitenstein S, Kambakamba P et al (2023) Implementation of the Dexter robot system in daily practice—first experiences in gall bladder and hernia surgery. Br J Surg 110(Supplement_5):znad178.033. https://doi.org/10.1093/bjs/znad178.033
34. Yi B, Wang G, Li J et al (2016) The first clinical use of domestically produced Chinese minimally invasive surgical robot system "Micro Hand S." Surg Endosc 30(6):2649–2655. https://doi.org/10.1007/s00464-015-4506-1
35. Yao Y, Liu Y, Li Z et al (2020) Chinese surgical robot micro hand S: A consecutive case series in general surgery. Int J Surg 75:55–59. https://doi.org/10.1016/j.ijsu.2020.01.013
36. Zeng Y, Wang G, Li Z et al (2021) The micro hand S vs. da Vinci surgical robot-assisted surgery on total mesorectal excision: short-term outcomes using propensity score matching analysis. Front Surg 8:656270. https://doi.org/10.3389/fsurg.2021.656270
37. Zheng J, Wang Y, Zhang J et al (2020) 5G ultra-remote robot-assisted laparoscopic surgery in China. Surg Endosc 34(11):5172–5180. https://doi.org/10.1007/s00464-020-07823-x
38. Wang Y, Qu M, Mei N et al (2021) A phase III randomized controlled study of a domestic endoscopic robot used in radical prostatectomy. Chin J Urol 2021:485–490
39. Ren C, Sun D (2022) Robot-assisted single-port laparoscopic bilateral ovarian cystectomy using the Shurui® system: A case report. Intell Surg 3:9–13. https://doi.org/10.1016/j.isurg.2022.06.001
40. Peng D, Jing T, Yao X et al (2023) Preliminary experience of partial nephrectomy through a new single-port surgical robot system. J Endourol 37(5):535–541. https://doi.org/10.1089/end.2022.0745
41. Madanpelle (2023) Made in India' surgical robot SSI mantra completes 100 successful surgeries
42. Fan S, Dai X, Yang K et al (2021) Robot-assisted pyeloplasty using a new robotic system, the KangDuo-Surgical Robot-01: a prospective, single-centre, single-arm clinical study. BJU Int 128(2):162–165. https://doi.org/10.1111/bju.15396
43. Li X, Xu W, Fan S et al (2023) Robot-assisted partial nephrectomy with the newly developed KangDuo surgical robot versus the da Vinci si surgical system: a double-center prospective randomized controlled noninferiority trial. Eur Urol Focus 9(1):133–140. https://doi.org/10.1016/j.euf.2022.07.008
44. Fan S, Zhang Z, Wang J et al (2022) Robot-assisted radical prostatectomy using the KangDuo surgical robot-01 system: a prospective, single-center. Single-Arm Clinical Study J Urol 208(1):119–127. https://doi.org/10.1097/JU.0000000000002498
45. Ho J (2023) Charged by surgical robot's approval, Shenzhen edge medical makes new IPO Bid—bamboo works—where China stocks meet global investors. https://thebambooworks.com/charged-by-surgical-robots-approval-shenzhen-edge-medical-makes-new-ipo-bid/. Accessed 16 Aug 2023
46. Innocenti B, Bori E (2021) Robotics in orthopaedic surgery: why, what and how? Arch Orthop Trauma Surg 141(12):2035–2042. https://doi.org/10.1007/s00402-021-04046-0
47. Anonymous (n.d.) Mako. https://www.stryker.com/us/en/portfolios/orthopaedics/joint-replacement/mako-robotic-arm-assisted-surgery.html. Accessed: 8 June 2023
48. Roche M (2021) The MAKO robotic-arm knee arthroplasty system. Arch Orthop Trauma Surg 141(12):2043–2047. https://doi.org/10.1007/s00402-021-04208-0
49. Siddiqi A, Horan T, Molloy RM et al (2021) A clinical review of robotic navigation in total knee arthroplasty: historical systems to modern design. EFORT Open Rev 6(4):252–269. https://doi.org/10.1302/2058-5241.6.200071
50. Vermue H, Batailler C, Monk P et al (2022) The evolution of robotic systems for total knee arthroplasty, each system must be assessed for its own value: a systematic review of clinical evidence and meta-analysis. Arch Orthop Trauma Surg 143(6):3369–3381. https://doi.org/10.1007/s00402-022-04632-w
51. Casper M, Mitra R, Khare R et al (2018) Accuracy assessment of a novel image-free handheld robot for Total Knee Arthroplasty in a cadaveric study. Comput Assist Surg 23(1):14–20. https://doi.org/10.1080/24699322.2018.1519038
52. Miller BA, Salehi A, Limbrick DD et al (2017) Applications of a robotic stereotactic arm for pediatric epilepsy and neurooncology surgery. J Neurosurg Pediatr 20(4):364–370. https://doi.org/10.3171/2017.5.PEDS1782
53. Batailler C, Hannouche D, Benazzo F et al (2021) Concepts and techniques of a new robotically assisted technique for

total knee arthroplasty: the ROSA knee system. Arch Orthop Trauma Surg 141(12):2049–2058. https://doi.org/10.1007/s00402-021-04048-y

54. Lefranc M, Peltier J (2016) Evaluation of the ROSA™ Spine robot for minimally invasive surgical procedures. Expert Rev Med Devices 13(10):899–906. https://doi.org/10.1080/17434440.2016.1236680
55. Rossi SMP, Sangaletti R, Perticarini L et al (2023) High accuracy of a new robotically assisted technique for total knee arthroplasty: an in vivo study. Knee Surg Sports Traumatol Arthrosc 31(3):1153–1161. https://doi.org/10.1007/s00167-021-06800-8
56. Anonymous (n.d.) VELYS™ Robotic-assisted solution | DePuy Synthes. https://www.jnjmedtech.com/en-US/products/digital-surgery/velys-robotic-assisted-solution. Accessed: 10 June 2023
57. Doan GW, Courtis RP, Wyss JG et al (2022) Image-free robotic-assisted total knee arthroplasty improves implant alignment accuracy: a cadaveric study. J Arthroplasty 37(4):795–801. https://doi.org/10.1016/j.arth.2021.12.035
58. Xia R, Zhai Z, Zhang J et al (2021) Verification and clinical translation of a newly designed “Skywalker” robot for total knee arthroplasty: a prospective clinical study. J Orthop Transl 29:143–151. https://doi.org/10.1016/j.jot.2021.05.006
59. Technology SR (2021) Honghu robot completes first 5G remote joint replacement surgery. https://www.surgicalroboticstechnology.com/news/honghu-surgical-robot-completes-first-5g-remote-joint-replacement-surgery/. Accessed 18 Aug 2023
60. Kwoh YS, Hou J, Jonckheere EA et al (1988) A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery. IEEE Trans Biomed Eng 35(2):153–160. https://doi.org/10.1109/10.1354
61. Singh R, Wang K, Qureshi MB et al (2022) Robotics in neurosurgery: current prevalence and future directions. Surg Neurol Int 13:373. https://doi.org/10.25259/SNI_522_2022
62. Anonymous (n.d.) ExcelsiusGPS® robotic navigation platform | Globus Medical. Available from: https://www.globusmedical.com/musculoskeletal-solutions/excelsiustechnology/excelsiusgps/. Accessed 11 June 2023
63. Vo CD, Jiang B, Azad TD et al (2020) Robotic spine surgery: current state in minimally invasive surgery. Glob Spine J 10(2_suppl):34S–40S. https://doi.org/10.1177/2192568219878131
64. Godzik J, Walker CT, Hartman C et al (2019) A Quantitative assessment of the accuracy and reliability of robotically guided percutaneous pedicle screw placement: technique and application accuracy. Oper Neurosurg 17(4):389–395. https://doi.org/10.1093/ons/opy413
65. Dreval’ ON, Rynkov IP, Kasparova KA et al (2014) Results of using spine assist Mazor in surgical treatment of spine disorders. Zh Vopr Neirokhir Im N N Burdenko 78(3):14–20
66. Khan A, Meyers JE, Siasios I et al (2019) Next-generation robotic spine surgery: first report on feasibility, safety, and learning curve. Oper Neurosurg 17(1):61–69. https://doi.org/10.1093/ons/opy280
67. O’Connor TE, O’Hehir MM, Khan A et al (2021) Mazor X stealth robotic technology: a technical note. World Neurosurg 145:435–442. https://doi.org/10.1016/j.wneu.2020.10.010
68. Medtronic (n.d.) Spine & orthopaedic products—Mazor X Steath Edition. https://www.medtronic.com/us-en/healthcare-professionals/products/spinal-orthopaedic/spine-robotics/mazor-x-stealth-edition.html. Accessed 9 July 2023
69. Püschel A, Schafmayer C, Groß J (2022) Robot-assisted techniques in vascular and endovascular surgery. Langenbecks Arch Surg 407(5):1789–1795. https://doi.org/10.1007/s00423-022-02465-0
70. Andreassi MG, Piccaluga E, Guagliumi G et al (2016) Occupational health risks in cardiac catheterization laboratory workers. Circ Cardiovasc Interv 9(4):e003273. https://doi.org/10.1161/CIRCINTERVENTIONS.115.003273
71. Weisz G, Metzger DC, Caputo RP et al (2013) Safety and feasibility of robotic percutaneous coronary intervention. J Am Coll Cardiol 61(15):1596–1600. https://doi.org/10.1016/j.jacc.2012.12.045
72. Mahmud E, Naghi J, Ang L et al (2017) Demonstration of the safety and feasibility of robotically assisted percutaneous coronary intervention in complex coronary lesions. JACC Cardiovasc Interv 10(13):1320–1327. https://doi.org/10.1016/j.jcin.2017.03.050
73. Legeza P, Britz GW, Loh T et al (2020) Current utilization and future directions of robotic-assisted endovascular surgery. Expert Rev Med Devices 17(9):919–927. https://doi.org/10.1080/17434440.2020.1814742
74. Smitson CC, Ang L, Pourdjabbar A et al (2018) Safety and feasibility of a novel, second-generation robotic-assisted system for percutaneous coronary intervention: first-in-human report. J Invasive Cardiol 30(4):152–156
75. Saglam R, Muslumanoglu AY, Tokatlı Z et al (2014) A new robot for flexible ureteroscopy: development and early clinical results (IDEAL stage 1–2b). Eur Urol 66(6):1092–1100. https://doi.org/10.1016/j.eururo.2014.06.047
76. Rassweiler J, Fiedler M, Charalampogiannis N et al (2018) Robot-assisted flexible ureteroscopy: an update. Urolithiasis 46(1):69–77. https://doi.org/10.1007/s00240-017-1024-8
77. Geavlete P, Saglam R, Georgescu D et al (2016) Robotic flexible ureteroscopy versus classic flexible ureteroscopy in renal stones: the initial romanian experience. Chir Buchar Rom 1990 111(4):326–329
78. Schuler PJ, Duvvuri U, Friedrich DT et al (2015) First use of a computer-assisted operator-controlled flexible endoscope for transoral surgery: flexible oropharyngeal surgery. Laryngoscope 125(3):645–648. https://doi.org/10.1002/lary.24957
79. Mattheis S, Hasskamp P, Holtmann L et al (2017) Flex robotic system in transoral robotic surgery: the first 40 patients. Head Neck 39(3):471–475. https://doi.org/10.1002/hed.24611
80. Funk E, Goldenberg D, Goyal N (2017) Demonstration of transoral robotic supraglottic laryngectomy and total laryngectomy in cadaveric specimens using the Medrobotics Flex System: Flex robotic laryngectomy. Head Neck 39(6):1218–1225. https://doi.org/10.1002/hed.24746
81. Johnson PJ, Serrano CMR, Castro M et al (2013) Demonstration of transoral surgery in cadaveric specimens with the medrobotics flex system. Laryngoscope 123(5):1168–1172. https://doi.org/10.1002/lary.23512
82. Groth S, Rex DK, Rösch T et al (2011) High cecal intubation rates with a new computer-assisted colonoscope: a feasibility study. Am J Gastroenterol 106(6):1075–1080. https://doi.org/10.1038/ajg.2011.52
83. Yeung C, Cheung JL, Sreedhar B (2019) Emerging next-generation robotic colonoscopy systems towards painless colonoscopy. J Dig Dis 20(4):196–205. https://doi.org/10.1111/1751-2980.12718
84. Kurniawan N, Keuchel M (2017) Flexible gastro-intestinal endoscopy—clinical challenges and technical achievements. Comput Struct Biotechnol J 15:168–179. https://doi.org/10.1016/j.csbj.2017.01.004
85. Anonymous (n.d.) MONARCH™ bronchoscopy | Ethicon. https://www.jnjmedtech.com/en-US/product/monarch-bronchoscopy. Accessed 10 July 2023
86. Lu M, Nath S, Semaan RW (2021) A review of robotic-assisted bronchoscopy platforms in the sampling of peripheral pulmonary lesions. J Clin Med 10(23):5678. https://doi.org/10.3390/jcm10235678

87. Chen AC, Gillespie CT (2018) Robotic endoscopic airway challenge: REACH assessment. Ann Thorac Surg 106(1):293–297. https://doi.org/10.1016/j.athoracsur.2018.01.051
88. Reisenauer J, Simoff MJ, Pritchett MA et al (2022) Ion: technology and techniques for shape-sensing robotic-assisted bronchoscopy. Ann Thorac Surg 113(1):308–315. https://doi.org/10.1016/j.athoracsur.2021.06.086
89. Anonymous (n.d.) Ion platform | robotic-assisted bronchoscopy | Intuitive. https://www.intuitive.com/en-us/products-and-services/ion. Accessed 18 Aug 2023
90. Lowenstein L, Matanes E, Weiner Z et al (2020) Robotic transvaginal natural orifice transluminal endoscopic surgery for bilateral salpingo oophorectomy. Eur J Obstet Gynecol Reprod Biol X 7:100113. https://doi.org/10.1016/j.eurox.2020.100113
91. Kaštelan Ž, Knežević N, Hudolin T et al (2019) Extraperitoneal radical prostatectomy with the Senhance Surgical System robotic platform. Croat Med J 60(6):556–559. https://doi.org/10.3325/cmj.2019.60.556
92. Stark M, Pomati S, D'Ambrosio A et al (2015) A new telesurgical platform—preliminary clinical results. Minim Invasive Ther Allied Technol 24(1):31–36. https://doi.org/10.3109/13645706.2014.1003945
93. Peters BS, Armijo PR, Krause C et al (2018) Review of emerging surgical robotic technology. Surg Endosc 32(4):1636–1655. https://doi.org/10.1007/s00464-018-6079-2
94. Jeong IG, Khandwala YS, Kim JH et al (2017) Association of robotic-assisted vs laparoscopic radical nephrectomy with perioperative outcomes and health care costs, 2003 to 2015. JAMA 318(16):1561. https://doi.org/10.1001/jama.2017.14586
95. Kayani B, Konan S, Ayuob A et al (2019) Robotic technology in total knee arthroplasty: a systematic review. EFORT Open Rev 4(10):611–617. https://doi.org/10.1302/2058-5241.4.190022
96. Karachalios Th, Varitimidis S, Bargiotas K et al (2016) An 11- to 15-year clinical outcome study of the Advance Medial Pivot total knee arthroplasty: pivot knee arthroplasty. Bone Jt J 98–B(8):1050–1055. https://doi.org/10.1302/0301-620X.98B8.36208.
97. Hampp E, Chughtai M, Scholl L et al (2019) Robotic-arm assisted total knee arthroplasty demonstrated greater accuracy and precision to plan compared with manual techniques. J Knee Surg 32(03):239–250. https://doi.org/10.1055/s-0038-1641729
98. Sodhi N, Khlopas A, Piuzzi N et al (2018) The learning curve associated with robotic total knee arthroplasty. J Knee Surg 31(01):017–021. https://doi.org/10.1055/s-0037-1608809
99. Joseph JR, Smith BW, Liu X et al (2017) Current applications of robotics in spine surgery: a systematic review of the literature. Neurosurg Focus 42(5):E2. https://doi.org/10.3171/2017.2.FOCUS16544
100. Ghasem A, Sharma A, Greif DN et al (2018) The arrival of robotics in spine surgery: a review of the literature. Spine 43(23):1670–1677. https://doi.org/10.1097/BRS.0000000000002695
101. Jiang B, Karim Ahmed A, Zygourakis CC et al (2018) Pedicle screw accuracy assessment in ExcelsiusGPS® robotic spine surgery: evaluation of deviation from pre-planned trajectory. Chin Neurosurg J 4(1):23. https://doi.org/10.1186/s41016-018-0131-x
102. Roser F, Tatagiba M, Maier G (2013) Spinal robotics: current applications and future perspectives. Neurosurgery 72(Supplement 1):A12–A18. https://doi.org/10.1227/NEU.0b013e318270d02c
103. Lonjon N, Chan-Seng E, Costalat V et al (2016) Robot-assisted spine surgery: feasibility study through a prospective case-matched analysis. Eur Spine J 25(3):947–955. https://doi.org/10.1007/s00586-015-3758-8
104. Menger RP, Savardekar AR, Farokhi F et al (2018) A cost-effectiveness analysis of the integration of robotic spine technology in spine surgery. Neurospine 15(3):216–224. https://doi.org/10.14245/ns.1836082.041
105. Olivas-Alanis LH, Calzada-Briseño RA, Segura-Ibarra V et al (2020) LAPKaans: tool-motion tracking and gripping force-sensing modular smart laparoscopic training system. Sensors 20(23):6937. https://doi.org/10.3390/s20236937
106. Kume K (2016) Flexible robotic endoscopy: current and original devices. Comput Assist Surg 21(1):150–159. https://doi.org/10.1080/24699322.2016.1242654
107. Larcher A, Turri F, Bianchi L et al (2019) Virtual reality validation of the ERUS simulation-based training programmes: results from a high-volume training centre for robot-assisted surgery. Eur Urol 75(5):885–887. https://doi.org/10.1016/j.eururo.2019.02.008
108. Bravi CA, Dell'Oglio P, Mazzone E et al (2023) The surgical learning curve for biochemical recurrence after robot-assisted radical prostatectomy. Eur Urol Oncol 6(4):414–421. https://doi.org/10.1016/j.euo.2022.06.010
109. Bhandari M, Zeffiro T, Reddiboina M (2020) Artificial intelligence and robotic surgery: current perspective and future directions. Curr Opin Urol 30(1):48–54. https://doi.org/10.1097/MOU.0000000000000692
110. Robinson PG, Clement ND, Hamilton D et al (2019) A systematic review of robotic-assisted unicompartmental knee arthroplasty: prosthesis design and type should be reported. Bone Jt J 101–B(7):838–847. https://doi.org/10.1302/0301-620X.101B7.BJJ-2018-1317.R1.
111. Alexander R, Schwartz C, Ladisich B et al (2018) CyberKnife radiosurgery in recurrent brain metastases: do the benefits outweigh the risks? Cureus. https://doi.org/10.7759/cureus.3741
112. Marescaux J, Leroy J, Rubino F et al (2002) Transcontinental robot-assisted remote telesurgery: feasibility and potential applications. Ann Surg 235(4):487–492. https://doi.org/10.1097/00000658-200204000-00005