Review

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Advances in Robotic Surgery: A Review of new Surgical Platforms

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Advances in Robotic Surgery: A Review of new Surgical Platforms

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Abstract: In recent decades, the development of surgical systems that minimize patient impact has been a major focus for surgeons and researchers, leading to the advent of robotic systems for minimally invasive surgery. These technologies offer significant patient benefits, including enhanced outcome quality and accuracy, reduced invasiveness, lower blood loss, decreased postoperative pain, diminished infection risk, and shorter hospitalization and recovery times. Surgeons benefit from the elimination of human tremor, ergonomic advantages, improved vision systems, better access to challenging anatomical areas, and magnified 3DHD visualization of the operating field. Since 2000, Intuitive Surgical has developed multiple generations of master-slave multi-arm robots, securing over 7,000 patents, which created significant barriers for competitors. This monopoly resulted in the widespread adoption of their technology, now used in over 11 million surgeries globally. With the expiration of key patents, new robotic platforms featuring innovative designs, such as modular systems, are emerging. This review examines advancements in robotic surgery within the fields of general, urological, and gynaecological surgery. The objective is to analyse the current robotic surgical platforms, their technological progress, and their impact on surgical practices. By examining these platforms, this review provides insights into their development, potential benefits, and future directions in robotic-assisted surgery.

Keywords: robotic-assisted surgery; new surgical robots; robotic surgery

1. Introduction

In recent decades, robotics has expanded beyond traditional industrial applications to serve humans more closely in diverse fields, most notably in healthcare [1,2]. One of the most groundbreaking advancements has been the integration of robots in the medical field, particularly in surgery. Robotic-assisted surgical systems (RASS) have gained considerable traction in minimally invasive surgery (MIS), where robots assist surgeons in performing intricate procedures with enhanced precision, dexterity, and control [3,4]. Initially met with scepticism, robotic surgery has evolved, and as new technologies have made systems more reliable, many patients now opt for robotic procedures without hesitation. This has resulted in the worldwide increase in robotic surgeries, which today account for approximately 3% of all surgeries, providing patients with the benefits of fewer complications, faster recovery times, reduced hospital stays, and a quicker return to normal activities [5,6].

The COVID-19 pandemic further underscored the role of robotics in healthcare, particularly in telemedicine. Hospitals, being high-risk environments for infectious disease transmission, saw an increase in the need for remote medical interventions. Robotic systems allowed healthcare professionals to maintain social distancing while still offering quality care, thus enhancing safety for both patients and medical staff [7]. In surgical settings, robotic systems are particularly valuable due to their ability to perform complex tasks with high precision, even in confined spaces. With their small size, optimized force control, and high accuracy, robots are now instrumental in performing procedures that minimize tissue trauma, such as those used in urology, gynecology, and general surgery [3,4–6]. For these reasons, the use of robotic surgery has grown more significantly in these surgical specialties compared to others [8,9].

RASS systems are designed to assist surgeons by providing highly dexterous instruments, enabling smaller and less traumatic access into the patient's body [2]. This precision leads to faster healing times and shorter hospital stays, ultimately reducing the overall costs of surgical procedures per patient. Moreover, the use of robotic arms for positioning and holding surgical tools alleviates the physical strain on assistants and reduces mental stress for surgeons, who can rely on the robot's enhanced positioning and working accuracy [10].

Despite these advancements, the widespread adoption of robotic surgery is hindered by several challenges. The technological complexity of these systems, coupled with a difficult patent landscape and stringent regulatory barriers, has slowed their integration into everyday surgical practice [11]. The high cost of robotic systems, as well as the significant time and effort required to train surgeons in new robotic techniques, further limit the widespread use of these systems [12].

Intuitive Surgical®'s Da Vinci system, the most widely recognized and used robotic surgical system, has dominated the market for more than two decades due to its set of patents, with over 7,500 installations worldwide and more than 11 million procedures performed as of early 2023 [13,14]. However, the scenario is changing: the expiration of key patents has paved the way for new competitors to enter the market, prompting the development of alternative robotic systems that aim to challenge Da Vinci's dominance [2,15,16].

Despite the initial barriers, the market for surgical robotics is expected to grow significantly in the coming years. This growth is fueled not only by technological advancements but also by increased demand for minimally invasive procedures, which offer better outcomes for patients in terms of safety and recovery [17].

However, the high cost of surgical robots, along with the need for specialized training, currently limits access to these systems, especially in low- and middle-income countries where healthcare resources are already scarce [18]. As robotic surgery continues to evolve, it is critical to ensure that these advancements are accessible to the broader global population, not just wealthier healthcare systems. Reducing the costs of these platforms is key to their worldwide adoption, and increased competition among industries can help achieve this goal.

This narrative review provides a comprehensive overview of the state-of-the-art robotic systems used to perform urology, gynecology and general surgery which represent an alternative to the Intuitive®'s robots. In particular, it is essential to examine the alternative platforms that have been developed and for which studies are available in the literature, focusing on both their technical aspects and the outcomes achieved. A thorough analysis of these platforms will provide insights into their design innovations, operational efficiency, and clinical performance, allowing a better understanding of their potential advantages and limitations.

2. Materials and Methods

A narrative literature review was conducted to provide a comprehensive overview of the surgical systems available for use in urology, gynecology, and general surgery.

An initial search was conducted in grey literature and online to identify newly available robotic platforms, distinct from the ones produced by the Intuitive Surgical® company.

An electronic search was carried out across the PubMed, Scopus, and Web of Science databases up to June 2024. The following keywords were used to perform the search: "avatera surgical robot", "senhance surgical robot", "canady surgical robot", "revo-i surgical robot", "autolap surgical robot", "enos surgical robot", "micro hand s surgical robot", "hugo surgical robot", "mira surgical robot", "vicarios surgical robot", "anovo surgical robot", "dexter surgical robot", "emaro surgical robot", "vista surgical robot", "panorama surgical robot", "Endomaster EASE system surgical robot", "hinotori surgical robot", "EPIONE surgical robot", "LBR Med surgical robot", "XACT surgical robot", "Galen surgical robot", "Versius surgical robot", "Bitrack surgical robot", "Verb surgical

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robot", "SurgiBot surgical robot", "PROCEPT surgical robot", "Roboflex surgical robot", "Flex surgical robot", Monarch surgical robot", "Maestro surgical robot", "Mantra surgical robot", "Kangduo surgical robot", "Sensei X surgical robot", "Toumai surgical robot".

The following criteria for inclusion were employed in the article selection process:

1. Written in English language.
2. Full articles excluding reviews, perspectives, and communications.
3. Full text available.
4. Published from 2014 to June 2024.
5. Any general surgery intervention performed in gynecology, urology or general surgery.
6. Any robotic system which has a console

Otherwise, the following exclusion criteria were considered:

1. Articles that contained simulation and tests.
2. Papers centered on telesurgery, telementoring or telepresence.
3. Studies which report only the procedure.
4. Papers related to study on animals or cadavers.
5. Articles which concern with the surgeon training.

The references from the review were examined to identify relevant papers for inclusion in the research. Titles and abstracts of the articles were screened to evaluate their relevance based on the inclusion and exclusion criteria.

3. Results

During the keyword searches in the relevant databases, several of the previously mentioned robots were excluded for two main reasons: their lack of relevance to the specific types of surgery being investigated and the absence of related articles in the literature. Consequently, the following robots were retained for further consideration: Avatera, Senhance®, Revo-i®, Micro Hand S, Hugo™, Dexter, Hinotori™, Versius®, Mantra, KangDuo, and Toumai®.

In searching for these robots across the databases, a total of 1,298 articles was re-trieved from the previously mentioned electronic research sources, along with 13 records identified through snowball sampling. After eliminating duplicates, 856 papers were left. Screening the titles and abstracts led to the exclusion of 649 items. Of the 197 articles that remained, 73 did not fulfil the inclusion criteria. The selection process is illustrated in the PRISMA flowchart (Figure 1).

Appendix A provides a comprehensive list of the 124 papers that were included in this review. Alongside each entry, key characteristics are detailed, including the surgical platform used, the surgical specialty, the publication year, and the country of origin.

This section is dedicated to presenting the findings of the review. The first paragraph (Section 3.1) offers an in-depth analysis of the characteristics of the studies under consideration, highlighting important aspects of their methodologies. In the second paragraph (Section 3.2), a summary of the technical features of each platform is provided, allowing for a comparative analysis that underscores the distinctions and similarities among them.

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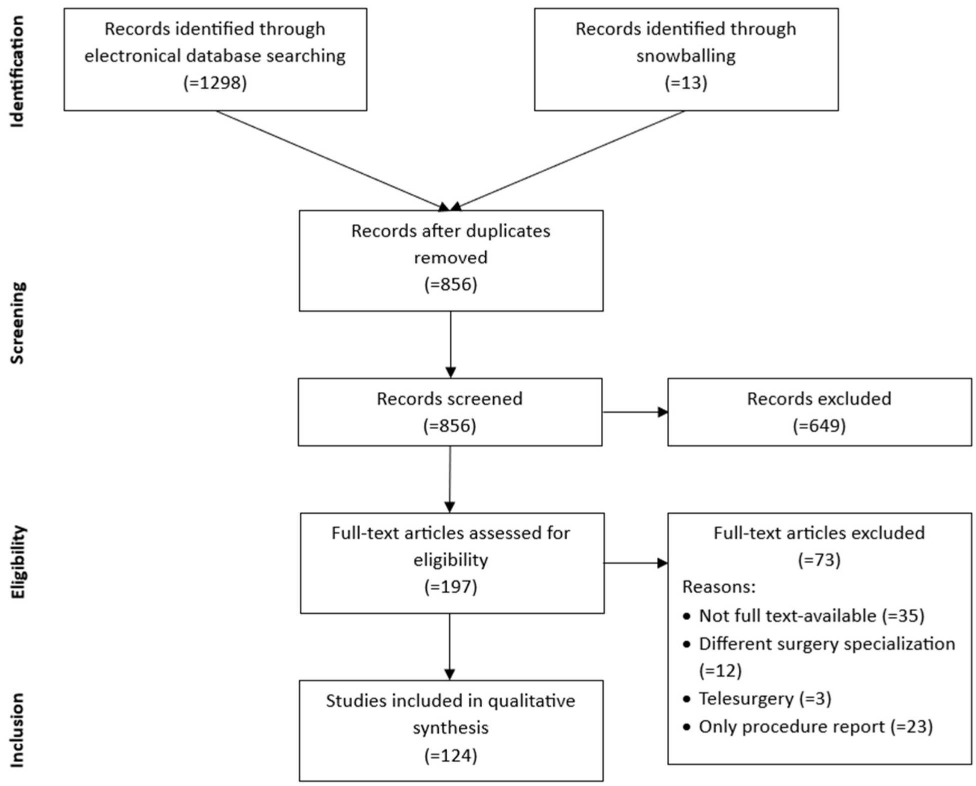

Figure 1. PRISMA flowchart.

3.1. Studies Characteristics

Among the studies included in this review, there were 22 case reports [19–40], 73 non-comparative studies [41–113], and 27 comparative studies [114–142]. In the majority of the comparative studies, the Da Vinci robot served as the primary comparator (n = 23), though in some cases, traditional laparoscopy (n = 6) and open surgery (n = 1) were also used. Of the comparative studies, only 4 were randomized controlled trials (RCTs).

Considering the studies included in this review, the total number of patients that are treated with the new platforms is 4993. The reported cases belong to different surgical specialties: general surgery [19–22,24,26,34,35,37,39,41,42,44–48,51,53,55,60,62,64,67,69,74,79,82,84–87,91,93,100–103,105,107,112,115–120,124,128,137–139], urology [23,25,28,30,33,36,40,49,54,56,58,59,63,66,68,71–73,75–78,80,83,89,90,92,94–99,104,109–111,113,114,121,123,125–127,129–136,140–142], gynecology [27,[29,31,32,38,43,50,52,57,61,70,81,88,106,108,122]. Table 1 reports the number of patients treated with the new surgical platform divided by specialty.

Table 1. The number of patients treated with a new surgical platform by specialty and surgical robot.

	Robotic platform										
Surgical Specialty	**Hugo™**	**Versius®**	**Senhance®**	**Revo-i®**	**Micro Hand S**	**Avatera**	**Dexter**	**Hinotori™**	**Mantra**	**KangDuo**	**Toumai®**
General Surgery	126	607	764	27	277	-	12	33	10	101	-
Gynaecology	253	204	114	-	-	-	1	12	-	-	-

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Urology	962	86	1036	48	-	9	11	105	-	175	20

The majority of the papers included in the review are studies conducted in Italy (n = 24), Japan (n = 20), China (n = 18), Belgium (n = 7) and Germany (n = 7). Figure 2 reports the number of papers for each country.

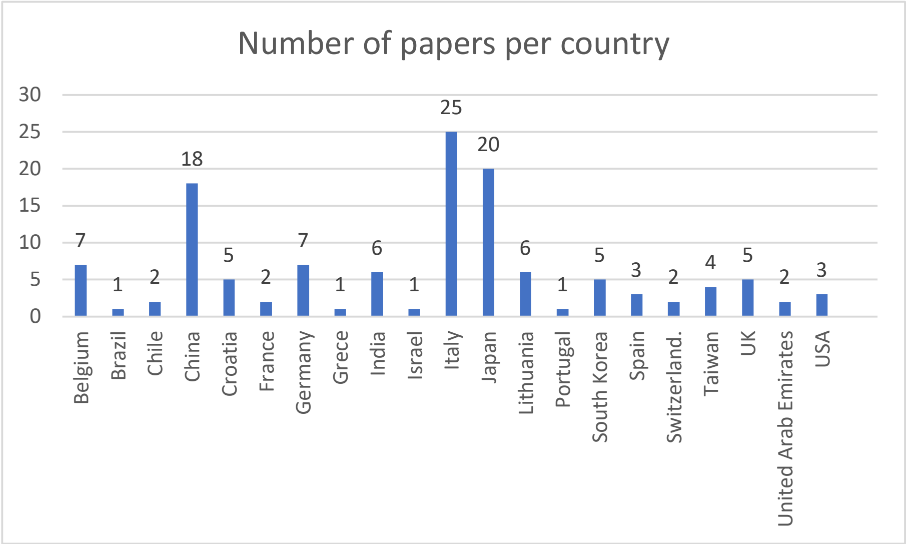

Figure 2. Number of paper per country.

3.2. Surgical Robotic Platforms

In this section, the new surgical robotic platforms are described, and a technical comparison is reported.

Table 2 reports the main information about the surgical robotic platforms that are included in this review.

Table 2. Main information about the new surgical platforms.

Surgical platform	Company	Year	Country	CE Mark	FDA approval	Approved in the origine nation
Senhance®	TransEnterix Surgical which became Asensus Surgical in 2021	2017	USA	yes	yes	yes
Revo-i®	Meerecompany Inc.	2017	South Korea	no	no	yes
Micro Hand S	Shandon Wego Surgical Robot Co	2017	China	no	no	yes
Toumai®	Shanghai MicroPort MedBot (Group)	2018	China	no	no	yes
Avatera	Avatera Medical	2019	Germany	yes	NAI	yes
Versius®	CMR Surgical	2019	UK	yes	no	yes
Hinotori™	Medicaroid Inc	2020	Japan	no	yes	yes
KangDuo	Suzhou KangDuo Robot Co., Ltd.	2020	China	NAI	no	yes

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Hugo™	Medtronic	2021	USA	yes	yes	yes
Dexter	Distalmotion	2022	Switzerland	yes	no	yes
Mantra	SS Innovation	2023	India	ongoing	ongoing	yes

NAI= Not Available Information.

3.2.1. Senhance®

The Senhance® Surgical System [143], developed by TransEnterix Surgical, Inc., is a robotic platform designed to improve precision and control in minimally invasive surgeries. Launched in 2017 after receiving FDA clearance and CE Mark approval in 2016, Senhance® (Figure 5) was introduced as a cost-effective alternative to systems like the da Vinci Surgical System [127,141]. It incorporates unique features such as haptic feedback, which provides tactile sensations to the surgeon, and eye-tracking camera control, allowing hands-free camera manipulation based on the surgeon's gaze.

The system uses standard laparoscopic ports, which reduces the learning curve for surgeons accustomed to traditional laparoscopy and makes conversion to standard surgery easier if needed. Reusable instruments significantly lower operational costs [127,141], a key advantage over other robotic systems that rely on expensive disposable tools. Senhance® also features an open cockpit design, where the surgeon sits in a comfortable, ergonomic position at the console, reducing physical strain during long procedures.

Senhance®'s multi-arm robotic design offers versatility in a wide range of surgeries, including general surgery, gynaecology and urology. Clinical studies and case reports have demonstrated its safety and feasibility [24,25,44,56,91], including its use in procedures such as laparoscopic gastrectomy for gastrointestinal tumours and robotic sigmoidectomy for colon cancer. The system is used in the United States, Europe, and Asia, with notable uptake in Japan following regulatory approval in 2019.

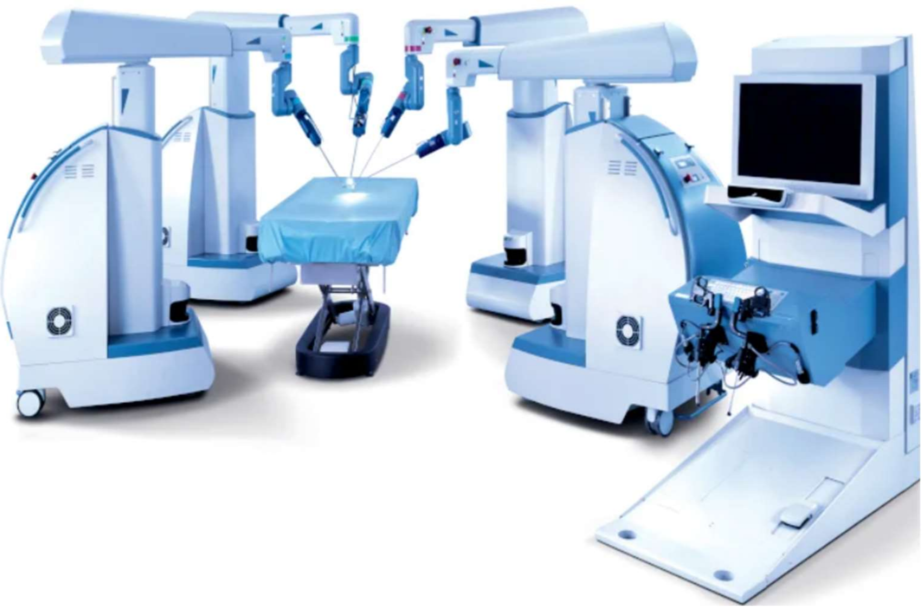

Figure 3. Senhance® robotic platform.

3.2.2. Revo-i®

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The Revo-i® (Figure 4) robotic surgical system, developed by South Korean company Meerecompany, was launched in 2017 [144]. It provides an affordable alternative to other robotic systems like the da Vinci [114,128], to offer lower costs. The system includes a master console that the surgeon operates, translating their movements into the robotic arms for precise, minimally invasive surgeries. The Revo-i® provides high-definition 3D visualization for enhanced depth perception and magnified views during surgery [20,48].

The system's robotic arms offer 7 degrees of freedom, allowing for flexibility in instrument movements, mimicking the natural movements of a human wrist. Additionally, the system features haptic feedback, enabling surgeons to feel tactile sensations, and enhancing precision during tissue manipulation. The Revo-i® is equipped with advanced optical control and camera-hopping technology, enabling the surgeon to adjust views dynamically during the procedure.

Cost efficiency is a key benefit, as the system incorporates reusable instruments [48], significantly reducing the cost per procedure compared to other robotic platforms. The clutching mechanism allows the surgeon to reposition instruments without moving the robotic arms, and this process is operated via finger or foot pedals.

Revo-i® is used in various surgical fields, including urology, gynecology general surgery, and thoracic surgery.

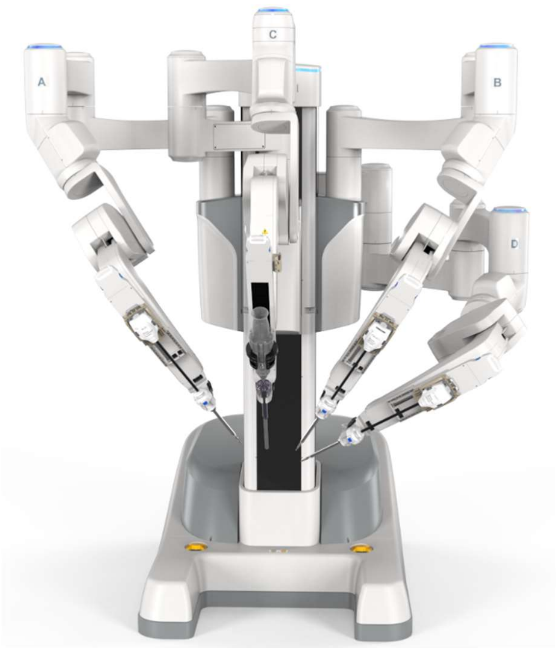

Figure 4. Revo-i® patient chart.

2.3.3. Micro Hand S

The Micro Hand S surgical system represents a significant advancement in minimally invasive surgical technology, developed domestically in China. Launched in clinical trials between 2017 and 2019, it was designed to meet the growing demand for precision and efficacy in surgeries, particularly in the realm of robotic-assisted procedures[19,120].

One of the standout features of the Micro Hand S is its articulated robotic arms, which offer seven degrees of freedom. This flexibility allows surgeons to perform intricate manoeuvres that would be challenging with traditional laparoscopic tools. Coupled with 3D visualization capabilities, the system enhances depth perception and spatial awareness, crucial for delicate operations.

The design also prioritizes ergonomics. The surgeon's console is crafted for comfort, enabling prolonged use without the physical strain that can accompany lengthy procedures. This focus on user experience is complemented by features such as tremor reduction and motion scaling, which help

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mitigate hand tremors and allow for greater control over instrument movements. Such advancements are particularly beneficial in surgeries where precision is paramount.

Clinical evaluations comparing the Micro Hand S to established robotic systems, such as the da Vinci, have shown promising results [116,117]. Although the operative time was slightly longer than laparoscopic techniques[119], the quality of surgical outcomes remained high, with a notable increase in sphincter-preserving procedures.

2.3.4. Hugo™

The Hugo™ Robotic-Assisted Surgery system (Figure 5) [145], developed by Medtronic, represents a significant advancement in minimally invasive surgical technology. Launched in Europe in March 2022, the system has received CE approval for various applications, including gynaecological and urological surgeries.

One of the defining features of the Hugo™ RAS system is its modular design, which allows for flexible configurations depending on the surgical procedure. It can accommodate setups with three or four robotic arms, enhancing the versatility of the surgical approach. The open console design is another notable aspect; it provides a 3D high-definition visualization system that allows both the surgeon and observers to view the surgical field simultaneously. This is particularly beneficial for training and collaborative surgical environments.

The system is equipped to support a variety of instruments, such as bipolar graspers, monopolar scissors, and needle drivers, all designed to enhance surgical precision. Its docking configurations, including the "compact" and "bridge" setups, allow for optimal access to different anatomical areas, reducing the likelihood of instrument collisions—a common challenge in robotic surgery.

While early experiences with the Hugo™ system have shown promising results, including significant symptom relief in procedures such as robotically assisted endometriosis surgery[29,108], further research is needed to compare its effectiveness against established robotic platforms like the da Vinci system [122,129,131,132]. Overall, the Hugo™ RAS system represents a valuable tool for surgeons seeking to enhance their capabilities in complex surgical scenarios.

Figure 5. Hugo™ robotic platform.

2.3.5. Hinotori™

The Hinotori™ Surgical Robot System (Figure 6), developed by Medicaroid Inc., marks a significant advancement in robotic surgical technology, particularly within Japan. Launched in 2020 and receiving clinical approval in November 2022, the Hinotori™ system is designed to enhance surgical precision and patient outcomes in minimally invasive procedures, such as robotic gastrectomy and colorectal surgeries.

One of the distinguishing features of the Hinotori™ system is its closed console design, which creates a stable and immersive environment for surgeons. This setup allows for a high-definition 3D

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visualization of the surgical field, utilizing a 16:9 monitor that expands the surgeon's view compared to traditional systems. The robotic arms feature eight axes of movement, enabling greater flexibility and reducing the risk of interference between instruments. This enhanced manoeuvrability is crucial during complex procedures, where precision is paramount.

Hinotori™ also integrates advanced imaging capabilities, including fluorescence imaging, which helps in identifying critical structures and assessing tissue viability during surgery. While the system currently lacks haptic feedback and eye-tracking features, its ergonomic design and intuitive controls contribute to a more comfortable surgical experience.

Despite being a newer entrant in the market, Hinotori™ has demonstrated its potential through successful clinical applications[34,89,125,126]. It has gained acceptance in Japan, where it was specifically developed to address the growing demand for robotic surgeries. The system's pricing is notably lower than that of its primary competitor, the da Vinci system [126,140], which may facilitate wider adoption and accessibility in surgical settings.

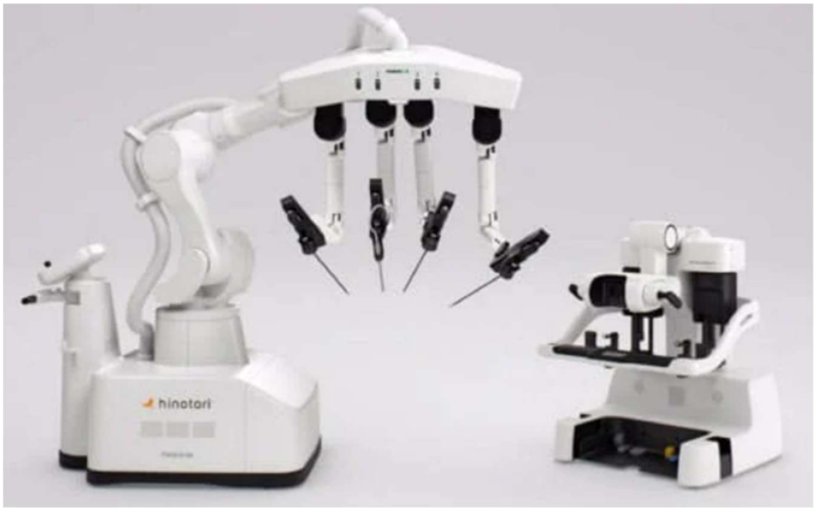

Figure 6. Hinorori™ surgical system.

2.3.6. KangDuo

The KangDuo Surgical System (Figure 7), developed by Kangduo Medical Robotics Co., Ltd., was launched in 2019 and is based in China. This innovative robotic surgical platform is designed to enhance the precision and effectiveness of minimally invasive surgeries across various medical fields, including general, urological, and gynaecological procedures [33,49,123,136].

One of the standout features of the KangDuo system is its high-definition imaging capabilities. While it does not include 3DHD vision, the system provides clear, detailed visuals that are crucial for surgeons during complex operations. The ergonomic design of the surgical console allows for optimal comfort and control, enabling surgeons to perform intricate tasks with improved dexterity.

The system's robotic arms are engineered for superior manoeuvrability, allowing surgeons to navigate through the surgical site with precision. This enhances the ability to perform delicate procedures while minimizing trauma to surrounding tissues. Additionally, the KangDuo system includes advanced fluorescence imaging technology, which aids in the visualization of critical structures and tissues during surgery, improving surgical outcomes.

With a focus on user experience, the KangDuo also features haptic feedback, providing surgeons with tactile sensations that simulate the feel of traditional surgery. This feedback is essential for maintaining control and accuracy. The inclusion of eye-tracking technology further enhances the system's usability, allowing surgeons to maintain focus and precision throughout the procedure.

The KangDuo Surgical System is CE marked, indicating its compliance with European health and safety standards, and it is commercially available, making it a competitive option in the field of robotic surgery. Its affordability and versatility make it an attractive choice for hospitals and surgical centres looking to adopt robotic-assisted techniques.

Figure 7. KangDuo Surgical system.

2.3.7. Versius®

The Versius® Surgical Robotic System [145] (Figure 8), developed by CMR Surgical, is a cutting-edge platform designed to enhance the precision and accessibility of minimally invasive surgeries. Launched in 2019, Versius® has gained recognition for its innovative approach to robotic surgery, offering several advantages over traditional systems.

One of the defining features of Versius® is its modular and flexible design. Unlike conventional robotic systems, which are often bulky and confined to specific setups, Versius® consists of independent robotic arms that can be arranged around the patient as needed. This flexibility allows it to adapt to various surgical environments, making it suitable for a wide range of procedures, including colorectal, urological, gynaecological, thoracic, and general surgeries.

The system is controlled by a surgeon console, which provides a high-definition 3D view of the surgical site and hand-held controllers that mimic the natural movements of the human hand. This precise control allows for intricate procedures with improved dexterity and range of motion compared to standard laparoscopic methods. Versius® was designed with surgeon ergonomics in mind, offering a seated position at the console to reduce fatigue during lengthy operations—a significant improvement over older systems.

Figure 8. Versius® surgical robot.

2.3.8. Avatera

The Avatera robotic system [146], launched in 2021 by the German company Avatera Medical GmbH, represents a major advancement in robotic-assisted surgery. Designed with both precision and ease of use in mind, this system offers surgeons enhanced control over minimally invasive procedures, aiming to improve patient outcomes while reducing surgical complexity.

At its core, the Avatera system features a modular design comprising a surgeon's console and a surgical unit with robotic arms. The console's slender eyepiece is ergonomically designed to allow the surgeon to maintain visual contact with the operating room team, fostering improved communication throughout procedures. This open design differentiates Avatera from other robotic systems that require the surgeon to be more isolated while operating.

One of the key innovations of the Avatera system is its use of single-use instruments. These disposable instruments not only ensure sterility for every procedure but also significantly reduce the risks associated with cross-contamination and infection. The robotic arms, equipped with seven degrees of freedom, provide surgeons with precise control for intricate tasks such as suturing and dissection, offering a high level of dexterity. The system supports 5 mm trocars, enabling less invasive access points for surgeries, thus promoting quicker recovery times for patients.

Additionally, the system operates on bipolar energy, which ensures safer tissue manipulation by minimizing the depth of energy penetration and reducing potential damage to surrounding tissues. This safety feature makes the Avatera system particularly appealing for complex surgeries.

With its compact, flexible setup and focus on ergonomics, safety, and accessibility, Avatera is positioned as a cost-effective alternative to existing robotic systems [68], offering a more streamlined and efficient solution for hospitals and surgical teams aiming to adopt robotic technology.

2.3.9. Dexter

The Dexter Robotic System [147], developed by Distalmotion SA in Switzerland and launched in 2020, is a groundbreaking robotic platform designed to enhance minimally invasive surgery. Unlike fully robotic systems that often replace traditional laparoscopic methods, Dexter offers a hybrid approach, combining the precision of robotics with the flexibility of standard laparoscopy. This on-demand setup allows surgeons to seamlessly switch between robotic and manual control, optimizing workflow and reducing procedure times.

Dexter's system consists of a sterile surgeon console, two patient carts, and a robotic endoscope arm. The robotic arms feature seven degrees of freedom and a 75-degree angulation, providing a wide range of motion and high dexterity, critical for intricate procedures like suturing or central vascular dissection. The endoscope arm is fully compatible with any 3D endoscopic system, allowing surgeons complete control of camera navigation from the console while ensuring stability and image clarity.

One of Dexter's significant advantages is its open platform design, allowing integration with existing operating room equipment, including insufflation devices, and 3D optics. This flexibility eliminates the need for specialized or proprietary tools, reducing costs and making it easier to implement in various surgical environments. Additionally, the system uses single-use instruments, such as needle holders and graspers, ensuring sterility and reliability during each procedure.

A key feature of Dexter is its ability to switch between robotic and laparoscopic modes in seconds [69]. The robotic arms can be folded back at the press of a button, providing space for traditional laparoscopic tools and techniques without undocking the robot. This seamless transition is particularly useful in colorectal and gynaecological surgeries, where certain tasks may be performed more efficiently through laparoscopy, while others benefit from robotic precision.

2.3.10. Mantra

The SSI Mantra Surgical System [148]is a groundbreaking robotic surgical platform launched in 2023 by SS Innovations. Designed to enhance the efficiency and effectiveness of minimally invasive surgeries, the Mantra system represents a significant advancement in surgical technology, aiming to make robotic surgery more accessible and cost-effective.

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One of the standout features of the Mantra system is its wristed instruments, which offer unparalleled dexterity. This allows surgeons to perform intricate movements with greater precision, particularly in confined spaces. Coupled with a high-definition three-dimensional camera system, the platform provides enhanced visualization, ensuring that surgeons have a clear and comprehensive view of the surgical field. This combination of advanced instruments and superior optics facilitates complex procedures that may be challenging with traditional laparoscopic techniques.

The port placement flexibility of the Mantra system is another significant advantage. By allowing meticulous placement of ports, the system maximizes the working space and minimizes the risk of complications. This feature is particularly beneficial during procedures like robotic transabdominal pre-peritoneal (rTAPP) hernia repairs[93], where precise manoeuvring is crucial.

A key aspect of the SSI Mantra Surgical System is its focus on cost-effectiveness. Robotic surgeries have traditionally been associated with high costs, which can limit their availability in many healthcare settings. The Mantra system addresses this concern by providing similar benefits to other robotic platforms at a significantly lower price point. This affordability has the potential to democratize access to robotic surgery, making it a viable option for a broader range of patients.

As the medical community begins to evaluate the long-term implications of the SSI Mantra system, early experiences suggest it is a promising tool for enhancing surgical outcomes while reducing costs. Continued research will be essential to fully understand its advantages and to establish its role in the evolving landscape of robotic surgery.

Figure 9. Mantra surgical robot.

2.3.11. Toumai®

The Toumai® surgical robotic platform is a cutting-edge system developed by Shanghai MicroPort MedBot (Group) Co., Ltd., a prominent Chinese company specializing in medical robotics. Introduced in the early 2020s, the platform represents a significant advancement in robotic-assisted surgery, particularly in the field of urology, and is poised to offer an affordable alternative to the dominant da Vinci robotic system.

The Toumai® system operates on a master-slave model, where the surgeon controls the robotic arms from a closed console. This setup allows for precision and dexterity during complex procedures, such as nephrectomies (both partial and radical) and radical prostatectomies. The system includes four robotic arms mounted on a cart, which can manipulate instruments with high accuracy.

The platform is equipped with high-definition 3D optics, providing the surgeon with a magnified, immersive view of the surgical field. However, details such as haptic feedback and camera-hopping technology are not disclosed, though these are common in modern surgical robotics

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to enhance the precision of procedures. The docking time for surgeries was reported to be efficient, with a median of 20-22 minutes depending on the type of procedure, and no major robotic malfunctions were observed [94].

2.3.12. Technical Comparison

Table 3 reports a comparison between the different robotic platforms from a technical point of view.

Table 3. Technical comparison of the surgical platforms.

Surgical platform	Single port or Multiport	Chart	Number of arms	Console	Vision	Fluorescence	Haptic Feedback	Eye tracking	Instruments
Senhance®	Multiport	multiple	4	Semi-open	3DHD	NAI	yes	NAI	Wristed, 5 mm, disposable
Revo-i®	Multiport	single	4	Open	3DHD	yes	yes	yes	rigid with a kit of wristed, unlimited uses, 5 mm
Micro Hand S	Multiport	single	4	Close	3D HD	no	yes	no	wristed, multi-uses (20)
Toumai®	Multiport	single	4	Open	3DHD	yes	no	no	wristed, reusable
Avatera	Multiport	single	4	open	3D HD	no	no	yes	wristed, Reusable
Versius®	Multiport	multiple	4	open	3D HD	yes	no	yes	wristed, disposable
Hinotori™	Multiport	single	4	semi-open	3D HD	NAI	no	no	wristed, reusable used up to 10 times
Kangduo	Multiport	single	3	Open	3D HD	yes	yes	NAI	Wristed, Reusable up to 10 uses
Hugo™	Multiport	multiple	4	Open	3D 4k	NAI	NAI	Yes	NAI
Dexter	Multiport	multiple	3	Open	3DHD	yes	No	NAI	reusable up to 10 times
Mantra	Multiport	multiple	5	open	3DHD	NA	NAI	NAI	NAI

NAI= Not Available Information.

All the robots included in the review have a multiport architecture.

Six robotic platforms (Revo-i®, Micro Hand S, Toumai®, Avatera, Hinotori™, and KangDuo) feature a single patient cart equipped with 3 to 4 robotic arms. In contrast, other systems utilize a modular multi-arm design, where each cart supports a single robotic arm, providing greater flexibility during surgery.

Most robotic surgical systems (Revo-i®, Toumai®, Avatera, Versius®, KangDuo, Hugo™, Dexter, and Mantra) use an open console for surgeon vision, allowing the surgeon to remain engaged with the operating room environment. Micro Hand S, however, features a closed console similar to the Da Vinci systems, where the surgeon's face is fully immersed in the vision system for a more immersive experience. Meanwhile, the Hinotori™ and Senhance® platforms offer a semi-open console design, which includes a visor, enabling the surgeon to maintain communication with the operating room staff while still benefiting from focused visual guidance.

4. Discussion

The evolution of surgical robotics has dramatically transformed the realm of minimally invasive surgery over the past two decades, particularly with the significant impact of the Da Vinci system by Intuitive Surgical [1–4,13,14]. Initially dominating the market due to its advanced capabilities and comprehensive regulatory approvals, the Da Vinci system has established a high standard that upcoming robotic platforms now seek to challenge [2,13–16]. Since the expiration of critical patents in 2019, a wave of new surgical robots has emerged, driven by technological advancements and the need for more cost-effective solutions. Many companies have developed innovative systems, some of which have already secured CE marking in Europe and have already obtained FDA approval. In some cases, the new robotic platforms include technological innovation. For instance, the Senhance® system [43,56] incorporates eye-tracking and haptic feedback, features that could enhance surgeon control and precision compared to the Da Vinci system, which notably lacks such advancements. This indicates a shift towards more ergonomic designs that prioritize user experience alongside clinical efficacy.

Furthermore, the design philosophies of newer platforms highlight a significant departure from the centralized multi-arm configuration characteristic of Da Vinci. Systems like CMR's Versius® [85,109] exemplify a modular approach that enhances flexibility in surgical settings, allowing surgeons to adapt robotic assistance to the specific needs of each operation. This modularity could be particularly beneficial in specialties such as colorectal and hepatobiliary surgery, where the complexity of procedures demands precise movements. Miniaturization of the system has also become a focal point, introducing compact robots designed for portability and ease of use. Such innovations could democratize access to robotic surgery, especially in smaller medical facilities that may not have the resources to accommodate larger, more expensive systems.

Despite these advancements, several challenges remain in evaluating the clinical efficacy and economic impact of these new robotic platforms. While recent reviews indicate that many surgical procedures performed with these systems have minimal adverse events, the existing studies often feature small sample sizes and lack long-term follow-up data, making it difficult to ascertain definitive conclusions regarding their efficacy. The number of randomized controlled trials in this area must be increased to provide a more robust evidence base for clinical practices. Furthermore, there is a pressing need for comprehensive cost analyses, safety evaluations, and studies assessing the organizational impact of adopting these new robotic systems.

The need for standardized training and credentialing programs presents another significant hurdle for the adoption of these new robotic platforms. While the Da Vinci system has established pathways for training, many of the newer systems lack a universal framework for assessing and certifying surgeon proficiency. This inconsistency raises concerns about skill transferability across platforms, which may complicate the integration of multiple robotic systems within hospitals. Efforts to develop simulation-based training and proctoring for new robots are encouraging but require further validation to ensure comprehensive adoption.

Looking ahead, the future of robotic surgery promises continued innovation, particularly with the integration of artificial intelligence and machine learning capabilities. As these technologies evolve, they may significantly enhance the capabilities of robotic surgery, ultimately leading to better patient outcomes and more efficient surgical practices. In summary, while the Da Vinci system remains a cornerstone of robotic surgery, the emergence of new platforms introduces possibilities and challenges that could reshape the future of surgical interventions. However, to realize the full

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potential of these new robotic systems, further rigorous research is essential, particularly in RCTs and comprehensive analyses covering costs, safety, and organizational impacts.

In conclusion, the emergence of new robotic surgery platforms presents significant advantages for market competition, potentially leading to reduced costs and continuous technological advancements.

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Appendix A

Source	Year	Surgical platform	Surgical specialty	Country
Yi, B., et al.[19]	2016	Micro Hand S	General surgery	China
Ku, G., et al. [20]	2020	Revo-i	General surgery	South Korea
Kang, I., et al.[21,22]	2020	Revo-i	General surgery	South Korea
Kondo, H., et al. [22]	2020	Senhance	General surgery	Japan
Kanego, G., et at. [23]	2021	Senhance	Urology	Japan
Minagawa, Y., et al. [24]	2021	Senhance	General surgery	Japan
Sugita, H., et al. [25]	2021	Senhance	General surgery	Japan
Hirano, Y., et al. [26]	2021	Senhance	General surgery	Japan
Monterossi, G., et al. [27]	2022	Hugo	Gynecology	Italy
Böhlen, D., et al. [28]	2023	Dexter	Urology	Switzerland
Pavone, M., et al. [29]	2023	Hugo	Gynecology	Italy
Mottaran, A., et al. [30]	2023	Hugo	Urology	Belgium
Panico, G., et al. [31]	2023	Hugo	Urogynecology	Italy
Campagna, G., et al. [32]	2023	Hugo	Gynecology	Italy
Chen, S., et al. [33]	2023	KangDuo	Urology	China
Miura, R., et al. [34]	2023	Hinotori	General surgery	Japan
Miyo, M., et al. [35]	2023	Hinotori	General surgery	Japan
Alkatout, I., et al. [36]	2024	Dexter	Gynecology	Germany
Formisano, G., et al. [37]	2024	Hugo	General surgery	Italy
Komatsu, H., et al. [38]	2024	Hugo	Gynecology	Japan
Tomihara, K., et al. [39]	2024	Hinotori	General surgery	Japan
Hayashi, T., et al. [40]	2024	Hinotori	Urology	Japan
Spinelli, A., et al. [41]	2017	Senhance	General Surgery	Italy
Stephan, D., et al. [42]	2018	Senhance	General surgery	Germany
Montlouis-Calixte, J., et al. [43]	2019	Senhance	Gynecology and General surgery	France
Melling, N., et al. [44]	2019	Senhance	General surgery	Germany
Yao, Y., et al. [45]	2020	Micro Hand S	General surgery	China
Li, J., et al. [46]	2020	Micro Hand S	General surgery	China

Samalavicius, N.E., et al. [47]	2020	Senhance	General Surgery, Gynecology, Urology	Lithuania
Lim, J.H., et al. [48]	2021	Revo-I	General Surgery	South Korea
Fan, S., et al. [49]	2021	Kangduo	Urology	China
Puntamberkar, S.P., et al. [50]	2021	Versius	Gynecology	india
Collins, D., et al. [51]	2021	Versius	General surgery	UK
Kelkar, D., et al. [52]	2021	Versius	Gynecology and General surgery	India
Dixon, F., et al. [53]	2021	Versius	General surgery	UK
Kastelan, Z., et al. [54]	2021	Senhance	Urology	Croatia
Lin, C.C., at al. [55]	2021	Senhance	General surgery	Taiwan
Venckus, R., et al. [56]	2021	Senhance	Urology	Lithuania
Siaulys, R., et al. [57]	2021	Senhance	Gynecology	Lithuania
Bravi, C.A., et al. [58]	2022	Hugo	Urology	Belgium
Fan, S., et al. [59]	2022	Kangduo	Urology	China
Puntamberkar, S.P., et al. [60]	2022	Versius	General surgery	UK
Borse, M., et al. [61]	2022	Versius	Gynecology	India
Puntambekar, S., et al. [62]	2022	Versius	General surgery	India
Knežević, N., et al. [63]	2022	Senhance	Urology	Croatia
Sasaki, M., et al. [64]	2022	Senhance	General surgery	Japan
Samalavicius, N.E., et al. [65]	2022	Senhance	General surgery	Lithuania
Sassani, J.C., et al. [66]	2022	Senhance	Urology	USA
Samalavicius, N.E., et al. [67]	2022	Senhance	General surgery	Multiple (Europe: Germany, Belarus, Lithuania)
Kallidonis, P., et al. [68]	2023	Avatera	Urology	Grece
Hahnloser, D., et al. [69]	2023	Dexter	general surgery	Switzerland.
Monterossi, G., et al. [70]	2023	Hugo	Gynecology	Italy
Bravi, C.A., et al. [71]	2023	Hugo	Urology	Belgium
Gallioli, A., et al. [72]	2023	Hugo	Urology	Spain
Territo, A., et al. [73]	2023	Hugo	Urology	Spain
Bianchi, P.P., et al. [74]	2023	Hugo	General surgery	Italy
Paciotti, M., et al. [75]	2023	Hugo	Urology	Belgium
Marques-Monteiro, M., et al. [76]	2023	Hugo	Urology	Portugal
Ou, Y.C., et al. [77]	2023	Hugo	Urology	Taiwan
Elorrieta, V., et al. [78]	2023	Hugo	Urology	Chile
Belyaev, O., et al. [79]	2023	Hugo	General surgery	Germany
Alfano, C.G., et al. [80]	2023	Hugo	Urology	USA
Panico, G., et al. [81]	2023	Hugo	Urogynecology	Italy
Raffaelli, M., et al. [82]	2023	Hugo	General surgery	Italy
Xiong, S., et al. [83]	2023	Kangduo	Urology	China

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Dong, J., et al. [84]	2023	Kangduo	General surgery	China
Kelkar, D.S., et al. [85]	2023	Versius	General surgery	UK
Wehrmann, S., et al. [86]	2023	Versius	General surgery	Germany
El Dahdad, J., et al. [87]	2023	Versius	General surgery	United Arab Emirates
Togami, S., et al. [88]	2023	Hinotori	Gynecological Surgery	Japan
Motoyama, D., et al. [89]	2023	Hinotori	Urology	Japan
Hudolin, T., et al. [90]	2023	Senhance	Urology	Croatia
Sasaki, T., et al. [91]	2023	Senhance	General surgery	Japan
Thillou, D., et al. [92]	2024	Dexter	Urology	France
Mehrotra, M., et al. [93]	2024	Mantra	General surgery	India
Pokhrel, G., et al. [94]	2024	Toumai	Urology	China
Prata, F., et al. [95]	2024	Hugo	Urology	Italy
Dell'Oglio, P., et al. [96]	2024	Hugo	Urology	Italy
Totaro, A., et al. [97]	2024	Hugo	Urology	Italy
Takahara, K., et al. [98]	2024	Hugo	Urology	Japan
Prata, F., et al. [99]	2024	Hugo	Urology	Italy
Prata, F., et al. [142]	2024	Hugo	Urology	Italy
Caputo, D., et al. [100]	2024	Hugo	General surgery	Italy
Belyaev, O., et al. [101]	2024	Hugo	General surgery	Germany
Jebakumar, S.G.S, et al. [102]	2024	Hugo	General surgery	India
Caputo, D., et al. [103]	2024	Hugo	General surgery	Italy
Andrede, G.M., et al. [104]	2024	Hugo	Urology	Brazil
Salem, S.A., et al. [105]	2024	Hugo	General surgery	Israel
Gioè, A., et al. [106]	2024	Hugo	Gynecology	Italy
Quezada, N., et al. [107]	2024	Hugo	General surgery	Chile
Pavone, M., et al. [108]	2024	Hugo	Gynecology	Italy
Dibitetto, F., et al. [109]	2024	Versius	Urology	Italy
Meneghetti, I., et al. [110]	2024	Versius	Urology	Italy
De Maria, M., et al. [111]	2024	Versius	Urology	Italy
Inoue, S., et al. [112]	2024	Hinotori	General surgery	Japan
Kulis, T., et al. [113]	2024	Senhance	Urology	Lithuania, Croatia
Chang, K.D., et al. [114]	2018	Revo-I	Urology	South Korea
Aggarwal, R., et al. [115]	2020	Senhance	General surgery	UK
Zeng, Y., et al. [116]	2021	Micro Hand S	General Surgery	China
Wang, Y., et al. [118]	2021	Micro Hand S	General surgery	China
Jiang, J., et al. [117]	2021	Micro Hand S	General surgery	China
Wang, Y., et al. [120]	2022	Micro Hand S	General Surgery	China

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Lei, Y., et al. [119]	2022	Micro Hand S	General surgery	China
Kulis, T., at al. [121]	2022	Senhance	Urology	Croatia
Collà Ruvolo, C., et al. [122]	2023	Hugo	Gynecology	Belgium
Li, X., et al. [123]	2023	Kangduo	Urology	China
Motoyama, D., et al. [124]	2023	Hinotori	general surgery	Japan
Motoyama, D., et al. [125]	2023	Hinotori	Urology	Japan
Motoyama, D., et al. [126]	2023	Hinotori	Urology	Japan
Glass Clark, S., et al. [127]	2023	Senhance	Urology	USA
Kim, J.S., et al. [128]	2024	Revo-I	General Surgery	South Korea
Bravi, C.A., et al. [129]	2024	Hugo	Urology	Belgium
Balestrazzi, E., et al. [130]	2024	Hugo	Urology	Belgium
Brime Menendez, R., et al. [131]	2024	Hugo	Urology	Spain
Ou, H.C., et al. [132]	2024	Hugo	Urology	Taiwan
Prata, F., et al. [133]	2024	Hugo	Urology	Italy
Grandi, C., et al. [134]	2024	Hugo	Urology	Italy
Antonelli, A., et al. [135]	2024	Hugo	Urology	Italy
Shen, C., et al. [136]	2024	Kangduo	Urology	China
Sun, Z., et al. [137]	2024	Kangduo	General surgery	China
Liu, Y., et al. [138]	2024	Kangduo	General surgery	China
Halabi, M., et al. [139]	2024	Versius	General surgery	United Arab Emirates
Kohjimoto, Y., et al. [140]	2024	Hinotori	Urology	Japan
Lin, Y.C., et al. [141]	2024	Senhance	Urology	Taiwan

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