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Review

The Evolution and Innovations of Robotic Surgery in Urology: From Early Pioneers to Emerging Competitor

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Abstract

The advent of robotic surgery has revolutionized multiple medical fields, notably in urology, gynecology, and both general and cardiovascular surgery. This article aims to explore the journey of robotic-assisted surgery (multi/single-port) in abdomen and pelvic surgeries, tracing its historical roots, examining its current landscape, and considering the potential future impact. A comprehensive review of the literature was conducted through PubMed/MEDLINE, utilizing keywords such as "robotic surgical systems," "robotic surgery devices," and "robotics AND urology." Reference lists from selected articles were also explored to ensure a broad scope of understanding. The focus was on robotic systems designed for laparoscopic urological surgeries, all of which have been granted regulatory approval for clinical use. The historical trajectory of robotic surgery is traced back to the late 1980s with early systems like the Probot®, preceding the transformative introduction of the daVinci® system in the early 2000s. In addition to daVinci®, the article introduces newer robotic platforms, including Senhance®, Revo-I®, Versius®, Avatera®, Hinotori®, Edge®, Shurui and HugoTM RAS, which are emerging as serious competitors. While daVinci® has been the dominant force in robotic surgery for over a decade, these new systems are making significant strides with innovative designs, enhanced precision, and improved cost-efficiency. The growing competition among these platforms promises to expand their potential applications, increase accessibility, and optimize surgical outcomes across various specialties. Furthermore, as new technologies continue to evolve, there is a clear need for more extensive clinical trials and real-world data to assess their long-term impact on surgical practices, healthcare delivery, and patient outcomes. It remains to be seen how these advanced systems will integrate into healthcare infrastructures and their ultimate role in shaping the future of minimally invasive surgery.

Keywords: robotic surgery; robot; urology; innovation; future

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1. Introduction

Robotic-assisted surgery emerged in the late twentieth century as a technological solution to improve precision, dexterity, and visualization in minimally invasive surgery.

The concept of the robot has evolved from mechanical curiosities to essential tools that influence nearly every sector of modern life—including healthcare [1]. To date, robotics is

everywhere: in operating rooms, on Mars, and in our homes. And tomorrow? Robots may become even more humanlike. They may help us overcome physical limitations or remind us, once again, that every machine is a reflection of the dreams, and the fears, of those who built it.

Among these aspects, healthcare has emerged as a major beneficiary. Robotic-assisted surgery, which first emerged in clinical settings in the early 1990s, represents one of the most significant shifts in modern medical practice. Initially developed to enhance the precision and dexterity of minimally invasive procedures, robotic platforms have since advanced rapidly, driven by innovations in imaging, artificial intelligence, and haptic feedback. Today, these systems are used in a growing array of specialties, from urology and gynecology to cardiac and neurosurgery, improving patient outcomes by reducing recovery times and minimizing complications.

Yet despite its promise, robotic surgery faces ongoing challenges: high costs, steep learning curves, and increasing competition among manufacturers. Understanding how robotic surgery emerged, and how it is poised to evolve, is crucial for clinicians, engineers, and policymakers alike [1]. This article explores the historical development of robotic surgery, traces its evolution from early pioneers to emerging competitors, assesses its present impact on healthcare, and considers the technologies shaping its future.

2. Materials and Methods

To explore the evolution and current landscape of robotic systems in urological surgery, we carried out a comprehensive literature review using the PubMed/MEDLINE database. Our search strategy included the following "mesh", as keywords: "robotic surgery", "robotic surgical system," "robotic surgical device," and the combination "robotics AND urology." In addition to database results, we manually screened the reference lists of relevant publications to identify further sources of interest. This review was designed to provide a broad overview rather than a systematic analysis. Our inclusion criteria primarily focused on clinical studies, prospective case series, comparative analyses, systematic reviews, and meta-analyses evaluating robotic platforms currently approved for clinical use in urology, as outlined schematically in Table 1. Attention was given to studies reporting perioperative outcomes, oncological safety, functional results, learning curve assessment, ergonomics, and cost-related aspects of robotic-assisted surgery. Experimental studies without clinical application, conference abstracts without peer review, editorials, and reports focusing exclusively on non-urological procedures were excluded. The selection process was conducted by two independent reviewers, and discrepancies were resolved through consensus discussion. Although no formal time restrictions were initially set, the selected literature predominantly covers the period from 2005 to 2025, reflecting the modern era of clinically adopted robotic surgical systems. By narrowing our scope to approved technologies within this surgical domain, we aimed to capture both current innovations and the most relevant developments shaping contemporary urological practice.

Table 1. Surgical landscape of worldwide Robotic platforms.

Robot Name	Manufacturer	Approval Year	Port Type	Arm Configuration	Surgical Applications
da Vinci X	Intuitive Surgical (Sunnyvale, CA, USA)	2011 (FDA)	Multiport	Integrated unit (4 arms)	Urology, Gynecology, General Surgery
da Vinci Xi	Intuitive Surgical (Sunnyvale, CA, USA)	2014 (FDA)	Multiport	Integrated unit (4 arms)	Urology, Gynecology, General Surgery, Thoracic, ENT
da Vinci SP	Intuitive Surgical (Sunnyvale, CA, USA)	2018 (FDA)	Single port	Integrated (3 arms + camera)	Urology, Transoral, Colorectal, ENT

Table 1. *Cont.*

Robot Name	Manufacturer	Approval Year	Port Type	Arm Configuration	Surgical Applications
Hugo RAS	Medtronic (Dublin, Ireland)	2021 (CE); US in rollout	Multiport	4 independent bedside arms	Urology, Gynecology, General Surgery, Colorectal
Versius	CMR Surgical (Cambridge, UK)	2019 (CE)	Multiport	4 modular arms	General Surgery, Colorectal, Gynecology, Urology, Thoracic
Shurui SP	Shurui Medical (Beijing, China)	2023 (China)	Single port	Integrated unit	Urology, Thoracic, Pediatric Surgery
Avatera	Avateramedical GmbH (Jena, Germany)	2019 (CE)—**no longer available**	Multiport	Integrated unit	Urology (Prostatectomy), Gynecology, General Surgery
Senhance	Asensus Surgical (Durham, NC, USA)	2017 (FDA & CE)	Multiport	3–4 modular arms	General, Gynecology, Urology, Pediatrics
Revo-i	Meere Company (Hwaseong-si, Republic of Korea)	2017 (K-FDA)	Multiport	Integrated unit	Urology, General Surgery
Hinotori	Medicaroid (Kobe, Japan)	2020 (PMDA—Japan)	Multiport	4 modular robotic arms	Urology, expanding into General Surgery and Gynecology
Edge SP1000	Edge Medical Robotics (Shenzhen, China)	2023 (early clinical use)	Single port	Integrated unit	Gynecology, Urology (early), Colorectal (preclinical)

3. Discussion

3.1. Historical Background

The development of surgical robotics originated from two main technological objectives: telemanipulation and automation of precise surgical tasks. Early progress in remote manipulation dates to 1951, when Goertz developed a mechanical master–slave manipulator to safely handle radioactive materials [2]. Shortly thereafter, industrial robotics advanced with the introduction of the Unimate® robot by Engelberger and Devol, marking the beginning of programmable robotic assistance in complex tasks [3].

In the late 1980s, Davies and colleagues adapted robotic technology for urological applications with the development of PROBOT®, designed to assist transurethral prostate surgery using ultrasound-guided targeting [2,4,5]. Although limited by imaging accuracy and intraoperative control, this system represented one of the first dedicated robotic platforms in urology. Further advances were achieved with the Stanford Research Institute telepresence system, which introduced the concept of remote surgical manipulation through integrated visualization and control units [6,7]. Shortly thereafter, Computer Motion developed AESOP®, the first FDA-approved robotic camera holder, followed by the ZEUS robotic surgical system, which enabled early experiences in minimally invasive telesurgery and urological procedures [8–14]. Parallel developments by Intuitive Surgical led to the creation of early prototypes such as Lenny and Mona, culminating in the introduction of the da Vinci® Surgical System, which received FDA approval in 2000 and marked the transition toward modern robotic-assisted surgery through enhanced visualization and articulated instrumentation [15–18]. The adoption of robot-assisted radical prostatectomy at the Vattikuti Institute further established robotic surgery as a reference technique in urology and contributed to its rapid clinical expansion [19–21]. To date, a recent study assessing the impact of the presence of a robotic platform in an institution showed a 49% increase in the case volume of RARP, compared to centers that did not perform robotic surgery [21].

3.2. The da Vinci® Revolution and Single Port

The introduction of the da Vinci® Surgical System marked a significant advancement in the field of robotic-assisted surgery, building on the limitations of earlier platforms. This next-generation system was designed with three core components for clear and accurate view of anatomical structures during procedures: the patient-side cart with robotic arms featured seven degrees of freedom and two additional axes of rotation, the surgeon console with foot pedals, and the vision system with three-dimensional endoscope. The system also eliminated natural hand tremors and allowed for motion scaling, ranging from a 1:1 to a 5:1 ratio, critical for executing highly refined and delicate tasks [22].

The first robot-assisted prostatectomy was realized in 2000, and the first radical nephrectomy in 2001. Nonetheless the da Vinci system received approval for this type of surgery in 2001 [23].

The da Vinci® platform underwent a series of technological upgrades over the following years. In 2006, the da Vinci S® model was introduced, featuring a 3D high-definition camera system that significantly improved image quality and an interactive touch-screen display. In 2009 the Si® model was released, enabling dual-console surgery, which opened new opportunities for surgical training and collaboration and the Firefly® fluorescence imaging [24].

The da Vinci system quickly established itself as a leading platform in major urologic oncologic surgery, thanks to all the benefits previously described. Its adoption rapidly expanded, particularly in prostatectomies [25], radical nephrectomies [26] and partial nephrectomies [27], becoming a standard of care in high-volume centers. Nowadays, the da Vinci system is increasingly becoming the standard of care for radical cystectomy [28]. Notably, it allows for the safe and effective performance of intracorporeal reconstruction of the urinary tract, including neobladder, ileal reservoir and ureteral anastomoses, which has been shown to reduce postoperative morbidity and shorten recovery times compared to traditional open approaches [29,30].

In 2011, the da Vinci X® system expanded its capabilities further by introducing curved, single-site instruments tailored for single-incision laparoscopic surgery and in 2014 the introduction of da Vinci Xi®, with major structural and functional upgrades, such as visualization technology and the ability to rotate a 30° endoscope and four robotic identical and interchangeable arms, granting the flexibility to move instruments or the camera between ports during a procedure, greatly enhancing intraoperative adaptability and its adoption in a wide range of complex operations [31].

Single-Port Robotic Platform

Before the introduction of dedicated single-port robotic platforms, early single-site robotic procedures were performed using adapted access devices such as GelPort systems and homemade glove ports. These makeshift solutions allowed the placement of multiple instruments through a single incision and represented an important transitional step in the evolution of robotic single-port surgery during the early 2010s [32].

More recently, Intuitive Surgical introduced its **Single-Port (SP®) system** was approved by the FDA in 2018 for use in urologic procedures, demonstrating particular success in challenging anatomical spaces, such as the deep pelvis and retroperitoneum, thanks to a single surgical arm which allows the introduction of a single 8 mm flexible, articulating camera and three 6 mm wristed instruments through a single 27 mm access port. Each instrument is positioned around a radial configuration resembling a clock face—typically at the 3, 6, 9, and 12 o'clock positions, with a Cobra Mode in which the camera is centered and flexed at approximately 30° an "Adjust Mode", when instruments maintain their relationship to the tissue while the trocar angle is repositioned. When lateral movement

becomes restricted, the "Relocation Pedal" allows the entire robotic arm to be repositioned as a unit [33].

Clinical reports have highlighted the SP® system's efficacy in performing advanced urologic surgeries, including radical prostatectomy [34], retroperitoneal partial nephrectomy [35], pediatric surgery [36], vesico-vaginal fistulas, etc. [37] with potential benefits in terms of reduced postoperative pain, quicker recovery times, and improved cosmetic outcomes. E. Kim et al. stressed the presence of a significant learning curve for that platform and at the same time a shorter hospital stay [34]. Pacini et al. realized a series of transvesical SP-Robot Assisted Simple Prostatectomy (RASP) between February 2020 and March 2024. They focused their analysis on the incidence of urinary incontinence (UI) and the time to continence recovery. (95.5%) patients were completely continent immediately after catheter removal, while 4 (4.5%) experienced UI [14,38].

3.3. New Robots

After 20 years of market leadership with the da Vinci System and the expiration of its patent, new robotic systems have emerged. Many companies worldwide have entered the field, aiming either to replicate or differentiate the robotic landscape with the introduction of various systems featuring distinct characteristics. A limited number of studies have compared novel robotic platforms to the da Vinci system in urological surgery, generally reporting comparable outcomes. Analysis by Reitano et al. stressed how novel multiport robotic systems (e.g., Hinotori, Hugo RAS, Versius, Senhance) deliver perioperative, oncological, and functional outcomes comparable to the established da Vinci system across a range of urological procedures—with similar complication and recurrence rates, as well as functional recovery like continence and biochemical recurrence [39]. However, the majority of these investigations are developmental or exploratory in nature, reflecting the early stages of clinical research. Furthermore, an important limitation of these studies is the comparison between first-generation platforms and a fourth-generation platform (da Vinci system) [40].

3.3.1. Senhance®

The **Senhance® surgical system** (TransEnterix Surgical Inc., Morrisville, NC, USA) was initially developed by the Italian company Sofar S.p.A. (Milan, Italy) and received CE Mark approval in 2016 for a broad range of abdominal and non-cardiac thoracic procedures. In October 2017, Senhance® became the first new robotic platform to obtain FDA clearance since 2000, although this authorization was limited to general surgery and gynecology.

Despite the current lack of comparative clinical trials, Senhance® presents several potential advantages over other established robotic systems. It operates using a multiport setup with up to four independently controlled robotic arms, each mounted on separate mobile carts and an open ergonomic console equipped with 3D high-definition visualization via polarized glasses. The system's eye-sensing control technology uses infrared tracking to move the camera based on the surgeon's eye movements, reducing the need for manual input [35]. In addition, the platform automatically monitors the force applied at the trocar fulcrum, minimizing tissue trauma at the entry points, with a distinctive feature of Senhance® being its haptic feedback, which provides the surgeon with tactile sensation during procedures, a valuable asset for fine dissection and intracorporeal suturing.

Initially employed in general surgery and gynecology, the Senhance® system has more recently been used in radical prostatectomy and other urological procedures across several European centers [41,42].

Kulis et al. within the TRUS study, an open-label, prospective and retrospective multicenter registry study, realized an important series of radical prostatectomy. Only 5%

(20 of 375 patients) were converted to laparoscopy and only 0.2% to open surgery, stressing the important advantages of incorporation of haptic feedback technology [43]. Moreover, Lin YC et al. highlighted the absence of statistically significant differences between the Senhance® robotic prostatectomy (SRP) group and the da Vinci robotic prostatectomy (DRP) group in several key outcome measures. Intraoperative blood loss was identical (180 mL; $p = 0.86$), and the overall postoperative complication rates (Clavien-Dindo grades I–IV) were also comparable for both groups (25.3% for SRP vs. 22.2% for DRP; $p = 0.21$). Additionally, no significant differences were observed in positive surgical margins, PSA recurrence rates and urinary incontinence rates at 3 months postoperatively [44,45].

3.3.2. Revo-I®

The **Revo-I® surgical system**, developed by Meere Company Inc. (Yongin, Republic of Korea), received regulatory approval for clinical use from the Korean Ministry of Food and Drug Safety in August 2017. Structurally, it is comparable to the da Vinci® Si® system, featuring a patient cart with four robotic arms designed for reuse up to 20 times, a closed surgeon console, and a high-definition vision cart [46].

The first human clinical application of the Revo-I® system was reported in 2018, in a case involving a RARP marking a significant milestone for Korean-developed robotic surgery platforms. Don Chang et al. realized a series of retzius sparing RARP using Revo-I® system. The median (IQR) operating time, docking time, console time and urethrovesical anastomosis time were 186 (163–200) min, 8 (7–11) min, 92 (85.5–133) min and 26 (23–31) min, respectively. At 3 months, 12 patients were completely dry, three patients were using one safety pad, and two patients were using two pads or more [47]. On the contrary, Alip et al. compared perioperative and oncologic outcomes between Vinci Si robot and the Revo-i robot, with comparable outcomes in terms of estimated blood loss, PSM, and postoperative complication rates. However, the length of hospital stay was significantly shorter in the Revo-i cohort. On the other hand, procedures performed with the da Vinci system were associated with shorter console times, faster suturing, and reduced overall operative duration. Importantly, both groups showed similar rates short-term oncologic outcomes [48,49].

3.3.3. Versius®

The European CE Mark was granted to the **Versius® surgical system** (Cambridge Medical Robotics Ltd., Cambridge, UK) in March 2019. The robotic arms of this surgical system (each consisting of a shoulder, elbow, and wrist joint) are individually mounted on movable carts and remotely controlled through an open console, which allows for a 3D HD view using polarized glasses. Surgeons also receive haptic feedback from the handles [50], with 5 mm instruments offering a complete range of motion with seven degrees of freedom [51]. De Maria et al. realized one of the first series with the platform, collecting data about their first 18 patients. At the 30-day follow-up, 10 patients (55.5%) had regained full urinary continence, and at the 2-month follow-up, the number of continent patients increased to 13 (72.2%), without observing severe incontinence. The median console time was 201 min (IQR: 170–242), while the median operative time was 213 min (IQR: 186–266). Importantly, no patients required conversion to open or laparoscopic surgery, and no transfusions were necessary [52]. Sighinolfi et al. realized a multicentric analysis of surgical setup and early outcomes of the Versius® for pelvic surgery. A total of 171 interventions were performed. The mostly performed pelvic procedure was RARP with 4 arms followed by annexectomy, with a median console time of 201 min [51]. An initial experience study evaluating the transition from the da Vinci to the Versius robotic surgical system across more than 100 consecutive procedures demonstrated comparable perioperative outcomes

between the two platforms. The adoption of Versius was not associated with increased operative time, blood loss, or complication rates. Notably, the transition phase did not adversely impact patient safety, supporting the feasibility of integrating the new system into clinical practice [53]. Alkatout et al. realized a systematic review on the application of the system; 17 studies and 328 procedures in various specialties, including urology, gynecology, colorectal, and general surgery were analized. All procedures in the review were successfully completed using the Versius system, with no conversions due to device malfunction. Complication rates ranged from 7.4% to 39%, depending on procedure type and complexity, but notably, none of the complications were directly attributed to the robotic platform. Also, they found that Docking times were short, and surgeons reported a low incidence of instrument collision, likely due to the system's modular bedside units and flexible configuration [25,54].

3.3.4. Avatera®

The Avatera® surgical system, developed in Jena, Germany, received European clearance in November 2019 for use in minimally invasive gynecologic and urologic procedures. The system includes a patient cart equipped with three robotic arms designed for 5 mm fully articulated disposable instruments, along with an additional arm for a 10 mm endoscope. All instruments provide seven degrees of freedom and are operated by the surgeon through loop-style hand controls. The surgeon interacts with the system via an open console, which offers 3D full high-definition visualization, while preserving direct visual contact with the surgical team to facilitate communication [55]. Gkeka et al. reported a series of 14 RARP. All the procedures were successfully completed without the need for conversion. The median draping, docking and console time were 9.5 min (range: 7–13), 10 min (range: 5–40) and 104 min (range: 90–121), respectively. At three and six months postoperatively, the overall continence rates improved to 71.4% and 78.6%, respectively. In the nerve-sparing subgroup, continence rates (defined as the use of no or one security pad) reached 77.7% at three months and 88.9% at six months. Additionally, 77.7% of the nerve-sparing patients regained potency sufficient for successful sexual intercourse [56]. However recently, this system is no longer available due to the company's bankruptcy [57].

3.3.5. Hinotori®

The **Hinotori® surgical system**, developed by Medicaroid Corporation in Kobe, Japan, received regulatory approval from the Japanese Ministry of Health, Labour and Welfare in August 2020. This master–slave robotic platform is composed of three core elements: the surgeon cockpit, the operative unit, and the vision unit. The operative unit is equipped with four robotic arms, each featuring multiple joints and offering eight degrees of movement, allowing for a high degree of surgical precision. The system includes a semi-enclosed surgeon console, which provides a 3D visual field through a microscope-style eyepiece. Surgeons control the articulated instruments using loop-style handles, allowing for intuitive manipulation. A recent meta-analysis. compared the Hinotori and da Vinci robotic systems across multiple urological procedures. The study demonstrated comparable perioperative, functional, and oncological outcomes between the two platforms. However, the hinotori system was associated with significantly longer operative and console times [58]. The first-in-human study of RARP was carried out as a multi-institutional observational study in 30 patients. The median console time was 165 min, and the median intraoperative blood loss was 162.5 mL. Across the 30 procedures, four recoverable system errors (13.3%) occurred, leading to prolonged operative time due to the need for intraoperative troubleshooting. A total of three perioperative adverse events (10%) classified as Clavien–Dindo grade $\geq$ III were recorded, including anastomotic leakage, paralytic ileus, and pulmonary embolism.

Regarding oncologic outcomes, positive surgical margins were found in 2 out of 26 patients (7.7%) with pT2 disease, and in 2 out of 4 cases (50%) with pT3 tumors [59,60].

3.3.6. HugoTM RAS

The **Hugo™ RAS system** (Medtronic, Minneapolis, MN, USA) features a console with two pistol-style arm controllers, complemented by a footswitch used to manage the camera, energy devices, and a reserve robotic arm. The platform includes four independent arm carts, each equipped with six joints to enhance the range of motion. Visualization is enabled through the use of special 3D glasses integrated with head-tracking technology. The first clinical case was performed in Chile in 2021, and the system subsequently received regulatory approval in 2022 for use in gynecological and urological procedures within the European Economic Area (EEA) [61]. The initial clinical series, reported by Ragavan and Mottrie in India, included seven procedures, such as radical prostatectomy, simple prostatectomy, radical nephrectomy, and simple nephrectomy [62]. However, docking time was longer with the Hugo™ system, although its independent arms offered greater flexibility and enhanced workspace for the surgical assistant. The study by Baunacke et al. demonstrates that, with laser-assisted cart positioning and increased surgical experience, the docking time of the Hugo™ RAS system can be significantly reduced. After a short learning curve, docking times become comparable to those of the da Vinci Xi system, confirming the efficiency and speed achievable with this modular robotic platform [63]. Over time, the clinical use of the Hugo™ robotic system has progressively expanded beyond initial procedures, reflecting increased surgical confidence and system adaptability. Thanks to its worldwide adoption and ongoing evolution, particularly due to its enhanced modularity, the robotic platform has enabled different configurations tailored to specific procedures. For example, an Italian group developed a simple three-arm configuration for RARP and RAPN, achieving excellent perioperative outcomes [64–66]. Since its introduction, the platform has been used for a wide range of procedures, not only in urology—from radical or partial nephrectomy to pyeloplasty [67] and robot-assisted radical cystectomy (RARC), but also in other specialties, including interventions as splenectomy [68], hysterectomy [69], and transhiatal oesophagectomy [70]. In the urological field, Papalia et al. reported and created a RARC with a novel neobladder configuration, termed the "Delta Neobladder", with a median console time for neobladder reconstruction of 192 min (IQR: 170–219). A reduction in median operative time was noted in the latter half of the series (305 vs. 322 min, $p = 0.12$). At the 12-month follow-up, renal function remained stable in all patients. Daytime and nighttime continence rates at 12 months were 80% and 60%, respectively [71,72].

3.3.7. Edge SP1000

The EDGE SP1000 is a next-generation single-port robotic surgical system developed by Edge Medical. Designed with a single-arm, single-port architecture, it incorporates a 3D high-definition endoscope and three fully articulated instruments introduced through a single access point. Each instrument offers seven degrees of freedom, enabling fine, sub-millimetric movements. Technologies such as AgileArm™, Hide-in-Sleeve™, and SmartAnchor™ allow the system to maintain a broad operative range, adapt to various surgical angles, and function effectively in both narrow and deep fields [73]. The surgeon operates from a dedicated console with immersive 3D visualization and dual manipulators, supported by a footswitch for auxiliary control. Zhang et al. demonstrated the application in urological surgery, with a first series of 6 patients (three RAPN and three extraperitoneal RARP). Equipment ergonomic comfort was assessed using the National Aeronautics and Space Administration Task Load Index (NASA-TLX). All six procedures were successfully completed without the need for conversion to open surgery, conventional laparoscopy, or

multiport robotic assistance. The mean total operative time was 207.92 ± 32.42 min, with an estimated blood loss of 100 mL (range: 10–900 mL). Docking time averaged 16.25 ± 5.68 min, and the mean warm ischemia time was 17.00 ± 2.65 min. The operating surgeon reported a favorable user experience, reflected in a NASA-TLX workload score of 35.67 ± 4.23 [74]. Yu Chen et al. reports a prospective study of 18 gynecologic surgeries performed with the EDGE SP1000 single-port robotic system, including 8 malignant and 10 benign cases. The mean operative time was 254 ± 59 min for malignant and 190 ± 83 min for benign cases, with no conversions or perioperative complications. Patients reported high cosmetic satisfaction, and blood loss was minimal (mean 25 mL) [75,76].

3.3.8. Shurui SP

The SHURUI SP system is engineered to replicate the capabilities of a multiport robotic platform by deploying multiple articulating, double-jointed instruments through a single multichannel port, utilizing a dual-continuum mechanism and a Nitinol Arm (Nitin Arm) technology, with an integrated unit, ensuring precise motion and stable force delivery within confined anatomical spaces [77]. A recent prospective study by Jing et al. demonstrated the feasibility and safety of this platform in SP-RARP, with 11 patients underwent successful procedures without conversion or the need for additional ports. Median operative time was 229 min, with a median blood loss of 40 mL and no transfusions required, with a 1 month-continence achieved in 72.7% of patients [78]. The SHURUI SP system has recently demonstrated promising performance in retroperitoneal RAPN, confirming its feasibility in confined anatomical spaces. In a prospective study of 2024, 16 patients with cT1a renal tumors underwent a SHURUI RAPN, with no intraoperative conversions, no positive surgical margins, and no Clavien-Dindo ≥3 complications. The median console time was 107 min, warm ischemia time averaged 26.5 min, and median blood loss was just 17.5 mL, highlighting the system's capacity for precise dissection and vascular control [79]. Moreover, Wu et al. recently evaluated both SHURUI SP and da Vinci SP platforms in the setting of SP-RARP. The analysis included 34 patients treated with SHURUI SP and 100 matched controls operated with the da Vinci SP system. The results showed that although operative and console times were significantly longer in the SHURUI group (215 min vs. 110 min; 162 min vs. 75 min, respectively), perioperative safety and oncological outcomes were comparable, with no conversions or major complications occurred in either group; finally positive surgical margin rates (18.5% vs. 14.8%) and continence at one year (96.3% in both groups) were similar [80]. Notably, the SHURUI SP platform was used predominantly via an extraperitoneal approach, which may offer specific advantages in select patient populations. These findings suggest that, despite being in an earlier phase of clinical adoption, SHURUI SP can achieve equivalent clinical outcomes to the well-established da Vinci SP system, while offering a novel alternative in single-port robotic prostate surgery [79].

3.4. Comparative Evidence Level and Clinical Maturity of Emerging Robotic Platforms

Despite the rapid expansion of alternative robotic platforms, the level of clinical evidence supporting their adoption in urology remains heterogeneous and generally limited compared with the da Vinci® system. Most studies evaluating Hugo™ RAS, Versius®, Senhance®, Hinotori®, Revo-i®, and newer single-port platforms consist primarily of feasibility studies, early prospective series, or institutional experiences involving relatively small patient cohorts [39,40]. According to the IDEAL framework for surgical innovation, the majority of these systems remain positioned between stage 1 (idea) and stage 2 (development), with only limited progression toward stage 3 comparative evaluation [40]. From a clinical maturity perspective, the da Vinci® platform remains the only robotic

system supported by large multicenter datasets and long-term oncological and functional outcome validation across multiple urological procedures [39]. In contrast, evidence for next-generation platforms is still largely restricted to short-term perioperative outcomes, with limited long-term follow-up data regarding oncological control, continence recovery, and complication profiles. Current comparative studies generally suggest similar safety and feasibility among platforms; however, these analyses are frequently affected by selection bias, early-adopter experience, and learning-curve effects, which limit their generalizability [40]. As a result, most emerging robotic systems should currently be considered promising alternatives rather than fully equivalent replacements in complex oncologic urological surgery. Practical limitations influencing the adoption of novel platforms include variability in instrument availability, differences in docking workflow, reduced procedural standardization, restricted global distribution, and the absence of structured training pathways comparable to those established for the da Vinci® ecosystem [81]. Furthermore, economic sustainability and maintenance infrastructure remain important determinants of real-world implementation beyond high-volume referral centers [82].

3.5. Economic Costs in Robotic Surgery

The introduction of multiple robotic systems has reduced the dominance of the da Vinci® system, making robotic surgery more accessible. However, despite the promise of broader availability, the cost of robotic systems remains a barrier, especially in resource-limited settings as highlighted by Farinha et al. [81]. While modular systems like Hugo™ and Versius® offer lower infrastructure costs and easier integration into existing operating rooms, the overall economic impact is still unclear, with high initial investments and ongoing maintenance costs. Indeed, economic analyses indicate a 15–30% cost reduction per procedure in institutions adopting multi-vendor robotic platforms [82]. Therefore, the economic impact of robotic surgery, especially in urology, has become an area of increasing focus in recent years. Robotic platforms, while offering clear advantages in terms of precision and patient outcomes, come with substantial costs related to the purchase of the robotic system, maintenance, and disposable instruments. The operating room time required for robotic surgery also tends to be higher compared to traditional laparoscopic approaches, further increasing costs [83]. A recent study highlighted that while the initial cost of the robotic system is a significant investment, the efficiency gains and reduced complication rates may offset these costs in high-volume centers. However, the true cost-effectiveness of robotic surgery is not only determined by the price of the equipment but also by longer-term factors such as complication rates, recovery times, and the potential for fewer reoperations. For example, recent analyses have suggested that the total cost of robotic partial nephrectomy is comparable to, or even less than, open partial nephrectomy when factoring in shorter hospital stays and faster recovery times [84]. Nonetheless, these studies emphasize the need for careful consideration of all variables, including hospital tariffs, consumable costs, and staff time, in evaluating the financial implications of robotic surgery [85,86].

4. Limitations

The scope of this review is intentionally limited to telepresence robotic systems used in multi-port/single-port surgeries for abdominal and lower pelvic procedures in urology. Therefore, firstly, this review tries to illustrate and contextualize the different robotic platforms currently available on the market, highlighting their technological characteristics and clinical indications, rather than to perform a direct comparative analysis among systems. Moreover, a head-to-head comparison across parameters such as cost, learning curve, ergonomics, or clinical outcomes would require a long robust body of comparative

studies, which is currently lacking. Long term data on all these parameters are currently scarce. However, robotic systems used for other urological applications, such as robot-assisted prostate biopsy, tumor ablation, and other forms of robotic intervention outside of laparoscopy, are beyond the scope of this paper and are not discussed in this review. Additionally, we deliberately omit certain lesser-known robotic systems or those still undergoing clinical trials, focusing instead on FDA-approved platforms with established market presence.

5. Conclusions

In the urological robotic landscape, the da Vinci system remains a milestone due to 20 years of experience and innovations. However, based on the systematic review, the novel emerging multi-port robotic systems (including Versius, Senhance, Revo-i and Hugo RAS) have demonstrated clinical outcomes comparable to the da Vinci system in low- to moderate-complexity soft tissue surgeries. Indeed, across 12 studies involving 1142 patients, the newer systems showed low rates of intraoperative complications (0–2.6%), conversion rates between 0 and 7.9%, and short hospital stays, mirroring da Vinci's safety and efficacy profile. Although operative times were generally longer. These findings confirm that next-generation robotic platforms are safe, feasible, and effective alternatives, paving the way for broader clinical adoption and cost competition [87].

While the decline of da Vinci's monopoly has democratized robotic surgery, challenges around standardized training, accessibility, and integration remain. Moving forward, a more comprehensive economic evaluation, standardization, and evidence-based data are needed to truly optimize robotic surgery in clinical practice. In conclusion, while robotic-assisted surgery is often criticized for its higher upfront and procedural costs, the findings of the analysis made by Lai et al. highlighted that such criticisms must be carefully contextualized. The majority of existing economic evaluations have not fully incorporated key RAS-specific variables such as learning curves, organizational integration, platform reusability, or evolving cost structures. Therefore, a more nuanced and comprehensive approach to economic evaluation is needed one that reflects real-world implementation scenarios and the long-term clinical and operational value that robotic platforms may offer across surgical specialties. This perspective challenges simplistic cost comparisons and supports the continued investigation of multi-dimensional value in robotic surgery [88].

6. Future Perspective

The concept of "tailored surgery" has evolved significantly with the widespread adoption of robotic platforms. Today, its meaning extends beyond surgical technique to include the choice of robotic platform itself. This advancement allows for procedures to be fully personalized, adapting the surgical approach to the individual patient's characteristics, anatomical variations, and the surgeon's preferences, making surgery increasingly precise and patient-centered.

Nonetheless, artificial intelligence is progressively transforming robotic surgery by enhancing intraoperative vision, motion control, and decision support through machine learning and computer vision techniques.

Current applications of artificial intelligence in urologic robotic surgery include computer vision algorithms for real-time instruments and anatomical structure recognition during robot-assisted prostatectomy and partial nephrectomy. Machine learning models have also been used to improve surgeon training, leading to a smoother learning curve robotic surgery. Predictive AI tools have also been developed to estimate perioperative and functional outcomes, such as continence and complication risk. Additionally, AI-driven

intraoperative guidance systems are being explored to support surgical decision-making during complex oncologic procedures [89].

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Abbreviations

The following abbreviations are used in this manuscript:

RARP	Robot-Assisted Radical Prostatectomy
RAPN	Robot-Assisted Partial Nephrectomy
RARC	Robot-Assisted Radical Cystectomy
SRP	Senhance Robotic Prostatectomy
DRP	da Vinci Robotic Prostatectomy
SP-RARP	Single-Port Robot-Assisted Radical Prostatectomy
VIP	Vattikuti Institute Prostatectomy
ZRSS	ZEUS Robotic Surgical System
SP	Single Port
FDA	Food and Drug Administration
PSM	Positive Surgical Margins
UI	Urinary Incontinence
NASA-TLX	National Aeronautics and Space Administration Task Load Index
FDA	U.S. Food and Drug Administration
CE	European Conformity marking
PMDA	Pharmaceuticals and Medical Devices Agency—Japan

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