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Review

The Evolution of Robotic Surgery through the Machine Design Innovation

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Abstract: To date, robotic surgery has gained much popularity, impacting deeply on surgical fields such as genitourinary system branches, general surgery, and cardiac surgery. We aim to outline the landscape of robotic surgery, focusing on design improvements, which have improved both the technical skills of surgeons and the outcomes of minimally invasive technique for patients. A thorough narrative literature review was conducted on PubMed/MEDLINE, employing keywords such as "robotic surgical system", "robotic surgical device", and "robotics AND urology". Furthermore, the reference lists of the retrieved articles were scrutinized. The analysis focused on urological surgical systems from the 2000s to the present day. Beginning with the daVinci® Era in the 2000s, new robotic competitors, including Senhance®, Revo-I®, Versius®, Avatera®, Hi-notori®, and HugoTM RAS, have entered the medical market. While daVinci® has maintained a high competitiveness, even more new platforms are now emerging in the medical market with new intriguing features. The growing competition, driven by unique features and novel designs in emerging robotic technologies, has the potential to improve application fields, enhance diffusion, and ameliorate the cost effectiveness of procedures. Since the impact of these new surgical technologies on different specialties and healthcare systems remains unclear, more experience and research are required to define their evolving role.

Keywords: robotic surgery; robotic platform; urology

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1. Introduction

From the ancient Egyptians' water clocks to Leonardo da Vinci's robotic marvels, humans have always been fascinated with the idea of independent operative machines that can move and act on their own.

The word "robot" was introduced in 1921 by the Czech playwright Karel Čapek in his play R.U.R. (Rossum's Universal Robots).

The first "robotic models" were conceived by ancient Egyptians and ancient Greeks, between 3000 BCE and 400 BCE. In the 12th century CE, a Muslim engineer named Ismail Al-Jazari wrote "The Book of Knowledge of Ingenious Mechanical Devices", describing around 50 machines.

Moreover, in the 15th century, the Italian artist and inventor Leonardo da Vinci designed several robotic machines, such as a walking human-like automaton that could move its arms, and turn its head. Da Vinci's designs were futuristics, and many of them were never built, but his work has inspired generations of engineers and scientists, and continues to inspire them even now [1].

The project of creating a robot is a complex and demanding effort and necessitates a deep knowledge of both mechanical engineering and artificial intelligence. Robots are expected to execute several tasks, ranging from simple manipulations to intricate decision-making processes, adapting themselves to various environments.

Creating a robotic platform starts with the establishment of the desired capabilities. Once these specifications are focused, a team of experts engineer a mechanical design that aligns with the defined requirements, involving the design of the robot's physical structure, the actuators responsible for its movement, and the sensors it uses for perception.

Simultaneously, the designer must make meticulous choices concerning the software and hardware components constituting the robot's control system. The latter assumes the critical role of interpreting the information gathered by the robot's sensors and orchestrating the actions of its actuators. The software, which is an integral part of the control system, is often intricate, handling diverse tasks like path planning, obstacle avoidance, and object recognition, making the design of a robotic platform a time-consuming and challenging procedure.

The goal of robot design is to produce platforms that are primarily safe and versatile, but also navigated and adaptive in dynamic environments with the help of artificial intelligence.

In the surgical field, robotic platforms have become well established since the introduction of the first robotic platforms in the early 2000s [2], with urological surgery still maintaining a pioneering role in the robotic surgery landscape. Additionally, the undeniable advantages of robotic surgery, such as more precision and accuracy during surgery and a faster recovery, have led to a widespread diffusion of robotic platforms not only in tertiary referral centers. Accordingly, there is a growing interest in designing new robotic platforms with ever-changing features [3].

This review aims to outline the historical background, design evolution, present status, and future perspectives of robotic surgery.

2. Materials and Methods

2.1. Ethical Considerations and Papers Selection

After approval by the Institutional Review Board of Fondazione Policlinico Universitario Campus Bio Medico di Roma (protocol code: RAS112022, approved in December 2022), we reviewed key scientific databases, such as PubMed and MEDLINE, to gain a broad understanding of the latest research on robotic surgery. We focused on keywords such as "robotic surgical system", "robotic surgical device", and "robotics AND urology". After selecting the papers, we checked the reference lists to identify articles ensuring coverage of relevant literature. We particularly focused on human-approved robotic surgical systems designed for laparoscopic procedures, which have been used in the urological field. With these settings, papers up until May 2024 were included in our narrative review.

2.2. Endpoint and Study Design

Due to the growing interest in the latest robotic platforms, the endpoint of our study was to describe the historical background, design evolution, present status, and future perspectives of robotic surgery. To enhance clarity, the Discussion was divided into two sections: events before and after the 2000s. In the first section, we consider the historical background, starting from the 1950s up to the 2000s, delving deeper into the innovations of those years. In the latter section, we illustrate the evolution of robotic surgical platforms from the da Vinci era to the present day. To improve understanding, the latest platforms were detailed under subheadings. Two figures describe the timeline before and after the 2000s, and a table summarizing the main features of the newest robotic platforms is provided.

3. Discussion

3.1. Robotic Platforms Preceding 2000s

The integration of robotics into surgery arose to achieve telepresence and perform precise tasks. In 1951, Raymond Goertz developed a remotely operated arm for handling radioactive materials. A decade later, Joseph Engelberger and George Devol created the first industrial robot, Unimate®, for General Motors. These milestones paved the way for a global integration of robotics across various industries [4–6].

The innovative concept of integrating robotics into surgical procedures began to gain popularity, but it was not until the late 1980s that a practical implementation commenced. A timeline and summarized design innovation of surgical robotics until the 2000s are represented in Figure 1.

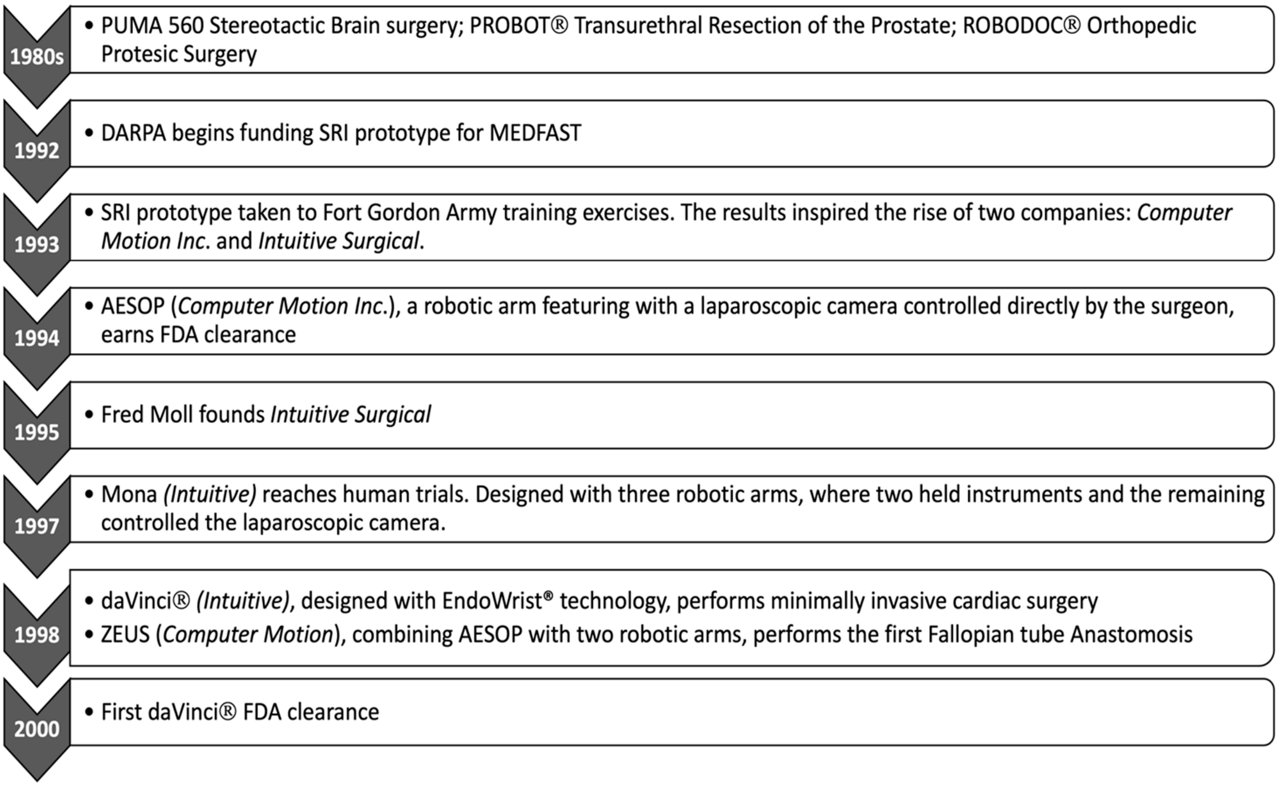

Figure 1. Timeline and design innovation of surgical robotics development preceding the 2000s.

Kwoh et al. performed the first contemporary robotic procedure in the 1980s, employing an innovative system named PUMA 560 for neurosurgical biopsies, pioneering stereo-tactic brain surgery [7]. In the same decade two more robotic systems were applied: PROBOT® and ROBODOC®.

Concerning the PUMA 560 system, Davies et al. adapted their innovation for the transurethral resection of prostate, resulting in this novel invention being further refined by Surgical Supplies LTD. PROBOT® was designed to guide a rotating blade within a predetermined virtual prostate reconstruction based on ultrasound scans [8]. While PROBOT® faced limitations, such as the need for manual coagulation at the procedure's conclusion and challenges related to the accuracy of 3D reconstructions of an increased gland, advancements in this direction persisted [7,9,10].

In fact, the same technology found application in the orthopedic field, leading to the creation of ROBODOC® for prosthetic surgery, the first robot to receive approval from the Food and Drug Administration (FDA) [11].

Within the surgical field, the master–slave configuration prevailed and was widely adopted. This design is based entirely on surgeon control over the machine, avoiding self-decisions made by the robots or pre-programmed actions [12–14].

This choice is easily understood when the indispensable qualities of a surgeon are considered, which include sensitivity, empathy, adaptability, and decision-making capabilities. These characteristics can make a crucial difference in the delicate balance between life and death, underscoring the intricate nature of surgery, a field that remains unsuitable for fully automated robotic systems.

The origin of this master–slave robotic design originated in the late 1980s. Pioneering surgeon Dr. Phil Green, at the Stanford Research Institute (SRI), merged two existing technologies: 3D vision developed by NASA in the 1960s and telepresence systems. This innovative combination laid the groundwork for today's master–slave surgical robots [15].

"SRI Green Telepresence" was the name of the first prototype, and it was constructed using two fundamental components: the telepresence surgeon's workstation (TSW) and the remote surgical unit (RSU). The first featured a stereoscopic video monitor and instrument manipulators designed to relay the surgeon's hand movements directly to the RSU, enabling precise control. The monitor provided an expansive 120-degree field of view, necessitating the use of passive polarized glasses by the surgeon to produce a sharp and clear 3D image. Regarding the RSU, it was equipped with manipulator end-effectors that had interchangeable instrument tips, making it possible to use a variety of surgical tools, including forceps, needle drivers, bowel graspers, scalpels, and cautery tips, all easily swapped through a twist–lock system. This flexibility was critical for accommodating different surgical tasks. Furthermore, the unit incorporated stereographic video cameras that were specifically designed to align perfectly with the surgeon's natural vision, thereby enhancing the accuracy and effectiveness of the telepresence system.

The Advanced Biomedical Technologies program began in the early 1990s to oversee the prototypes of these systems. During this period, the Defense Advanced Research Projects Agency (DARPA) embarked on an ambitious initiative to significantly reduce battlefield casualties. Their goal was to halve the time it takes to deliver first aid, eliminating the dangers faced by medical personnel on the front lines [16,17]. To achieve this aim, an armored vehicle carrying a cutting-edge RSU that could be deployed directly on the battlefield was created: the "MEDFAST" platform.

Through a Telepresence Surgeon's Workstation (TSW) situated in the second lines, surgeons could conduct "damage control surgery" interventions remotely [18]. In June 1993, the TSU debuted during military drills at Fort Gordon in Augusta, USA, followed by a comprehensive showcase in October 1994 at the Association of the U.S. Army Annual Convention. Attendees, even those without surgical experience, were invited to try the SRI system by performing a suture and knot on a simulated bleeding wound. Their success highlighted the system's user friendliness, marking a significant milestone in its development [19].

Despite being a research prototype, the SRI system's impressive results in the early 1990s attracted the eye of private investors. This led to the emergence of two companies that would become leading forces in robotic surgery for the next decade: Computer Motion Inc. and Intuitive Surgical.

Computer Motion Inc., based in Goleta, California, introduced the Automated Endoscopic System for Optimal Positioning (AESOP®). This 1994 FDA-approved robotic arm revolutionized minimally invasive surgery by giving surgeons direct control of the laparoscopic camera using a foot pedal or even voice commands. AESOP ensured a steady view of the surgical area, avoiding the need for a surgical assistant and reducing fatigue during long procedures [20]. Its application extended to laparoscopic cholecystectomies, hernioplasties, fundoplications, and colectomies [21].

Founded in California in 1995 by Frederick H. Moll and Robert Younge, Intuitive Surgical took a big step forward in robotic surgery. They built upon the SRI Green Telepresence system, creating their first prototype named "Lenny". This innovative design featured three robotic arms mounted on the operating table: two for surgical instruments and one for the camera, offering improved functionality. In 1997, Intuitive made another breakthrough with "Mona," the second-generation robot. This system became the first surgical platform used in a human trial, performed by surgeons at Saint-Blasium General Hospital in Belgium for a cholecystectomy [22].

Then, in 1998, Intuitive Surgical introduced the third generation of their surgical platform, featuring a revolutionary advancement: the daVinci® robotic arms with wrists that could move in six directions (six degrees of freedom). This platform allowed cardiac surgeons at the Leipzig Heart Center in Germany to perform complex minimally invasive procedures, including heart valve repairs and coronary artery bypass graft surgeries [23]. The introduction of EndoWrist® technology marked a turning point in the history of surgical robotics. It democratized minimally invasive surgery by making it accessible to a wider range of surgeons. This innovative technology empowered more doctors to perform these complex procedures with greater dexterity and control.

In response to Intuitive Surgical advancements, Computer Motion introduced the ZEUS® Robotic Surgical System (ZRSS), in 1998. This innovative platform combined the established AESOP camera arm with two additional robotic arms, each offering a range of four movements. ZEUS operated directly at the patient's side, being mounted on the operating table. Surgeons controlled the system from a separate console, where features like tremor filtering and scaled-down hand movements (2:1 to 10:1) enhanced precision during surgery [24].

If the first employment was described during a fallopian tube anastomosis in 1998 [25], ZEUS primary focus shifted to cardiac surgery, including mammary artery harvest and coronary artery bypass [22,26–28].

In the year 2000, the daVinci® obtained FDA approval for general laparoscopic procedures, marking a significant milestone as the inaugural surgical robot employed in operations in the United States. Robotic-assisted prostatectomy was extensively documented by the Vattikuti Institute of Detroit, showing positive outcomes [29–33]. Unlike the ZEUS®, which was mounted directly on the operating table, the daVinci® offered a more flexible approach. Its patient-side components were designed on a separate, mobile cart. Additionally, the daVinci® boasted significant improvements in the stereoscopic viewer, providing surgeons with a clearer and more immersive view of the surgical field. Finally, the daVinci® prioritized ergonomics with a more comfortable design for surgeons operating from the control console.

3.2. Crafting the Future: The Evolution of Robotic Design in the Third Millennium

3.2.1. From ZEUS® to daVinci® SP®

On 3 September 2001, ZEUS® achieved a historic milestone by facilitating the first transatlantic telesurgery: Jacques Marescaux, who was located in New York in the United States, successfully achieved a laparoscopic cholecystectomy in France, specifically in Strasburg [24,34].

The daVinci® surgical system revolutionized robotic surgery with its innovative three-component design. It comprised a mobile patient cart, a surgeon console for control, and a sophisticated imaging system. Unlike previous systems, the daVinci® featured robotic arms with exceptional dexterity. These arms, boasting seven degrees of freedom and the ability to rotate on two axes, were connected to the patient cart, offering greater flexibility, and eliminating the need for direct attachment to the operating table. These arms replicated the movement of a human wrist, and a 3D endoscope captured surgical field images, projecting them onto synchronized screens in the surgeon console for a genuine three-dimensional visualization without the need for specific goggles. The first daVinci® robot, approved by the FDA in 2000, had three robotic arms. This innovative design offered surgeons greater control and precision. In 2002, an enhanced version with four arms was introduced, further improving surgical exposure, and reducing the need for an assistant. At the surgeon's console, intuitive hand controls translated their movements into precise actions carried out by the robotic arms, effectively eliminating hand tremors for steadier procedures. The system could scale down movements from 1:1 to 5:1 for delicate maneuvers, and a pedal unit accommodated various energy uses.

Intuitive and Computer Motion finally merged in 2003, following a legal dispute that spanned three years. This merger ultimately led to the incorporation of some of ZEUS® elements into the following generations of the daVinci®.

Over the years, the platform underwent upgrades, with models like the daVinci® S® (2006) introducing a 3D High-Definition (3D HD) camera and an interactive touch screen display. The Si® model (2009) enabled dual console surgery, and the called Firefly® technology (2011), to improve the decision-making process during surgery, allowing for real-time fluorescence imaging. Novel curved instruments for single-site surgery were introduced in the same year.

The most advanced system, the Xi® model (2014), featured a newly designed patient cart to enhance mobility and flexibility, boom-mounted architecture for docking from any angle, and upgraded arm design for broader internal range of motion and minimized external collisions. The Xi® system provided upgraded visualization technology, offering surgeons autonomous control of an 8 mm camera delivered with crystal-clear, high-resolution images with superior brightness, and an enhanced view of the surgical field.

In 2018, Intuitive Surgical released the Single-Port (SP®) platform, which was FDA-approved for urological procedures after showcasing successful applications in complex surgeries such as prostatectomy, donor nephrectomy, and cystectomy through numerous case reports [35–42]. The innovations achieved after the 2000s by Intuitive Surgical and Computer Motion, and those resulting from their merger, are represented in Figure 2.

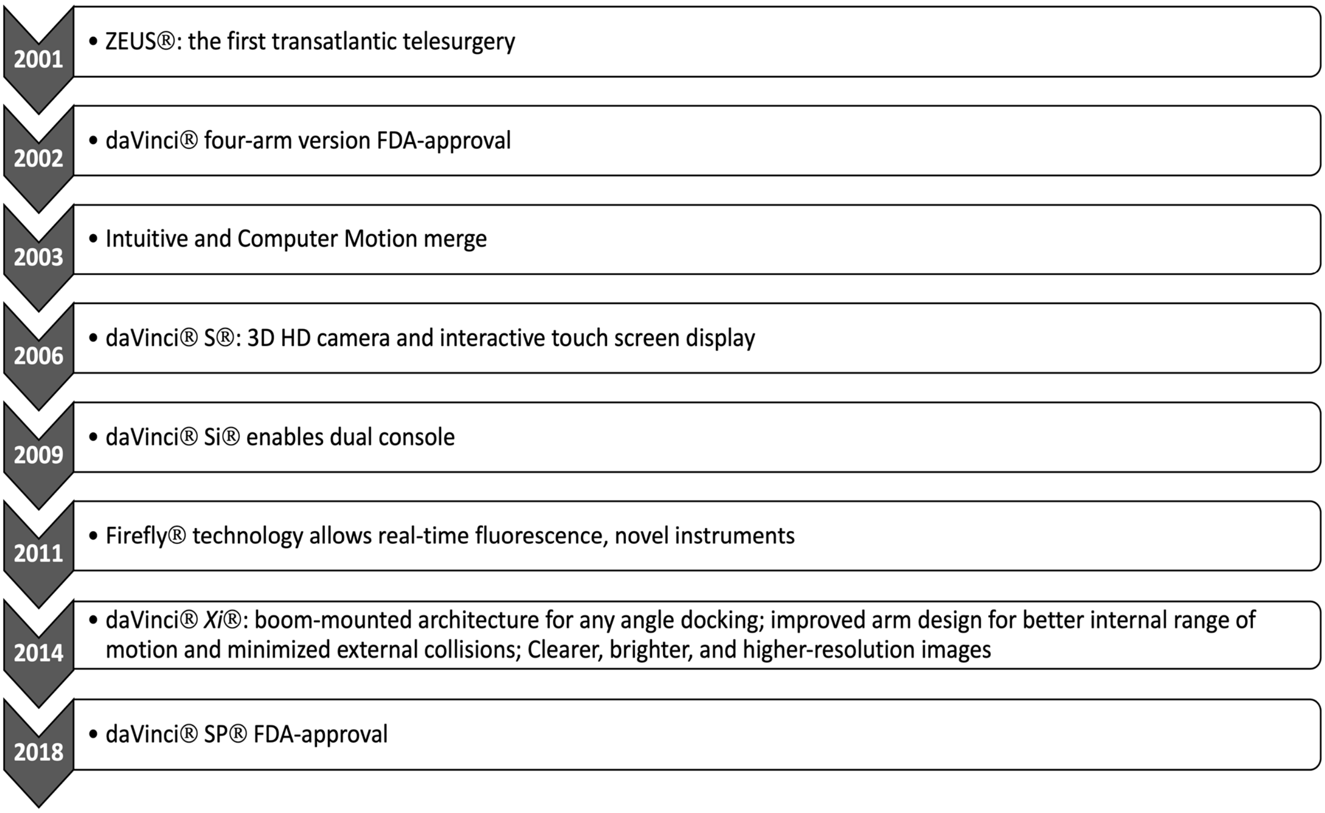

Figure 2. Innovations from Intuitive Surgical and Computer Motion after the 2000s.

While daVinci® showed the world the potential applications of robotic surgery, from 2016 onwards, new companies were starting to impact the medical market with new platforms, providing alternative choices for the surgeons (Table 1).

Table 1. New platform on the medical market.

Robotic Platform	Clearance	N° of Robotic Arm Carts	Haptic Feedback	Special Features and Design
Senhance®	2017 FDA	Up to 4, independent	✓	• Integration: It works with standard laparoscopic equipments. • Safety focus: force tracking used on the trocars during surgery, preventing tissue damage. • Eye control: the "eye-sensing control" technology allows the surgeon to control the camera through eyes movement. • Console Design: four independent robotic arms with separate carts and an open designed console. • 3D Visualization: 3D HD screen ad polarized goggles.
Revo-I®	2017 Korean Ministry of Food and Drug Safety	1	✗	• Dexterity: free wrist capability with seven degrees of freedom. • Cost-effective: designed for up to 20 uses. • Console Design: patient cart with four arms with an enclosed surgeon console. • 3D vision.
Versius®	2019 European CE Mark	Up to 4, independent	✓	• Dexterity: movements with seven degrees of freedom. • Console Design: robotic arms located on movable independent carts. • 3D vision: 3D HD view using polarized glasses.
Avatera®	2019 Europe	1	✗	• Console design: open console features for a better communication with the surgical team. • 3D vision.
Hinotori®	2020 Japanese Ministry of Health, Labor, and Welfare	1	✗	• Dexterity: robotic movements in eight axes. • Controllers: instruments are manipulated through loop-like hand controls shaped. • Console design: Semi-closed console architecture, incorporating a microscope-like eyepiece. • 3D vision.
Hugo™ RAS	2022 European Economic Area (EEA)	Up to 4, independent	✗	• Controllers: Surgeons maneuver pistol-grip for instruments control, while a footswitch manages the camera, energy source, and backup arm. • Dexterity: arm carts with six joints. • Console design: open console to improve communication with the surgical team. Four independent arm carts for customizable docking. • 3D glasses for head tracking technology, 3D glasses for trainee or other equipe members.

3.2.2. Senhance®

The Senhance® surgical system, from the Italian company Sofar and later acquired by TransEnterix Surgical, appeared in the field in 2016 with CE Mark approval in Europe for a wide range of abdominal and thoracic procedures. The next year, in 2017, Senhance® became the first new robotic system to receive FDA clearance in the US since the 2000s. Although direct comparisons with existing systems are needed, Senhance® offers several potential advantages. One key feature is its multiport design, utilizing independent robotic arms on separate carts, and eliminating the need for specialized operating rooms. Surgeons operate from a designed open console, where a HD 3D monitor utilizes polarized glasses to provide an immersive view of the surgical field. Communication with the surgical team is further enhanced by the "eye-sensing control" technology, an eye-tracking system that can be used to manipulate the camera. Moreover, Senhance® utilizes standard laparoscopic trocars for instrument insertion, allowing for an easy switch to a conventional laparoscopy if needed during surgery. Furthermore, the system incorporates a safety feature that autonomously monitors the force exerted by the robotic arms, preventing excessive pulling on the insertion points, minimizing tissue damage. An interesting feature is represented by the haptic feedback technology, attempting to offer the sense of touch.

Initially applied in general surgery and gynecology, recent reports highlight its successful utilization in radical prostatectomy and other urological procedures within Europe [43–48].

3.2.3. Revo-I®

The Revo-I® platform, created by the Meere Company in Republic of Korea, received the green light for human use in its home country in August 2017. This technology shares similarities with the daVinci® Si® system, featuring a patient cart equipped with four robotic arms, a surgeon console for precise control, and an HD vision cart for a more clear vision of the surgical field. The Revo-I® engaged a 10 mm 3D endoscope and 7.4 mm associated instruments, with a full wrist capability and seven degrees of freedom. These instruments are also designed for reusability, with a lifespan of up to 20 uses, potentially reducing costs associated with disposable tools [49,50]. The first human study involving the Revo-I® was published in 2018, demonstrating the platform's effectiveness in performing a radical prostatectomy [51].

3.2.4. Versius®

In 2019, the Versius® surgical system, developed by Cambridge Medical Robotics, entered the European market with CE Mark approval. Unlike its bulkier counterparts, Versius® has modular robotic arms, each equipped with a shoulder, elbow, and wrist joint. These independent arms are mounted on mobile carts, offering surgeons docking flexibility during procedures. Control is maintained remotely through an open console, where surgeons utilize polarized glasses to experience an HD 3D view. Versius® incorporated haptic feedback technology. The system engaged 5 mm instruments with seven degrees of freedom, and a complete range of motion. Initial trials conducted on cadavers and pigs have shown promising results in prostate and kidney surgeries, as well as pelvic lymph node dissections [52–54]. A recent clinical report detailed the successful application of Versius® in 30 robotic radical hysterectomies [55].

3.2.5. Avatera®

The Avatera® surgical system, a German innovation from Jena, entered the scene, obtaining the European clearance in November 2019. Designed for minimally invasive gynecological and urological procedures, the system is designed around a patient cart equipped with three robotic arms. Each arm holds a 5 mm instrument with seven degrees of freedom. A separate fourth arm manages a 10 mm endoscope, providing a HD 3D view.

Avatera® features an open console, enhancing communication between the surgeon and the surgical team [56,57].

3.2.6. Hinotori®

From Kobe, Japan, the Hinotori® surgical system, developed by Medicaroid Corporation, gained approval in its home country in August 2020. The operative unit showed a semi-closed console design with four robotic arms, equipped with eight axes of movement. The surgeon controls the wristed instruments through intuitive loop-like handles. While data from initial human trials are still lacking, the Hinotori® system has generated interest in the medical market [58,59].

3.2.7. Hugo™ RAS

The Hugo™ RAS system, developed by Medtronic, is composed of an open surgeon console featuring two pistol-grip arm controllers. A footswitch provides additional control over the camera, energy source, and reserve arm. Unlike traditional systems with robotic arms attached to the console, Hugo™ utilized a modular design. Four separate arm carts, each equipped with six joints, surround the patient, allowing for customizable positioning and docking during surgery. Moreover, the system incorporates specialized 3D glasses with head-tracking and console-control technology. Similar 3D glasses, without any tracking or control technology, are available for other surgeons to assist the procedure, improving the training process.

While still awaiting FDA approval in the United States, Hugo™ has already made its mark in other parts of the world. In 2021, it was successfully used in its first clinical case performed in Chile. The system received clearance for gynecological and urological procedures in the European Economic Area (EEA) in 2022. In a recent study by Ragavan and Mottrie in India, the versatility of Hugo™ was demonstrated in seven procedures, including radical and simple prostatectomies, as well as radical and simple nephrectomies [60]. A nonrandomized study comparing outcomes of radical prostatectomy between the Hugo™ RAS and the da Vinci system found no differences in total operative time or console time. Although the docking process took longer with the Hugo™ RAS, the system's independent arms provided better flexibility and more workspace for the assistant [61].

A recent study investigated the use of Hugo™ RAS for a minimally invasive kidney surgery (RAPN) on seven patients with no complications, instrument clashes, or technical malfunctions reported in all cases, suggesting the promising potential for the Hugo™ RAS system in this application [62].

This review was not devoid of limitations. The main drawbacks of our research were the lack of data in the literature concerning the latest platforms, the limitation to English language sources, and the focus on human-approved surgical robotic systems.

As the literature on this new platform continues to grow, involving more challenging case report, case series, and review [63–66], the analysis of the spread, financial impact, and potential benefits for hospitals using robotic surgery would be insightful [67].

4. Conclusions

The growing interest in the medical market has led to the emergence of new companies aiming to provide surgeons with better and diverse alternative options presenting unique features such as an open console, modularity, compatibility with traditional instruments, reduced size, and reduced costs. As clinical experience advances and technology evolves, the role of these new systems in various surgical fields and healthcare systems will become clearer.

While robotic surgery offers clear technical advancements and potential patient benefits, its widespread adoption hinges on robust clinical trials proving these advantages.

Finally, delving deeper into the future perspective of robotic surgery technology, the impact of emerging Artificial Intelligence (AI) holds the promise of revolutionizing surgical practice by improving precision, reducing human error, and expanding access to high-quality surgical care. The success of these technologies will depend on overcoming challenges related to latency, internet reliability, regulatory hurdles, ethical considerations, and ensuring surgeon proficiency in an AI-assisted environment. The full potential of these advancements is expected to unfold in the near future.

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