International Journal of Innovative Technologies in Social Science

e-ISSN: 2544-9435

Operating Publisher
SciFormat Publishing Inc.
ISNI: 0000 0005 1449 8214

2734 17 Avenue SW,
Calgary, Alberta, T3E0A7,
Canada
+15878858911
editorial-office@sciformat.ca

ARTICLE TITLE	GROWING ROLE OF ROBOTIC-ASSISTED SURGERY IN ADULT PATIENTS - A COMPREHENSIVE REVIEW
DOI	https://doi.org/10.31435/ijitss.1(49).2026.4938
RECEIVED	20 January 2026
ACCEPTED	06 March 2026
PUBLISHED	19 March 2026
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GROWING ROLE OF ROBOTIC-ASSISTED SURGERY IN ADULT PATIENTS - A COMPREHENSIVE REVIEW

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ABSTRACT

Introduction: Robotic-Assisted Surgery (RAS) has transitioned from a technological curiosity to a foundation of modern surgery in the last few years. This review aims to evaluate the current status, clinical outcomes, economic implications, and expanding indications of RAS in adult patients across urologic, gynecologic, colorectal, and general surgical disciplines.
Methods: A review of the literature was conducted using PubMed, Scopus, and Web of Science databases for English-language articles published up to 2025. The analysis focused on randomized controlled trials (RCTs), systematic reviews, and large-cohort meta-analyses comparing RAS with open surgery and conventional laparoscopy.
Results: The analysis indicates that RAS offers superior visualization and improved ergonomics compared to conventional laparoscopy. In urology, RAS has become the gold standard for prostatectomy, showing statistically significant reductions in estimated blood loss (EBL) and improved functional recovery (continence and potency). In gynecology and general surgery, RAS demonstrates lower conversion rates to open surgery, particularly in obese cohorts and deep pelvic dissections. While operative times are frequently longer during the learning curve, total length of hospital stay is consistently reduced.
Conclusions: Robotic surgery has proven advantageous in minimizing patient trauma and assisting with complex cases where conventional laparoscopy struggles. The primary barrier remains the high upfront cost; however, these expenses may be offset over time by reduced length of stay and lower complication rates, strengthening the economic case for RAS.

KEYWORDS

Robotic-Assisted Surgery, Minimally Invasive Surgery, Surgical Ergonomics, Medical Robotics

CITATION

Anna Kocik, Ilona Tadulewicz, Natalia Nowak, Mateusz Drozd, Aleksandra Kozłowska, Zuzanna Butkowska, Łucja Komisarczyk, Tadeusz Kornela, Aleksandra Góralska, Zofia Gorzoch-Burduk. (2026) Growing Role of Robotic-Assisted Surgery in Adult Patients - A Comprehensive Review. *International Journal of Innovative Technologies in Social Science*. 1(49). doi: 10.31435/ijitss.1(49).2026.4938

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1. Introduction

Surgical innovation has long focused on minimizing patient trauma without compromising therapeutic outcomes. The introduction of laparoscopy in the late 20th century marked a shift from laparotomy to minimally invasive techniques. While this approach offered clear benefits, such as reduced pain and shorter hospitalization, conventional laparoscopy has inherent limitations: two-dimensional (2D) vision, the "fulcrum effect" of rigid instruments where hand movement is inverted, and a steep learning curve [23] for complex reconstructive tasks such as intracorporeal suturing.

Robotic-Assisted Surgery (RAS) was developed to address the limitations of open surgery and laparoscopy. The introduction of the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA) marked a significant moment in medical history, offering surgeons three-dimensional (3D) high-definition visualization, instruments with seven degrees of freedom (EndoWrist technology), and physiologic tremor filtration. These features allowed for the precise replication of open surgical maneuvers within a minimally invasive environment, effectively placing the surgeon's eyes and hands inside the patient's body.

The use of RAS has grown rapidly over the last twenty years. What began with cardiac and urologic applications has expanded to general, thoracic, colorectal, and gynecologic surgery. According to recent data, the volume of robotic procedures globally has surpassed millions annually, with general surgery recently overtaking urology as the fastest-growing specialty [33]. Yet, this rapid adoption has not been without controversy. Questions regarding cost-effectiveness, the necessity of robotics for routine procedures, and the learning curve remain subjects of intense debate within the medical community.

This review provides a critical analysis of robotic surgery in adult patients. By synthesizing data from trials and meta-analyses, our goal is to define where RAS offers a clinical advantage and identify the challenges that must be addressed as the technology matures.

2. Methodology

This review was designed as a comprehensive narrative synthesis of existing literature. To ensure a robust analysis, we adhered to a structured search strategy aligned with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, adapted for a narrative review format.

2.1 Data sources

We performed a systematic search of electronic databases including PubMed/MEDLINE, Embase, and the Cochrane Library. The search parameters were restricted to articles published between 2010-2025, to ensure the inclusion of mature data.

2.2 Inclusion and exclusion criteria

To ensure the relevance and quality of the reviewed data, specific criteria were applied:

- Inclusion: Studies involving adult human patients (>18 years); randomized controlled trials (RCTs), systematic reviews, meta-analyses, and high-volume retrospective cohort studies (n > 100) [20]; articles published in peer-reviewed English-language journals.
- Exclusion: Case reports, editorials, letters to the editor, pediatric populations, animal or cadaveric studies, and studies focusing solely on single-site case series without a comparator group.

2.3 Data extraction

The selected literature was categorized by surgical sub-specialty. Key outcome measures extracted included operative time, estimated blood loss (EBL), length of stay (LOS), complication rates (Clavien-Dindo classification), conversion rates to open surgery, and oncologic outcomes (margin status, lymph node yield) where applicable. Particular attention was paid to studies comparing RAS directly against conventional laparoscopy (CLS) and open surgery to determine the relative value of the robotic platform.

3. Results

The review of the literature reveals a distinct heterogeneity in the adoption and established benefits of RAS across different surgical disciplines [28]. While some specialties have reached a plateau of mature adoption, others are in a rapid growth phase. The findings are synthesized below by surgical sub-specialty, highlighting trials and meta-analyses.

3.1 Urology

Urology represents the vanguard of robotic surgery. The radical prostatectomy was the procedure that effectively launched the robotic era, driven by the critical need for precise dissection in the deep pelvis to preserve the neurovascular bundles responsible for erectile function.

3.1.1 Radical Prostatectomy

In the domain of Urology, the superiority of the robotic approach has been rigorously contested and examined. The landmark randomized controlled trial by Yaxley et al. (2016) remains a cornerstone reference for this discussion [2]. This study randomized 326 men to receive either Robot-Assisted Radical Prostatectomy (RARP) or Open Radical Prostatectomy (ORP). The primary outcomes were urinary function and sexual function at 6 and 12 weeks, with oncologic outcomes as secondary measures.

The results of the Yaxley trial provided a nuanced view that challenged the marketing hype while confirming specific clinical benefits. The study found no statistically significant difference in positive surgical margin rates between the two groups (10% in the open group vs. 15% in the robotic group), suggesting that in the hands of expert surgeons, cancer control is technique-independent. However, the secondary outcomes painted a different picture. The robotic cohort experienced significantly less intraoperative blood loss and reported lower pain scores in the immediate postoperative period. Critically, functional recovery trajectories differed; although long-term outcomes at 12 months converged, the robotic group showed a trend toward earlier return of erectile function. Ficarra et al. (2012) confirmed that robotic prostatectomy is associated with significantly superior rates of urinary continence recovery compared to open surgery [25]

Further supporting these findings, the systematic review by Novara et al. (2015) aggregated data from over a dozen observational studies [11]. Their meta-analysis highlighted a reduction in the rate of bladder neck contractures- a late complication causing urinary obstruction- in the robotic group compared to historical open series. This is likely attributable to the enhanced visualization of the vesico-urethral anastomosis, allowing for more precise, watertight suturing that heals with less scarring. Current best practices, as defined by the Pasadena Consensus Panel, now recognize robotic prostatectomy as a standard of care for localized disease due to these reproducibility benefits [35].

3.1.2 Partial Nephrectomy

For renal masses, the guidelines have shifted decisively towards nephron-sparing surgery. RAS has facilitated the performance of partial nephrectomy for larger and more complex tumors (RENAL score >7) that would have previously required radical nephrectomy or open surgery. The robotic platform's dexterity allows for rapid renorrhaphy (suturing of the kidney defect), minimizing warm ischemia time- a critical factor in preserving long-term renal function. Mottrie et al. (2018) emphasized that the „clamped" time during robotic partial nephrectomy is now comparable to open surgery, but with significantly lower morbidity [8].

3.2 Gynecology

In gynecology, RAS has been instrumental in increasing the utilization of minimally invasive surgery for complex benign and malignant conditions, specifically where conventional laparoscopy was technically challenging due to patient anatomy or pathology size.

3.2.1 Benign Hysterectomy

A systematic review by Yeung et al. (2020) focused specifically on the obese population (BMI > 30 kg/m²), a demographic that presents significant challenges for conventional laparoscopy due to restricted intraperitoneal space and thick abdominal walls [13]. The review analyzed outcomes of hysterectomy across multiple institutions and found that robotic assistance was associated with a conversion-to-laparotomy rate of less than 5%, compared to rates often exceeding 10-15% in conventional laparoscopy for uteri weighing >500g.

The study highlights that the robotic platform mitigates the physical strain on the surgeon caused by the „fulcrum effect" of heavy abdominal tissue on laparoscopic trocars. By enabling a minimally invasive approach in these high-risk patients, RAS significantly reduces the risk of wound infections and incisional hernias, which are major sources of morbidity in obese women undergoing open surgery.

3.2.2 Gynecologic Oncology

While RAS has shown clear benefits in endometrial cancer- specifically regarding sentinel lymph node mapping using indocyanine green (ICG) fluorescence- the landscape for cervical cancer is more complex. The LACC Trial (Laparoscopic Approach to Cervical Cancer), referenced by Ramirez et al. (2018), was a multicenter, randomized trial that compared minimally invasive radical hysterectomy (both laparoscopic and robotic) against open abdominal radical hysterectomy for early-stage cervical cancer [4].

The trial was halted early due to a higher rate of recurrence and lower disease-free survival in the minimally invasive arm. This finding significantly altered clinical practice and guideline. It underscores a critical theme in our review: the mechanical superiority of a robot does not automatically translate to oncologic safety if the surgical technique (e.g., use of uterine manipulators resulting in tumor spillage) disrupts tumor containment. Thus, while robotics excels in benign hysterectomy and endometrial cancer staging, its role in cervical malignancy is now carefully restricted to specific, low-risk criteria [16].

3.3 General Surgery

While Urology and Gynecology were early adopters, General Surgery has seen the most rapid growth in robotic case volume over the last five years, particularly in abdominal wall reconstruction and complex hepatobiliary procedures.

3.3.1 Abdominal Wall Reconstruction (Hernia Repair)

The management of complex ventral and incisional hernias has been revolutionized by the robotic platform. Traditional laparoscopic repair often required traumatic fixation devices (tacks) and had limitations in closing large fascial defects. Robotic Transversus Abdominis Release (r-TAR) has emerged as a superior technique for massive hernias. By facilitating precise retro-muscular dissection and suturing of the posterior and anterior rectus sheaths, robotics allows for substantial mesh placement outside the peritoneal cavity.

In their analysis of perioperative outcomes, Carbonell et al. (2018) compared robotic repairs to open component separations [1]. The study found that while the operative time for robotic repair was on average 45-60 minutes longer, the length of stay was reduced from a mean of 5 days in the open group to just 1.8 days in the robotic group. This dramatic reduction in hospitalization- and the associated reduction in hospital costs- provides a compelling counter-argument to the high cost of robotic instrumentation. Furthermore, the study noted a drastic reduction in wound complications (surgical site infections, seromas, and dehiscence). In open hernia repair, large skin flaps are often raised, devascularizing the tissue and leading to infection rates as high as 20%. The robotic approach, utilizing small keyhole incisions to perform massive internal reconstructions, effectively eliminates this morbidity [15]. Furthermore, in the repair of inguinal hernias, systematic reviews indicate that the robotic platform may reduce chronic postoperative pain compared to conventional laparoscopic techniques [36].

3.3.2 Bariatric & Gastric Surgery

Robotic assistance is increasingly utilized for complex gastric bypass and gastrectomy. Cirocchi et al. (2013) and Bailey et al. (2014) found that in the super-obese patient population, robotics reduced anastomotic leak rates and improved suturing mechanics compared to standard laparoscopy [22, 31]. Similarly, for gastric cancer, Chen et al. (2016) reported that robotic gastrectomy facilitated the harvest of a significantly higher number of lymph nodes than laparoscopic approaches, potentially improving oncologic staging [24]. While Holtzman et al. (2011) argued that the operative costs were higher, they noted that the precision is vital for GIST resections in difficult anatomical locations [28].

3.3.3 Hepatobiliary and Pancreatic Surgery

Robotic Pancreaticoduodenectomy (Whipple procedure) represents one of the most technically demanding applications of the platform. The robotic approach offers the stability required for the delicate biliary and pancreatic reconstruction phases. Although the learning curve is steep- often cited as requiring 40-80 cases for proficiency- meta-analyses suggest that in expert hands, the robotic Whipple is associated with reduced delayed gastric emptying and shorter hospital stays compared to open surgery, with equivalent oncologic lymph node retrieval [5].

3.4 Colorectal Surgery

Colorectal surgery, specifically for rectal cancer, shares anatomical challenges with urology- working in the deep, narrow confine of the bony pelvis where visibility is limited and nerve density is high.

3.4.1 Rectal Cancer

The debate regarding the utility of robotics in colorectal surgery largely centers on the results of the ROLARR trial (Robotic vs. Laparoscopic Resection for Rectal Cancer), published by Jayne et al. In 2017 [3]. This international, multicenter, randomized controlled trial involved 471 patients and was designed to definitively answer whether the high cost of robotics was justified by clinical gains.

The primary endpoint of ROLARR was the rate of conversion to open surgery. The hypothesis was that the robot's superior maneuverability in the narrow pelvis would prevent the need for large incisions. Surprisingly, the intention-to-treat analysis showed no statistically significant difference in conversion rates between the robotic (8.1%) and laparoscopic (12.2%) groups (Odds Ratio 0.61; p=0.16). Critics frequently cite this lack of statistical significance to challenge the economic viability of the technology, arguing that the substantial increased costs of the robotic platform are unjustified in the absence of a proven reduction in conversion rates for the general patient population.

However, a deeper interrogation of the ROLARR data, as performed in subsequent sub-analyses [8], reveals the „learning curve effect." Many surgeons participating in the ROLARR trial were highly experienced laparoscopists but were still in the early-to-mid phase of their robotic learning curve. When the data is stratified by surgeon experience and patient complexity (e.g., male patients with narrow pelves and high BMI), the robotic advantage becomes statistically apparent. Furthermore, the robotic group demonstrated a significantly lower rate of bladder dysfunction and sexual dysfunction post-operatively, confirming the „nerve-sparing" advantage proposed by early adopters [21]. Despite the ROLARR findings, other major trials like COLOR II have established the baseline safety of minimally invasive approaches [34]. Meta-analyses by Truin et al. (2017) further suggest that for TME, robotics significantly lowers the rate of conversion to open surgery compared to laparoscopy [32].

3.4.2 Right Colectomy and Intracorporeal Anastomosis

For right-sided colonic procedures, the benefit is arguably less about access and more about reconstruction. Intracorporeal anastomosis (ICA) is technically challenging via straight-stick laparoscopy, often leading surgeons to extract the bowel and perform the connection extracorporeally. Robotics facilitates ICA, which has been linked to faster recovery of bowel function (less traction on the mesentery) and lower incision-related hernia rates because the extraction site can be smaller and placed in a less stress-bearing location [18].

Functional Disorders: Beyond cancer, robotics has shown utility in functional repairs. Flynn et al. (2021) demonstrated that robotic ventral rectopexy for rectal prolapse is safe and effective, offering improved ergonomic angles for suturing in the deep pelvis [9].

3.5 Thoracic Surgery

Robotic-Assisted Thoracic Surgery (RATS) is rapidly displacing Video-Assisted Thoracic Surgery (VATS) for lung cancer treatment.

3.5.1 Lobectomy and Nodal Upstaging

The primary advantage of RATS over VATS is the manipulation of the hilar structures. Dissecting the pulmonary artery branches and performing mediastinal lymph node dissection is safer with the fine articulation of robotic instruments. A large-scale propensity-matched study using the STS General Thoracic Surgery Database, analyzed by Oh et al. (2017), showed that RATS lobectomy was associated with improved lymph node upstaging compared to VATS [14]. Accurate staging is critical for determining the need for adjuvant chemotherapy, suggesting that RATS may offer an oncologic advantage by facilitating a more thorough lymphadenectomy.

Furthermore, long-term survival data published by Cerfolio et al. (2018) demonstrated that robotic lobectomy achieves 5-year survival rates comparable to open thoracotomy, but with significantly reduced perioperative morbidity and pain [6].

From a financial perspective, Sheet et al. (2019) noted that while RATS supplies are more expensive, the procedure is cost-effective for early-stage lung cancer when accounting for the shorter length of hospital stay [10].

4. Procedural standards

To understand the clinical outcomes described previously, it is necessary to examine the technical execution of these complex procedures. Unlike open surgery, where exposure is achieved via retraction, or laparoscopy, where exposure is dynamic and assistant-dependent, robotic surgery relies on a static, surgeon-controlled environment. The following subsections detail the standardized technical steps for the two most representative procedures in adult robotic surgery: Radical Prostatectomy and Ventral Hernia Repair.

4.1 Robot-Assisted Radical Prostatectomy (RARP)

The RARP procedure is typically performed using a transperitoneal approach, although extraperitoneal approaches exist. The patient is placed in a steep Trendelenburg position (approximately 25–30 degrees) to allow the bowel to gravitate cephalad, exposing the pelvic cul-de-sac.

4.1.1 Port placement and docking

The standard configuration for the da Vinci Xi system involves a linear port placement. The camera port (8mm) is placed supra-umbilically. Three robotic arm ports (8mm) are placed spaced 6–8 cm apart along the same horizontal line, with one assistant port (12mm) placed laterally for suction and suture introduction. A critical technical evolution in the Xi platform is the „boom" rotation, allowing the patient-side cart to dock from the side, facilitating easier anesthesia access to the head.

4.1.2 Step-by-step dissection

Bladder Drop: The procedure begins with the incision of the parietal peritoneum to mobilize the bladder. The space of Retzius is entered, and the fat overlying the prostate is removed to expose the endopelvic fascia.

Bladder Neck Transection: This is a crucial step for preserving urinary continence. The surgeon identifies the demarcation between the bladder detrusor muscle and the prostate. Using the robotic monopolar scissors, the bladder neck is transected, preserving the circular muscle fibers. The posterior lip is dissected to expose the seminal vesicles.

Seminal Vesicle and Vas Deferens Release: The vas deferens are transected, and the seminal vesicles are dissected free from the posterior bladder aspect. This exposes the Denonvilliers' fascia.

Neurovascular Bundle Preservation: This is the step where robotic magnification (10x) is most critical. Using an athermal technique (avoiding cautery to prevent nerve damage), the surgeon separates the cavernous nerves (responsible for erection) from the prostate capsule. This is often referred to as the „Veil of Aphrodite" technique. The high-definition 3D view allows for the visualization of microscopic nerve fibers that would be invisible to the naked eye.

Apical Dissection and Urethral Transection: The apex of the prostate is dissected, maximizing urethral length to ensure future continence. The urethra is transected, and the prostate is placed in an retrieval bag.

Vesico-Urethral Anastomosis: The reconstruction of the urinary tract is performed using a running barbed suture (e.g., V-Loc). The robotic dexterity allows for a watertight anastomosis, typically tested by filling the bladder with 200ml of saline.

4.2 Robotic Transversus Abdominis Release (r-TAR)

For large ventral hernias (defect width >10 cm), a simple suture closure is insufficient due to high tension. The r-TAR technique allows for the release of lateral muscle tension, enabling the closure of the fascia and the placement of a massive sublay mesh.

4.2.1 Access and setup

The patient is positioned supine with arms tucked. The robotic ports are typically placed in a lateral configuration (flank approach) on the side opposite to the initial dissection. The da Vinci system's „targeting" feature allows the boom to align automatically with the hernia defect.

4.2.2 Procedural sequence

Retromuscular Space Entry: An incision is made in the posterior rectus sheath. The surgeon dissects the space behind the rectus muscle but in front of the posterior sheath/peritoneum. This creates a „tunnel" extending from the costal margin to the pubis.

The TAR Maneuver: Upon reaching the linea semilunaris (the lateral edge of the rectus muscle), the surgeon identifies the neurovascular bundles perforating the muscle. Just medial to these nerves, the Transversus Abdominis muscle is incised. This releases the tension on the posterior fascia, allowing it to be mobilized medially.

Contralateral Crossover: One of the unique capabilities of the robotic platform is the ability to work „up to the ceiling." The surgeon dissects across the midline (pre-peritoneal crossover) to access the other side of the abdomen without making a second skin incision for ports, a maneuver that is ergonomically extremely difficult in standard laparoscopy.

Posterior Closure and Mesh Placement: The posterior rectus sheaths are sutured together to isolate the bowel from the mesh. A large macroporous mesh is then deployed in the retro-rectus space. Because the mesh is placed outside the peritoneal cavity, it does not come into contact with the intestines, significantly reducing the risk of adhesions and bowel erosion.

Anterior Fascial Closure: Finally, the anterior fascia (the strength layer) is re-approximated over the mesh, restoring the functional abdominal wall.

5. Discussion

The synthesis of data from the mentioned specialties illustrates a clear trajectory: robotic surgery is transitioning from a „marketing tool" to an evidence-based necessity for complex pathologies. Several key themes emerge from the literature regarding the significance of this shift.

5.1 Surgical innovation

Historically, the conversation around surgical innovation focused solely on the patient. However, the sustainability of the surgical workforce is essential. Conventional laparoscopy is physically taxing; a survey of laparoscopic surgeons revealed that over 70% report work-related musculoskeletal symptoms due to the „straight-stick" fulcrum effect and non-ergonomic monitor positions.

RAS addresses this directly. The seated console, supported forearms, and 3D stereoscopic vision reduce physical fatigue and eye strain. A randomized controlled trial by Zihni et al. (2018) compared the physical workload of surgeons performing simulated tasks robotically versus laparoscopically. The study found significantly lower electromyographic (EMG) activity in the trapezius and deltoid muscles during robotic tasks [12]. By preserving the physical health of the surgeon, RAS potentially extends careers and maintains high-level performance during long, complex cases (e.g., multi-quadrant surgeries), which indirectly benefits patient safety. Pineda-Solorio et al. (2022) emphasize that these ergonomic benefits are critical for preventing career-ending injuries in high-volume surgeons [30].

5.2 The economics

No review of robotic surgery is comprehensive without addressing the financial implications. The criticism that RAS is „prohibitively expensive" is well-documented in the literature. Barbash and Glied (2010) estimated that performing a procedure robotically adds approximately $1,600 to $2,500 to the direct cost of the case compared to conventional laparoscopy, primarily driven by the amortization of the $2 million system and the use of disposable instruments (limited to 10 lives) [37].

However, this „per-case" accounting method is increasingly viewed as antiquated. A more sophisticated analysis involves the „Total Episode of Care" model. Kelles et al. (2021) conducted a systematic review of cost-effectiveness and found that when complications and readmissions are factored into the equation, the cost disparity narrows or reverses [29]. For example, a single surgical site infection (SSI) following an open colorectal resection can cost a hospital system upwards of $30,000 in readmission care, antibiotics, and wound management. By reducing the SSI rate from 15% (open) to <5% (robotic), the health system realizes savings that offset the initial instrument costs.

Furthermore, the societal cost- measured in „Return to Work" time- favors robotics. Patients undergoing robotic prostatectomy or hysterectomy typically return to the workforce 2-3 weeks earlier than those undergoing open surgery. While this economic benefit does not appear on a hospital's balance sheet, it represents a significant preservation of productivity for the broader economy.

5.3 Training

The rapid diffusion of robotic technology has created a pressing need for standardized credentialing. Unlike open surgery, where a resident learns by assisting for years, robotic surgery separates the trainee from the patient. This has necessitated the development of „dual-console" systems, where a mentor can take control of the instruments instantly, similar to a driving instructor with a secondary brake pedal [25].

The role of virtual reality (VR) simulation has also become central to robotic training. Studies have shown that proficiency in VR drills (such as needle driving and clutch control) correlates strongly with intraoperative performance. However, a major controversy remains: How many cases define competence? The „learning curve" varies by procedure; literature suggests it may be as low as 20 cases for simple prostatectomy but exceed 80 cases for complex pancreaticoduodenectomy. The lack of a universal consensus on credentialing thresholds (some hospitals require 5 proctored cases, others 20) remains a significant gap in surgical governance that future guidelines must address [21].

5.4 Limitations

Despite the benefits, RAS is not a universal solution for all surgical problems. It offers little benefit for simple, short-duration procedures (e.g., uncomplicated appendectomy) where the setup time and cost outweigh the marginal gains. Furthermore, the lack of haptic feedback (tactile sense) remains a limitation, forcing surgeons to rely on „visual haptics" (seeing tissue deformation) to judge tension.

6. Future horizons

As we move further into the 21st century, the definition of robotic surgery is expanding. The initial phase of „master-slave" manipulation- where the robot simply mimics the surgeon's hands-is concluding. We are now entering the era of „Digital Surgery," defined by the integration of Artificial Intelligence (AI), Augmented Reality (AR), and advanced connectivity [38].

6.1 Artificial Intelligence

The current generation of surgical robots generates a massive amount of kinematic and video data that, historically, has been discarded after the procedure. Future platforms will utilize this data to train Machine Learning (ML) algorithms.

Computer Vision and Safety: AI algorithms are being developed to identify critical anatomical structures in real-time. For example, during a robotic cholecystectomy (gallbladder removal), the system could overlay a „no-fly zone" warning on the surgeon's screen if the instrument approaches the Common Bile Duct or the hepatic artery, potentially preventing catastrophic injuries.

Performance Metrics: Currently, assessing a surgeon's skill is subjective. AI-driven platforms like the Da Vinci SimNow or independent analytics software (e.g., C-SATS) can now analyze video to track instrument path efficiency, smoothness of motion, and idle time. This provides objective „performance report cards," allowing surgeons to benchmark their technique against global experts and identify specific steps where they are inefficient [39].

6.2 Augmented Reality (AR)

One of the significant limitations of current surgery is the disconnect between preoperative imaging (CT/MRI) and the intraoperative view. The surgeon must mentally reconstruct the 3D location of a tumor based on 2D scans viewed on a separate wall monitor.

Emerging AR technologies seek to bridge this gap by performing „Image Fusion." By importing the patient's CT scan into the robotic console, the system can create a 3D hologram of the tumor and vascular anatomy that is superimposed directly onto the live surgical video. For instance, during a partial nephrectomy for a deep renal tumor, the surgeon could „see through" the surface of the kidney to identify exactly where the tumor margins lie and where the major arteries are located. This technology, often referred to as „TilePro" or „Firefly" in current iterations (utilizing fluorescence), is evolving into fully immersive 3D navigation [40].

6.3 Telesurgery

As mentioned in the historical overview, the dream of remote surgery was initially stalled by latency issues. However, the rollout of 5G telecommunication networks has reignited interest in this field. 5G offers ultra-low latency (less than 10 milliseconds) and high bandwidth, theoretically allowing a surgeon in a major academic center to operate on a patient in a rural hospital hundreds of miles away.

Recent experimental trials in 2019 and 2020 successfully demonstrated remote robotic surgeries over 5G networks in animal models and selected human cases in China and Italy. While regulatory, legal, and cybersecurity hurdles remain immense, the technological barrier has largely been overcome. This has profound implications for global health equity, potentially allowing expert surgical care to reach underserved populations without the need for patient transport [41].

6.4 Cost reduction

Finally, the future of RAS will be defined by market competition. For twenty years, Intuitive Surgical held a virtual monopoly. The recent entry of new competitors- such as Medtronic's Hugo RAS system, CMR Surgical's Versius, and Johnson & Johnson's Ottava- is expected to drive innovation and, crucially, drive down costs.

These new platforms offer different modular designs. For example, the Versius system uses independent bedside arms that can be moved between operating rooms, rather than a single massive cart. This modularity appeals to smaller hospitals with limited space and budget. As competition increases, the „per-procedure" cost of consumables is expected to decrease, removing the single largest barrier to the universal adoption of robotic surgery in the adult population.

6.5 Force feedback technology

While the lack of haptic feedback has historically been a major limitation of RAS, 2025 marked a significant shift with the clinical validation of the da Vinci 5 system. Unlike previous generations, this platform integrates Force Feedback technology, allowing surgeons to sense tissue tension in real-time. A 2025 study by Kneuertz et al. Analyzed the first year of this technology's clinical use and confirmed that „FFB technology is associated with reduced average and peak instrument forces [...] particularly at medium and high settings" [42]. This clinical data validates earlier pre-clinical findings suggesting that force feedback can reduce tissue trauma by up to 43%, marking the end of the era of relying solely on „visual haptics."

7. Conclusions

The evolution of Robotic-Assisted Surgery represents one of the most significant shifts in the history of adult surgical care. As this review has demonstrated, the platform has successfully transcended its initial novelty to become a proven, indispensable tool across multiple subspecialties.

The data consistently supports the conclusion that while robotic surgery may incur higher immediate operative costs, it offers substantial downstream value. By reducing surgical trauma, RAS facilitates faster recovery, decreases length of hospital stay, and minimizes complications such as blood loss and infection. In urology, it has already established itself as the gold standard for prostatectomy. In general, colorectal, and thoracic surgery, it is rapidly expanding the boundaries of what is possible via a minimally invasive approach, particularly for high-risk and obese patient populations who were previously relegated to open surgery.

As we look to the future, the focus must shift from merely proving safety to optimizing training and cost-efficiency. The integration of artificial intelligence, advanced imaging, and competitive platforms will likely improve the access to this technology. For the modern adult patient, the robotic interface provides the precision of a machine guided by the judgment of a surgeon, offering the best chance for a curative outcome with minimal disruption to quality of life.

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Aleksandra Góralska- visualization
Aleksandra Kozłowska- stylistic correctness
Zuzanna Butkowska- proof-reading and editing
Natalia Nowak- review, investigation
Łucja Komisarczyk- editing, supervision
Tadeusz Kornela- stylistic correctness
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All authors read and approved the final manuscript.
Conflict of interest: The authors declare that there is no conflict of interest.
Funding: This study has not received any external funding.

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