MAŁACHOWSKI, Aleksander, WÓJCIK, Jakub, BŁASZCZAK, Ewa, WÓJCIK, Bartlomiej, MIKOŁAJCZYK, Oskar, SUCHOŁBIAK, Aleksandra, JUCHA, Hubert, ŻAK, Katarzyna and SAŁATA, Julia. Increasing Role of Robotic-assisted Surgery in Children: Literature Review. *Journal of Education, Health and Sport*. 2025;86:66908. eISSN 2391-8306.
https://doi.org/10.12775/JEHS.2025.86.66908
https://apcz.umk.pl/JEHS/article/view/66908

The journal has had 40 points in Minister of Science and Higher Education of Poland parametric evaluation. Annex to the announcement of the Minister of Education and Science of 05.01.2024 No. 32318. Has a Journal's Unique Identifier: 201159. Scientific disciplines assigned: Physical culture sciences (Field of medical and health sciences); Health Sciences (Field of medical and health sciences).
Punkty Ministerialne 40 punktów. Załącznik do komunikatu Ministra Nauki i Szkolnictwa Wyższego z dnia 05.01.2024 Lp. 32318. Posiada Unikatowy Identyfikator Czasopisma: 201159. Przypisane dyscypliny naukowe: Nauki o kulturze fizycznej (Dziedzina nauk medycznych i nauk o zdrowiu); Nauki o zdrowiu (Dziedzina nauk medycznych i nauk o zdrowiu). **© The Authors 2025;**
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The authors declare that there is no conflict of interests regarding the publication of this paper.
Received: 26.11.2025. Revised: 08.12.2025. Accepted: 08.12.2025. Published: 12.12.2025.

Increasing Role of Robotic - assisted Surgery in Children: Literature Review

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Introduction:

This article evaluates the current state of robotic surgery in pediatrics. Since the early 21st century, robotic-assisted surgery has gained increasing prominence in this field. Since the introduction of the da Vinci surgical system (Intuitive Surgical, Sunnyvale, CA, USA) and its initial application in pediatric surgery in 2001 [1], the role of robotics in children's surgery has expanded steadily across multiple specialties. Among these, pediatric urology has emerged as the most active and well-documented field, making it an ideal reference point for evaluating the broader impact of robotic technology in pediatric surgery.

Robotic-assisted surgery has transformed minimally-invasive procedures by overcoming the limitations of traditional laparoscopy, such as restricted dexterity, a steep learning curve, and two-dimensional visualization [2–4]. The da Vinci Surgical System introduced three-dimensional imaging, tremor filtration, motion scaling, and enhanced instrument articulation, leading to greater precision and control [5–6]. These advancements have contributed to a shorter learning curve for robotic-assisted surgery, as its intuitive motion mimics natural hand movements, unlike laparoscopy, which requires inverted instrument handling [7]. Additionally, the system's ergonomic design reduces surgeon fatigue, further increasing its appeal in clinical practice [8–9]. The broader application of robotic surgery across specialties including urology, gastrointestinal, and gynecologic surgery, has helped establish it as the gold standard for many procedures and contributed to its continued expansion [4–5].

Robots' assistance in children offers several advantages, particularly in complex reconstructive procedures [10]. The robotic platform's enhanced articulation and motion scaling allow for greater precision in small anatomical spaces, which is beneficial in pediatric urology [4,7]. However, significant challenges remain, as the larger size of robotic instruments and the required port spacing make their use difficult in neonates and infants [9]. Additionally, the high cost of robotic platforms and maintenance limits widespread adoption, especially in pediatric hospitals with a lower volume of eligible patients [6]. Nonetheless, robotic surgery in pediatrics continues to evolve, with ongoing adaptations to improve its feasibility and accessibility.

Although pediatric robotic surgery initially lagged behind its adoption in adult populations, it has seen steady growth in recent years, particularly in urology. The first reported case of robotic-assisted surgery in pediatric urology dates back to 2002 [3]. Today, pediatric urology represents the most active field within pediatric robotic surgery, accounting for over half of cases and associated literature [6]. The widespread adoption of robotic-assisted surgery in this specialty has led many centers to establish it as the standard of care, often replacing open surgery due to its advantages in precision and recovery [2,10]. Among the most performed robotic procedures in pediatric urology, pyeloplasty and ureteral reimplantation account for the majority, with other procedures varying by institution [4–5].

This trend highlights the increasing role of robotic technology in pediatric urology and sets the stage for further discussion on its impact and future developments; thus, this review uses it as the primary lens to examine the current state and role of robotic-assisted surgery in children.

Methods:

To conduct this review, multiple electronic databases, including PubMed, MEDLINE, and Google Scholar, were independently searched between December 7th and 10th, 2024 to identify relevant literature on robotic surgery in pediatric urology. The search strategy employed Boolean operators "AND" and "OR" to combine the following key terms in various combinations: "robotic," "surgery," "pediatric," "urology," "children," "minimally invasive," "robot-assisted," "robotic-assisted," "RAS," "laparoscopic", "versus" and "open". No language restrictions were applied. The inclusion criteria encompassed studies involving pediatric patients under 18 years of age, published within the last five years (2020–2024), to reflect the current state of the field. Preference was given to major studies such as meta-analyses and systematic reviews. Commentaries, editorials, short notes, letters to the editor and repeat publications were excluded from consideration. All extracted abstracts and titles were screened for relevance. Discrepancies in study selection were resolved through consensus among the reviewers. This review aims to synthesize the current evidence on robotic-assisted surgery in pediatric urology, focusing on its efficacy, advantages, limitations, and future implications in the field.

Results:

The search yielded 93 articles, of which 47 were included in the review. The selected literature was analyzed to assess the current state of robotic surgery in pediatric urology with an emphasis on parameters such as surgical success rates, complication rates, operative times, length of hospital stay, conversion rates, costs, and learning curves. The comparative outcomes of robotic-assisted, laparoscopic, and open surgical techniques were also assessed for select procedures. The selected studies were grouped into the following chapters. Given that the majority of studies focus on the two most performed robotic-assisted procedures in pediatric urology: pyelopasty and ureteral reimplantation, each will be analyzed in dedicated chapters. The next chapter will examine other robotic procedures in the field. Additionally, there have also been a few studies that tackle the robotic systems themselves and advancements in the technical aspects of robot-assisted surgery, which will be explored in a separate chapter. Finally, broader considerations including anesthetic, ethical, and economic perspectives of robot-assisted surgery were included to provide a more comprehensive overview of the topic.

Keywords: Robotic-assisted surgery, pediatric surgery, Pyeloplasty, ureteral reimplantation, image-guided surgery, da Vinci surgical system

Pyeloplasty:

Robot-assisted laparoscopic pyeloplasty (RALP) has emerged as one of the most transformative advancements in pediatric urology [2,11]. Primarily indicated for ureteropelvic junction obstruction (UPJO), RALP aims to relieve obstruction, preserve renal function, and prevent progressive hydronephrosis and infections [12]. Historically dominated by open surgical techniques, the treatment landscape has shifted dramatically with the advent of minimally invasive approaches.

RALP now competes with, and in many scenarios surpasses, open and conventional laparoscopic pyeloplasty [13], especially in centers with advanced robotic platforms and trained personnel. Its precision, enhanced visualization, and faster recovery times have made it a preferred option not only for standard cases but also for complex anatomical situations and reoperations [14].
RALPs adoption is facilitated by a relatively short learning curve. Proficiency is typically achieved after 15 to 40 cases, notably faster than traditional laparoscopic pyeloplasty [15]. Several factors contribute to this acceleration, including intuitive controls and improved visualization, which ease the technical demands of suturing [16]. Simulation-based training has further supported skill acquisition, enabling surgeons to practice complex tasks in risk-free environments.

Clinical Effectiveness and Safety:
Extensive clinical evidence supports the high efficacy and safety of RALP in pediatric populations. Success rates consistently exceed 90%, with some studies reporting rates as high as 97.8% [12,15,17]. Complication rates remain low and are predominantly minor, [13,16]. A large single-center study involving 327 patients reported a success rate of 94.2%, noting that most reoperations occurred within the first postoperative year, underscoring the durability of outcomes [17]. Hospital stays after RALP are notably brief. Many studies report an average stay of just 1 to 2 days, significantly shorter than traditional methods [15,18]. This shorter hospitalization not only benefits the patient and family but also reduces healthcare costs and resource utilization.

RALP in infants:
Initially, the use of RALP in infants raised concerns due to limited working space and the fragility of pediatric tissues [2]. However, current evidence dispels these worries. Studies confirm that RALP is both feasible and safe in children under one year old, maintaining high success rates comparable to older populations [12–13]. Notably, a dedicated infant cohort study reported a 96% success rate with RALP compared to 91% with LP, along with shorter hospital stays and a manageable learning curve for surgeons [19]. These outcomes affirm that, with appropriate training and adapted equipment, RALP is a viable option even for the youngest patients.

RALP in Complex Cases and Reoperations:
RALP offers clear benefits in complex anatomical scenarios and reoperations. Its enhanced 3D visualization reduces the risk of missing crossing vessels, a common cause of surgical failure [20]. Although technically more challenging, redo RALP cases show excellent outcomes, with success rates of 90% or higher and significant postoperative improvements in hydronephrosis [12,14]. Operative times tend to be longer compared to primary procedures, but functional outcomes and hospital stays are comparable [11]. These findings solidify RALP as the preferred choice for salvage surgeries and complex UPJO cases requiring precise anatomical dissection.

Comparison to Open and Laparoscopic Approaches:
While open pyeloplasty (OP) has historically been considered the gold standard, especially for infants, RALP has proven to be a formidable alternative. Although OP generally offers shorter operative times due to direct access and familiarity [13,21], RALP matches or surpasses OP in success rates while offering advantages such as reduced hospital stay and improved cosmetic outcomes [7,16,22]. Compared to conventional laparoscopic pyeloplasty, RALP provides superior ergonomics and easier suturing, which translates to better surgeon comfort and potentially fewer errors [23]. RALPs minimally invasive nature, combined with its technological benefits, positions it as an increasingly preferred choice, particularly in well-equipped, high-volume centers [11,14].

Outpatient feasibility:
A significant recent advancement is the successful implementation of outpatient RALP protocols. Select centers have demonstrated safe same-day discharge for retroperitoneal RALP (R-RALP), with low complication rates and high parental satisfaction [18]. The retroperitoneal approach offers specific advantages that make it particularly well-suited for outpatient surgery. By avoiding entry into the peritoneal cavity, this technique minimizes gastrointestinal disturbances and reduces postoperative pain, contributing to a faster recovery and early mobilization. In the French study of 32 children undergoing R-RALP, 84% were safely discharged the same day, with a median hospital stay of just 12.7 hours [18]. Importantly, there were no readmissions, and only two children required emergency department visits without subsequent hospitalization. This aligns with broader healthcare goals of minimizing inpatient stays and enhancing patient and family experiences, while also improving hospital efficiency [24]. The growing success of outpatient RALP highlights its role in advancing patient-centered, efficient surgical care pathways.

Ureteral Reimplantation:
Robotic-assisted laparoscopic ureteral reimplantation (RALUR) has emerged as a transformative technique in pediatric urology, offering a minimally invasive solution for managing vesicoureteral reflux (VUR) and complex ureteral anomalies [25]. Once considered controversial due to early mixed outcomes, more recent multicenter studies and systematic reviews have established RALUR as a safe and effective procedure [2,11]. Indications for RALUR include high-grade VUR, primary obstructive megaureter, and complex ureteral anatomy unresponsive to conservative or endoscopic treatments [26–28]. Particularly in pediatric populations, where delicate anatomy and reduced postoperative morbidity are paramount, RALUR represents a promising evolution in surgical management [29]. Its utility extends beyond primary cases to reoperations and anatomically challenging scenarios [30].

Extravesical approach:
The extravesical (EV) approach has become the dominant technique in robotic-assisted ureteral reimplantation, largely due to its favorable balance of safety, efficacy, and technical advantages in pediatric patients [10]. By avoiding entry into the bladder, the EV method minimizes the risk of bladder-related complications and supports smoother postoperative recovery.

Multiple reviews have emphasized the consistent success of this approach, highlighting its role as the preferred method in robotic pediatric urology [25,27,29]. The EV approach benefits significantly from the enhanced precision and visualization afforded by robotic platforms. These technical advantages are particularly important in the narrow pelvic space of children, allowing for meticulous dissection and reduced tissue trauma [31]. Additionally, the EV technique is associated with a shorter learning curve compared to traditional laparoscopic surgery, making it an accessible option for surgeons as robotic experience increases [29].

Success Rates, Complications, and Hospitalization Times:
RALUR consistently demonstrates high success rates in the pediatric population [29]. A comprehensive review of over 1,300 children undergoing RALUR-EV procedures reported an overall success rate of 92.2%, reinforcing the effectiveness of robotic techniques in managing vesicoureteral reflux [25]. Complication rates are generally low, with most studies reporting either no perioperative complications or only minor events, emphasizing the favorable safety profile of RALUR [29–30]. These findings are consistent across both larger series and smaller cohorts, which further support the safety of robotic approaches in pediatric urology [26]. Hospitalization times are likewise favorable, with large reviews reporting mean stays of approximately 1.9 days, reflecting the minimally invasive nature of RALUR and its contribution to faster recovery and earlier discharge [25].

Comparison to Open Approaches:
When comparing RALUR to traditional open ureteral reimplantation, available data suggest meaningful advantages favoring the robotic approach. In a multicenter European study, RALUR demonstrated a slightly higher success rate of 98.5% compared to 94% for open surgery, alongside a markedly shorter hospital stay (2 vs. 5 days) and a faster postoperative recovery, including shorter time to stool and fewer catheter days [27]. Operative times were slightly longer in the RALUR group (120 minutes vs. 100 minutes), reflective of both the technical complexity and the learning curve associated with robotic procedures. Complication rates were comparable between the two approaches, underscoring the safety of RALUR in experienced hands. Other reviews have similarly noted that RALUR offers lower morbidity and improved recovery profiles compared to open procedures, supporting its growing preference in many centers [10,29].

Other Robotic Procedures in Pediatric Urology:
Beyond the well-established role of robotic surgery in pyeloplasty and ureteral reimplantation, the field has rapidly expanded its repertoire of robotic-assisted procedures. From reconstructive surgeries to precision-enhancing technologies like ICG fluorescence, robotic systems now offer versatile solutions tailored to the pediatric population. This chapter highlights selected procedures that reflect the breadth and potential of robotic surgery in pediatric urology.

Reconstructive Procedures for Neurogenic Bladder:
Robotic surgery is gaining traction in complex reconstructions for children with neurogenic bladder. Robot-assisted augmentation ileocystoplasty and Mitrofanoff appendicovesicostomy (RALIMA) offer minimally invasive alternatives to traditional open surgery, with comparable functional outcomes and faster recovery [10]. In one series, robotic augmentation showed a mean increase in bladder capacity of 244% and reduced postoperative pain compared to open surgery [32]. A separate comparative analysis of robotic versus open appendicovesicostomy (APV) found similar complication rates between approaches, but notably shorter hospital stays in the robotic group: just 2.6 days versus 9.3 days for open surgery [33]. Additionally, the first purely robotic ileocystoplasty performed in Spain demonstrated the feasibility of fully robotic execution, with excellent continence outcomes maintained over a 32-month follow-up [34].

Salvage and Complex Upper Tract Reconstruction:
In difficult cases such as recurrent ureteropelvic junction obstruction or failed pyeloplasty, robotic ureterocalycostomy offers a valuable salvage option [35]. Unlike standard pyeloplasty, this technique bypasses the scarred renal pelvis by connecting the ureter directly to a dependent renal calyx. Studies report high success rates, with all patients in one case series achieving anatomical success at over four years of follow-up [35]. A large multicenter study comparing ureterocalycostomy (robotic and laparoscopic) to pyeloplasty in 130 patients confirmed that ureterocalycostomy is an effective alternative, especially in complex cases and salvage settings, with surgical success rates of 100% for this group [36].

ICG Fluorescence Imaging in Robotic Surgery:
Indocyanine Green (ICG) fluorescence imaging, coupled with near-infrared (NIR) technology, has emerged as an important adjunct in robotic-assisted pediatric urology. This technique allows for real-time, intraoperative visualization of critical anatomical structures, including blood vessels, lymphatics, and areas of pathology, thus significantly enhancing surgical accuracy and safety [37]. Across various robotic pediatric procedures, such as pyeloplasty, nephrectomy, partial nephrectomy, varicocelectomy, and renal cyst removal, ICG imaging has demonstrated clear advantages, such as reduced blood loss, enhanced lymphatic preservation, minimized complications, and reduced conversion rates to open surgery [38]. The growing evidence base, including multiple large series, confirms its efficacy, ease of use, and safety profile, establishing ICG fluorescence imaging as a valuable component of advanced pediatric robotic surgical care [37-40]. Among the procedures included in this review, partial nephrectomy and varicocelectomy were explicitly reported to benefit from ICG fluorescence, underscoring its utility in improving surgical precision and outcomes.
Robotic-assisted partial nephrectomy (RALPN) has emerged as a safe and effective method for managing duplex systems and non-functioning renal segments in children [10]. Operative times ranged from 135 to 301 minutes, with success rates as high as 100% in some reports, and no conversions to open surgery were noted [39]. The integration of technologies like ICG fluorescence mapping, further enhances surgical precision. It facilitates the identification and preservation of functional renal segments, thereby reducing blood loss and helping to preserve renal function.

Varicocelectomy is one of the most common procedures in pediatric urology, particularly in adolescents with symptomatic varicocele or testicular hypotrophy. Robotic-assisted varicocelectomy offers precision and is particularly suited for lymphatic-sparing techniques using ICG fluorescence [40]. ICG allows for real-time visualization of lymphatic vessels, which enables surgeons to avoid lymphatic injuries, preventing postoperative hydrocele [37]. In a large series, most patients were discharged the same day, with a median operative time of 48 minutes [41]. However, comparative studies show that laparoscopic varicocelectomy maintains advantages in operative time, cosmetic outcomes, and cost-effectiveness, with robotic procedures costing over three times more [40].

Emerging Applications:

While the procedures listed above comprise the majority of applications for robotic surgery in pediatric urology, several emerging procedures are being explored with promising results.

Robotic-assisted kidney transplantation (RAKT) represents an exciting frontier, with early reports showing excellent graft function, favorable recovery, and promising outcomes in select pediatric patients [42]. Though currently limited to highly specialized centers, RAKT reflects the ongoing innovation and potential of robotic systems to expand into complex, traditionally open surgeries. Other reported applications include robotic-assisted urolithiasis surgery, particularly in children with complex anatomy or large stone burdens. While literature remains limited, initial series show high stone-free rates with low complication profiles when combined with endoscopic techniques [11]. Robotic orchiopexy has also been explored for non-palpable testes, offering improved precision and visualization, particularly in cases requiring vessel ligation or mobilization. Early studies report zero conversions and no testicular atrophy in follow-up, supporting its feasibility in experienced hands [11]. As experience and technology continue to evolve, these less common procedures may become more widely adopted, further broadening the scope of robotic-assisted surgery in pediatric urology.

Newly Introduced Robotic Systems:

The evolution of robotic surgery in pediatric urology has progressed from early multiport platforms to increasingly refined systems that better accommodate pediatric anatomy and surgical needs. The da Vinci SP, introduced in 2018 as the fourth generation of Intuitive Surgical's platforms, represents a shift toward single-incision surgery, utilizing a 2.5 cm cannula that houses three articulating instruments and a fully wristed 3D camera [43]. It has been successfully applied in pediatric pyeloplasty, nephroureterectomy, and appendicovesicostomy, offering comparable or shorter operative times than traditional multiport systems (for example, 2.4 vs. 3.0 hours in pyeloplasty) while maintaining similar complication rates and improving cosmetic outcomes [43]. However, the system's off-label status in children, the requirement for a 10 cm working distance, and high acquisition costs limit its accessibility, particularly in non-academic or freestanding pediatric hospitals.

The Senhance system, presented by Asensus Surgical in 2020, has demonstrated initial feasibility in pediatric patients with its successful use in a 1.5-year-old undergoing robotic pyeloplasty [44].

The system features haptic feedback, infrared eye-tracking, and 5 mm instruments, which provide improved precision and ergonomics in small anatomical spaces. The procedure was completed without complications, and follow-up at six months confirmed normal renal function and no recurrence, though broader validation is needed to confirm safety and reproducibility in larger cohorts [44].

The Versius system, designed by CMR Surgical in 2020, offers a modular, compact robotic architecture and laparoscopy-style port placements, aiming to reduce the learning curve for surgeons while maintaining high instrument dexterity [45]. Its 5 mm articulated instruments make it a strong candidate for pediatric procedures, and preclinical data suggest benefits in cosmesis, postoperative pain, and hospital stay durations. However, despite its promising design, the system has not yet been clinically applied in children, and regulatory approval for pediatric use remains pending [45].

These emerging technologies reflect a broader shift toward miniaturization, surgeon-centric design, and patient-centered outcomes in pediatric robotic surgery. However, their successful integration into routine practice will depend on overcoming significant hurdles, including regulatory approval, cost-effectiveness, and institutional resource disparities. Most critically, large-scale, comparative pediatric studies and long-term outcome data are needed to guide adoption, optimize training, and ensure that these advanced systems truly improve the quality of care in pediatric urology.

Anesthetic, Ethical, and Economic Considerations:

While previous chapters have examined in detail the technical advancements and training required for robotic surgery in pediatric urology, it is equally important to consider broader factors that shape the field. Anesthetic management, ethical oversight, and economic implications are important in understanding the current and future state of robotic surgery in children.

Anesthetic Challenges:

Robotic surgery presents specific anesthetic demands, especially in pediatric patients. The physiological effects of CO_2 insufflation, necessary for pneumoperitoneum, along with the steep positioning required for optimal surgical access, present significant challenges to ventilation and hemodynamic stability in children [46–47]. Prolonged operative times and limited physical access to the patient once the robot is docked further complicate anesthetic management.

To address these risks, pediatric anesthesiologists have adopted tailored strategies such as lower insufflation pressures, dual antiemetic prophylaxis to mitigate postoperative nausea, and local anesthetic infiltration to reduce opioid requirements [46]. Despite these efforts, there remains a notable gap: the absence of standardized anesthetic protocols specifically for pediatric robotic surgery. Enhanced Recovery After Surgery (ERAS) protocols show early promise in improving outcomes, but broader validation and implementation are needed [2] [47].

Ethical and Regulatory Considerations:

Ethical concerns arise from using robotic systems not specifically designed for pediatric patients [48]. This mismatch restricts surgical precision and prompts important questions about the ethical use of technology not originally intended for children. Frameworks such as the ETHICAL model have been proposed to guide responsible innovation, emphasizing robust institutional oversight, transparent reporting of outcomes, and meaningful informed consent, particularly in pediatric contexts where parents must make complex decisions on behalf of their children [48]. Balancing the promise of surgical advancement with patient safety and ethical responsibility is essential to maintaining trust and integrity in the field.

Economic Impact and Cost Consideration

The economic burden of robotic surgery remains a substantial barrier to wider adoption. Each pediatric robotic case incurs approximately $3,000 in additional costs compared to traditional techniques [46]. These expenses extend beyond the operative suite, encompassing the acquisition and maintenance of robotic systems, as well as the significant investment required for team training [47].

The relatively small volume of pediatric surgical cases has limited market incentives for developing child-specific instruments, further entrenching reliance on adult-adapted tools [48]. This dynamic not only limits the scalability of pediatric robotic surgery but also raises concerns about equitable access, particularly for patients in under-resourced settings [47]. Nevertheless, successful programs established in resource-limited regions, such as India, highlight the growing global feasibility of implementing robotic surgery through strategic implementation [15].

While robotic surgery involves significant upfront costs, including acquisition, maintenance, and training, some economic offsets have been suggested. Shorter hospital stays and quicker recovery may reduce the total cost of care, though robust cost-effectiveness analyses are still lacking [33] [27]. High-volume centers may achieve better economic efficiency by spreading the fixed costs across more cases, thus reducing the per-case expense [14–15].

Overall, while robotic surgery offers technical and recovery advantages, its high costs remain a significant limitation to widespread adoption in pediatric urology. Strategic initiatives, such as concentrating cases in high-volume centers, developing pediatric-specific instruments, and conducting comprehensive cost-effectiveness studies, are crucial to improving accessibility and long-term sustainability.

Conclusion:

This literature review represents the increasing role of robotic-assisted surgery in children's procedures, with pediatric urology emerging as the well-developed and widely documented domain reflecting this trend. Over the past two decades, robotic-assisted techniques, especially in pyeloplasty and ureteral reimplantation, have moved from experimental adoption to becoming the standard of care in many high-volume centers. Across these and other reconstructive and precision-guided procedures, the literature consistently reports high success rates, low complication profiles, and faster recovery compared with traditional open and laparoscopic approaches.

The integration of complementary technologies such as ICG fluorescence and the introduction of new robotic platforms continue to enhance precision, ergonomics, and applicability, even in complex or infant cases.
However, the current evidence is dominated by retrospective, single-center studies with short- to medium-term follow-up. Methodological heterogeneity, variable outcome reporting, and a lack of multicenter randomized trials limit the generalizability of results. Cost analyses are often incomplete, rarely incorporating broader economic impacts such as parental productivity loss or long-term quality of life. The underrepresentation of neonates, infants, and resource-limited settings further narrows the scope of available data.
Economic and ethical barriers remain significant. High acquisition and maintenance costs, the absence of pediatric-specific instruments, and the use of adult-adapted platforms raise questions about both scalability and equity of access. While high-volume centers demonstrate clear benefits and efficiencies, widespread adoption will depend on targeted strategies to reduce costs, improve access, and develop tailored pediatric technology.
Looking forward, the next phase of advancement will require coordinated efforts: designing robust, multicenter prospective trials; standardizing outcome reporting; conducting comprehensive cost-effectiveness studies; and addressing ethical considerations in innovation. If these challenges are met, robotic-assisted surgery is well-positioned to remain a cornerstone of modern pediatric surgery, delivering minimally invasive precision, improved recovery, and sustainable long-term outcomes for the youngest patients.

Authors Contributions: Conceptualization: A.M. and J.W.; Literature review: A.M., J.W. and E.B.; Writing – Abstract: A.M., J.W. and B.W.; Writing – Introduction: A.M. and H.J.; Writing – Methods: O.M. and A.S.; Writing – Results: A.M. and J.S.; Writing – Pyeloplasty, A.M., K.Ż.; Writing – Ureteral Reimplantation: J.W. and E.B.; Writing – Other Robotic Procedures, B.W. and O.M.; Writing - Newly Introduced Robotic Systems, A.M and J.S.; Writing - Anesthetic, Ethical, and Economic Considerations – A.S and H.J.; Writing- Conclusion, A.M. J.W; Editing and reviewing, A.M., E.B. and J.W.

All authors have read and agreed with the published version of the manuscript.

Funding Statement:
This research received no external funding.

Conflict of Interest Statement:
The authors declare no conflict of interest.

Declaration of the use of AI and AI-assisted technologies in the writing process: Artificial intelligence (AI) tools such as ChatGPT were employed in this research solely to assist in refining the academic English language of the manuscript. Their purpose was to ensure clarity, consistency, and adherence to scientific writing standards. AI tools were used strictly for additional linguistic polishing-focused on proper grammar, style, and clarity of the text in presenting the results. Importantly, these tools were used only as support under the direct supervision of the authors.

All final interpretations, classification of findings, and conclusions were determined exclusively by human experts with formal training in clinical medicine. The role of AI was limited to enhancing the efficiency of language refinement, pattern recognition, and data processing, and it did not replace human judgment in the analytical process.

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