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Chirurgia

Robotic and Laser-Assisted Techniques in Urologic Surgery: Current Applications

Techniki robotyczne i wspomagane laserowo w chirurgii urologicznej: aktualne zastosowania

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Streszczenie

Wstęp: Niniejszy przegląd syntetyzuje współczesne dane naukowe (2018–2025) dotyczące technik robotycznych i laserowych w urologii, koncentrując się na aktualnych zastosowaniach klinicznych, porównawczej skuteczności, kosztach, szkoleniu oraz aspektach etycznych. Techniki małoinwazyjne zrewolucjonizowały chirurgię urologiczną w ostatnich dekadach. Systemy robotyczne oferują trójwymiarową wizualizację, zwiększoną precyzję instrumentów oraz filtrację drgań, co ułatwia przeprowadzanie zabiegów od radykalnej prostatektomii po złożone operacje rekonstrukcyjne i pediatryczne. Równocześnie, procedury z użyciem lasera, takie jak enukleacja prostaty laserem holmowym (HoLEP) oraz fotoselektywna waporyzacja o wysokiej mocy (PVP), wykazały trwałą poprawę funkcji przy zmniejszonej chorobowości w leczeniu łagodnego rozrostu gruczołu krokowego (BPH).

Cel przeglądu: Chirurgia wspomagana robotem rozrosła się wykładniczo, na czele z systemem chirurgicznym da Vinci, który został powszechnie przyjęty ze względu na jego zalety w wizualizacji, zręczności i wynikach pacjentów. Jednocześnie technologie laserowe - zwłaszcza holm, tul i lasery zielonego światła - zostały wdrożone w leczeniu łagodnego rozrostu gruczołu krokowego i kamieni dróg moczowych, zapewniając skuteczne i minimalnie inwazyjne alternatywy dla konwencjonalnych technik. Niniejszy przegląd literatury ma na celu ocenę aktualnych zastosowań klinicznych, korzyści i ograniczeń technik zrobotyzowanych i wspomaganych laserowo w chirurgii urologicznej, ze szczególnym uwzględnieniem najnowszych dowodów i ewoluujących praktyk.

Wnioski: Ewolucja technologii zrobotyzowanych i wspomaganych laserem zasadniczo zmieniła współczesną chirurgię urologiczną, oferując mniej inwazyjne, bardziej precyzyjne i klinicznie skuteczne alternatywy dla tradycyjnych metod chirurgicznych. Jednocześnie interwencje oparte na laserach, takie jak HoLEP i PVP, stały się dobrze ugruntowanymi opcjami w leczeniu łagodnego rozrostu gruczołu krokowego, oferując lepsze wyniki funkcjonalne z niższym ryzykiem okołooperacyjnym.

Słowa kluczowe: chirurgia zrobotyzowana, chirurgia wspomagana laserowo, onkologia urologiczna, minimalnie inwazyjna enukleacja (HoLEP), system chirurgiczny Da Vinci, robotyczna prostatektomia, kamica moczowa, leczenie BPH

Abstract

Background: Robotic and laser-assisted techniques provide safe, effective, and minimally invasive alternatives to traditional urologic surgeries. Robotic prostatectomy and nephrectomy reduce blood loss and hospital stay, while laser procedures offer excellent functional outcomes in BPH. However, implementation is costly and requires specialized training.

Introduction: In recent decades, urologic surgery has been revolutionized by robotic and laser technologies. The da Vinci system allows for precise operations through 3D visualization and enhanced instrument dexterity. Simultaneously, laser-based techniques such as HoLEP and PVP have become standards in treating BPH and urolithiasis.

Conclusions: Modern technologies are reshaping urologic surgery, offering benefits to both patients and surgical teams. Further technological development and clinical research will be crucial to improving access and optimizing these methods.

Key words: robotic surgery, urologic oncology, laser-assisted surger, HoLEP, Da Vinci Surgical System

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Methods

This narrative literature review was conducted by systematically searching online databases including PubMed, Scopus, and Cochrane Library for publications between January 2018 and May 2025. The primary focus was on clinical applications of robotic and laser-assisted surgical techniques in urology. The search strategy employed keywords and Boolean operators such as:

- „robotic surgery" AND „urology",
- „laser enucleation" OR „HoLEP" OR „PVP",
- „minimally invasive" AND „urologic cancer",
- „robot-assisted prostatectomy" OR „robot-assisted nephrectomy".

Inclusion criteria were:

- Peer-reviewed studies, clinical trials, meta-analyses, and systematic reviews.
- Publications in English.
- Studies involving adult patients undergoing urologic procedures.
- Focus on either robotic-assisted or laser-assisted interventions.

Exclusion criteria were:

- Case reports, letters to the editor, or editorials without data.
- Non-English publications.
- Studies focused exclusively on veterinary or pediatric populations (except where relevant for robotic urology).

A total of 137 articles were identified. After screening titles and abstracts, 68 full-text articles were reviewed, and 38 studies were included in this review based on relevance, methodological quality, and recency.

The primary endpoints analyzed were operative time, estimated blood loss (EBL), length of hospital stay, complication rates, and functional outcomes. Secondary endpoints included cost analysis, training requirements, and ethical implications.

→ Robotic-Assisted Urologic Procedures

Robotic-assisted surgery has revolutionized the field of urology by enhancing precision, minimizing invasiveness, and improving postoperative outcomes. The da Vinci Surgical System, approved by the FDA in 2000, remains the most widely used platform. Robotic platforms enable three-dimensional magnified vision, greater instrument articulation, and improved ergonomics, all of which are critical for complex pelvic and retroperitoneal procedures.

→ Robotic Radical Prostatectomy (RARP)

Radical prostatectomy is one of the most established robotic procedures in urology. Robotic-assisted radical prostatectomy (RARP) has largely replaced open and laparoscopic techniques due to superior visualization of the neurovascular bundles and improved continence and erectile function recovery in some cohorts [1]. Multiple studies demonstrate comparable oncologic control between RARP and open surgery, with significantly reduced blood loss, lower transfusion rates, and shorter hospitalization [2]. Innovations like dual-console systems and nerve-sparing algorithms are further enhancing patient outcomes.

→ Robotic Partial and Radical Nephrectomy

Robotic partial nephrectomy (RPN) is considered the standard for small renal masses due to its nephron-sparing advantages. The robotic approach allows precise tumor excision with minimal warm ischemia time and improved suturing of the renal defect [3]. Compared to laparoscopic partial nephrectomy, RPN demonstrates lower conversion rates and better postoperative renal function [4] Robotic radical nephrectomy, while less commonly used than partial nephrectomy, is advantageous in selected cases for complex tumor locations or large renal masses.

→ Robotic Radical Cystectomy

Robotic radical cystectomy (RARC) with intracorporeal urinary diversion is increasingly performed in muscle-invasive bladder cancer. The RAZOR trial confirmed that RARC is non-inferior to open cystectomy regarding oncologic outcomes, with the added benefit of fewer complications and reduced blood loss [5].

→ Pediatric and Reconstructive Applications

Robotic surgery is being adopted in pediatric urology, particularly for pyeloplasty, ureteral reimplantation, and bladder augmentation. Despite technical challenges due to smaller anatomy, outcomes have been favorable, with reduced postoperative pain and faster recovery [6]. In reconstructive surgery, robotic approaches have been used for ureteral reimplantation, vesicovaginal fistula repair, and urethral reconstruction, offering precise dissection and suturing capabilities, especially in re-do or complex cases [7].

→ Outcomes and Complications

Robotic procedures in urology generally yield:

- Shorter hospital stays
- Less blood loss
- Lower analgesic requirements
- Comparable or improved functional outcomes

However, disadvantages include:

- Longer operative times (particularly early in the learning curve)
- High capital and maintenance costs
- Equipment failure risks (1–2%)

Robotic complications may include port-site hernias, nerve injuries, or device malfunction, though serious adverse events are rare and conversion to open surgery is uncommon [8].

Laser-Assisted Urologic Techniques

Laser technology in urology offers a powerful, precise, and minimally invasive method for managing benign prostatic hyperplasia (BPH), urolithiasis, strictures, and certain urothelial lesions. The most widely used lasers in urology include holmium: yttrium-aluminum-garnet (Ho:YAG), thulium, and potassium titanyl phosphate (KTP/"„reen light") systems.

○ Holmium Laser Enucleation of the Prostate (HoLEP)

HoLEP is regarded as the most versatile and size-independent surgical option for BPH. It involves endoscopic enucleation of obstructive adenomatous tissue using a high-powered holmium laser, followed by morcellation. Compared to transurethral resection of the prostate (TURP), HoLEP offers:

- Superior long-term functional outcomes
- Lower bleeding risk
- Shorter catheterization and hospital stay
- Suitability for anticoagulated patients [9]

A meta-analysis of randomized trials confirms HoLEP's superiority in terms of Qmax, IPSS score reduction, and lower reoperation rates even at 5-year follow-up [10]. Additionally, newer pulse-modulated Ho:YAG devices offer smoother cutting and faster hemostasis.

○ Photoselective Vaporization of the Prostate (PVP)

PVP uses a high-powered KTP or lithium triborate laser (often referred to as „green light") to vaporize prostatic tissue, creating an open prostatic channel. It is especially useful in:

- Small to moderate gland sizes
- Patients on anticoagulation
- Outpatient settings

The GOLIATH trial demonstrated equivalent efficacy to TURP, with fewer bleeding complications and shorter catheter time [11]. While some data suggest slightly inferior debulking compared to HoLEP, PVP remains a widely accepted, low-morbidity option.

○ Thulium Laser Techniques

Thulium lasers emit continuous or pulsed energy, enabling precise vaporesection or enucleation. Thulium vapoenucleation of the prostate (ThuLEP) and thulium laser vaporesection (ThuVARP) show:

- Comparable efficacy to HoLEP and TURP
- Less intraoperative bleeding
- Potential for shorter operative times in experienced hands [12]

Thulium technology is gaining favor in Europe and Asia and is considered particularly effective in prostates of 30–80 mL volume.

○ Laser Use in Stone Surgery and Ureteral Strictures

Holmium laser lithotripsy remains the gold standard for treating renal and ureteric calculi, including:

- Flexible ureteroscopy (fURS)
- Percutaneous nephrolithotomy (mini-PCNL)
- Dusting and fragmentation modes

Thulium fiber lasers (TFL) are a newer alternative, offering:

- Finer control
- Faster ablation
- Less retropulsion

Lasers are also used for precise incisions in ureteral and urethral strictures, improving outcomes and reducing recurrence [13].

○ Safety and Complications

Laser surgery is generally very safe. Potential complications include:

- Transitory dysuria or hematuria
- Urinary retention (rare)
- Capsular perforation or ureteric injury (in stone surgery)

Proper technique, energy modulation, and real-time endoscopic control are crucial to minimize adverse events.

Image-Guided and Hybrid Techniques

Recent advances in imaging and intraoperative guidance have further enhanced the safety, precision, and efficacy of robotic and laser-assisted urologic procedures. These enhancements include fluorescence-guided surgery, augmented reality (AR) integration, and hybrid operating rooms that combine advanced imaging modalities with surgical robotics.

◇ Fluorescence-Guided Surgery with Indocyanine Green (ICG)

Indocyanine green (ICG) is a near-infrared fluorescent dye that enables real-time vascular and lymphatic mapping during robotic surgery. When injected intravenously, ICG highlights:

- Renal vasculature during partial nephrectomy
- Ureteral anatomy during pelvic dissection
- Sentinel lymph nodes during lymphadenectomy

In robotic partial nephrectomy, ICG helps differentiate tumor tissue from normal parenchyma, allowing for precise excision while preserving nephrons [14]. ICG guidance has also improved lymph node dissection in prostate and bladder cancer by improving identification of sentinel nodes and reducing missed metastases [15].

◇ Augmented Reality and Image Fusion

Augmented reality (AR) systems overlay preoperative imaging (e.g., MRI, CT) onto the surgical field using real-time navigation. Applications include:

- Robotic partial nephrectomy, enabling accurate tumor localization
- Pelvic surgery, for identifying neurovascular bundles or masses

Image fusion, especially in robot-assisted prostatectomy, enhances surgical planning and margin control. For example, preoperative MRI can be fused with real-time intraoperative views for precision in apical dissection or nerve-sparing approaches [16].

◇ Hybrid Operating Rooms

Hybrid ORs integrate robotic systems with intraoperative CT, cone-beam CT, ultrasound, and fluoroscopy. These rooms are particularly beneficial for:

- Complex stone disease
- Urologic trauma
- Robotic reconstructive procedures

They allow the surgical team to verify anatomy or pathology mid-procedure without the need to transfer the patient. Although costly, hybrid ORs are becoming more common in high-volume academic centers and advanced cancer programs.

◇ Limitations and Training Requirements

The adoption of these image-guided enhancements requires:

- Advanced training in image interpretation
- Familiarity with multiple software and navigation platforms
- Significant capital investment in hardware

Furthermore, AR and fluorescence systems must be calibrated precisely to avoid misregistration and surgical errors.

Cost, Training, and Ethical Considerations

While robotic and laser-assisted urologic surgeries offer clinical advantages, their widespread adoption raises critical issues related to financial cost, surgeon training, system accessibility, and ethical use.

✓ Financial Costs and Resource Utilization

Robotic systems, particularly the da Vinci platform, involve substantial financial investment. The average cost includes:

- Initial purchase: $1.5–2.5 million per system
- Annual maintenance: $100,000–200,000
- Disposable instruments per case: $2,000–3,000

Although some studies suggest shorter hospital stays and fewer complications may offset costs over time, high upfront expenditures remain a barrier for widespread implementation, especially in resource-limited settings [17]. In contrast, laser systems (e.g., Ho:YAG or TFL generators) have lower acquisition and maintenance costs, but still require operating room integration and endoscopic expertise.

✓ Training and Learning Curves

Both robotic and laser techniques demand specialized training. For robotic surgery:

- The learning curve for radical prostatectomy is estimated at 20–-40 cases for basic proficiency and 100+ for optimal outcomes [18].
- Fellowship programs, dry-lab simulation, and dual-console mentoring have become essential for surgical education.

Laser systems require endoscopic skills, knowledge of laser physics, energy modulation, and tissue interactions. For instance, HoLEP is technically demanding with a steep learning curve, often requiring 30–-50 cases to achieve proficiency [19]. Simulation platforms and validated skill assessments (e.g., GEARS for robotics) are increasingly used to ensure safe adoption.

✓ Access and Equity

Technological disparities between academic centers and smaller hospitals have created inequities in patient access. This is particularly problematic in rural and underserved areas, where robotic systems are unavailable or unaffordable. Efforts to democratize access include:

- Development of lower-cost robotic systems (e.g., CMR Versius, Hugo RAS)
- Mobile surgical units
- Tele-mentoring and virtual proctoring

✓ Ethical and Legal Implications

Emerging concerns include:

- Informed consent: Patients must understand the technology's benefits, limitations, and operator experience.
- Autonomy and oversight: As semi-autonomous systems evolve, questions arise about surgeon accountability and machine-driven decision-making.
- Justice: The allocation of costly surgical systems must be balanced with broader healthcare priorities.

From a legal standpoint, system malfunctions or adverse outcomes involving robotic assistance can result in complex liability cases. Institutions are advised to implement formal credentialing processes and standardized complication reporting [20].

Future Directions

As robotic and laser technologies continue to evolve, the future of urologic surgery lies in enhanced automation, improved imaging integration, and broader accessibility. These advancements aim to refine precision, reduce operator variability, and democratize high-quality surgical care.

• Next-Generation Robotic Systems

Beyond the da Vinci platform, new robotic systems are emerging to address cost, modularity, and flexibility:

- CMR Surgical's Versius: Compact, modular arms with open console design
- Medtronic's Hugo RAS: Multi-quadrant capability with video integration
- REVO-I and Hinotori: Asian-developed platforms gaining clinical traction

These systems aim to lower acquisition costs and promote competition, which may reduce pricing over time [21].

• Haptic Feedback and AI Integration

One of the longstanding limitations of robotic surgery is the absence of tactile sensation. Several companies are developing haptic-enabled systems to improve tissue discrimination, potentially reducing errors during dissection or suturing.

Additionally, artificial intelligence (AI) is being integrated into:

- Real-time instrument guidance
- Gesture recognition and performance scoring
- Automated camera navigation and focus adjustment

AI-driven platforms may assist in identifying anatomical landmarks, predicting complications, and even automating low-complexity steps (e.g., suturing, dissection), acting as digital "co-pilots" during procedures [22].

• Augmented and Virtual Reality (AR/VR)

Augmented reality overlays and virtual reality simulation are becoming core components of both preoperative planning and surgical education. Applications include:

- Tumor mapping in partial nephrectomy
- AR-assisted training for urethral reconstruction
- Full-immersion VR rehearsal of robotic steps

These tools not only accelerate skill acquisition but also standardize training across institutions [23].

• Advances in Laser Technology

Laser evolution continues toward smaller, more powerful, and fiber-optic friendly systems, such as:

- Thulium fiber laser (TFL): Superior ablation speed, lower retropulsion, and quieter operation
- Super pulse modulated Ho:YAG: More efficient tissue cutting with less collateral damage

These advances aim to enhance precision in enucleation, lithotripsy, and ureteral surgery while reducing operative time and thermal injury [24].

• Global Collaboration and Tele-surgery

With the advent of 5G technology and low-latency networks, remote robotic surgery (tele-surgery) is becoming technically feasible. Pilot studies from China and Europe have demonstrated real-time robotic intervention across long distances, which could benefit isolated or underserved regions. The future of global urologic surgery may include:

- International case collaboration
- Remote mentoring for rural hospitals
- Cloud-based surgical coaching platforms

Tabela 1: Timeline of robotic and laser-assisted techniques in urology (2000–2030)

Year	Event / clinical significance
2000	FDA approval of the da Vinci Surgical System; beginning of the robotic era in urology.
2003	Standardized prostatectomy technique described (Vattikuti Institute); foundation for RARP.
2005	HoLEP recognized as a size-independent option for BPH; first long-term superiority data over TURP.
2010	Debate on costs and economic impact of robotic surgery in healthcare.
2012	Meta-analyses confirm oncologic non-inferiority of RARP vs open surgery, with reduced blood loss.
2014	Multicenter studies on RPN learning curve; popularization of nephron-sparing techniques.
2014–2018	PVP (GOLIATH) and RARC (RAZOR) RCTs confirm safety and efficacy.
2018	Review of advances in stone laser therapy: TFL and improved Ho:YAG (faster ablation, less retropulsion).
2017–2020	Introduction of fluorescence imaging (ICG) and AR / image fusion for intraoperative navigation.
2019–2021	Simulators, dual-console, and structured training (GEARS) – standardization of robotic education.
2021–2024	New robotic platforms: Versius, Hugo RAS, Hinotori; greater modularity and cost competition.
2024–2025	Wider adoption of TFL in stone and enucleation surgery; integration of AI (gesture analysis, guidance, automated camera control).
By 2030 (forecast)	Haptics in robotic systems, more autonomous modules (suturing, dissection), standardized AR/VR in planning and training, low-latency tele-mentoring, and initial tele-surgery implementations via 5G/6G networks.

Discussion

Robotic and laser-assisted techniques have dramatically redefined the landscape of modern urologic surgery. They offer compelling advantages over traditional open and laparoscopic procedures, including enhanced visualization, improved dexterity, reduced perioperative morbidity, and quicker recovery. However, widespread implementation must be balanced against practical limitations including cost, training requirements, and access disparities.

▷ Robotic Surgery: Strengths and Challenges

Robotic platforms have demonstrated consistent benefits in prostatectomy, partial nephrectomy, and cystectomy, with evidence supporting:

- Reduced blood loss and hospital stay
- Comparable or superior functional outcomes (continence, potency)
- Oncologic non-inferiority in multiple malignancies [1, 3, 5]

However, high equipment and maintenance costs, lack of tactile feedback, and longer operative times—especially during early adoption—remain significant concerns. Furthermore, outcomes are operator-dependent, and learning curves are steep, necessitating structured training and mentorship programs [18, 19].

▷ Laser Applications: Refinement of Endourology

Holmium and thulium lasers have transformed the management of BPH and urinary stones. HoLEP has emerged as a size-independent gold standard for prostate enucleation, showing better long-term outcomes compared to TURP. Thulium fiber lasers are now favored for their low retropulsion and quiet operation in stone management [10, 12, 24].

Still, laser surgery requires significant endoscopic expertise, and some techniques (e.g., HoLEP) may not be readily adopted outside tertiary centers due to technical demands and limited training availability.

▷ Technology Integration and the Future

The convergence of robotics with real-time imaging (e.g., ICG fluorescence, augmented reality) is redefining intraoperative navigation. These tools improve precision and safety—particularly in oncologic and reconstructive settings. Meanwhile, the emergence of next-generation robotic systems and AI-assisted platforms promises further automation, personalization, and standardization of urologic procedures [21, 22]. Yet ethical concerns persist regarding:

- Patient consent in semi-autonomous procedures
- Data privacy from AI-integrated platforms
- Equitable access to advanced systems in underfunded regions

▷ Evidence Limitations and Gaps

Although promising, many studies supporting robotic and laser techniques are:

- Single-center or non-randomized
- Influenced by surgeon experience
- Limited in long-term oncologic or functional follow-up

There is a need for more robust prospective, multicenter randomized trials directly comparing robotic and laser interventions with established surgical standards across diverse populations.

▷ Clinical Implications

For clinical practice, robotic and laser techniques should be:

- Offered based on indication, surgeon expertise, and patient preference
- Paired with transparent discussion of risks, benefits, and costs
- Integrated into multidisciplinary treatment planning, especially in oncology

Ultimately, the decision to use robotic or laser assistance should be patient-centered, evidence-informed, and guided by institutional resources and surgeon training.

Conclusion

Robotic and laser-assisted techniques represent a transformative evolution in urologic surgery. Robotic systems have demonstrated remarkable advantages in performing complex oncologic and reconstructive procedures with greater precision, reduced blood loss, and improved functional outcomes. Likewise, laser-assisted interventions—particularly holmium and thulium-based technologies—have redefined the management of benign prostatic hyperplasia and urinary stone disease.

Despite their benefits, these technologies are not without limitations. High costs, steep learning curves, and limited access in under-resourced settings pose ongoing challenges. Moreover, the future integration of artificial intelligence, augmented reality, and advanced imaging will require careful ethical consideration and global collaboration to ensure equitable deployment.

Continued innovation, supported by robust clinical evidence, training infrastructure, and multidisciplinary cooperation, will be essential to optimize the safety, efficacy, and accessibility of robotic and laser technologies in urology.

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Tabela 2: Comparison of robotic and laser-assisted techniques in urologic surgery

Feature	Robotic techniques	Laser-assisted techniques
Main indications	RARP, RPN, RARC, urologic reconstructive surgery, pediatric urology	BPH (HoLEP, PVP, ThuLEP), urolithiasis, urethral and ureteral strictures
Advantages	3D visualization, high precision, surgeon ergonomics, reduced blood loss and shorter hospital stay	Minimally invasive, excellent hemostasis, suitable for anticoagulated patients
Limitations	High purchase and maintenance cost, long learning curve, lack of tactile feedback	Learning curve (especially HoLEP), requires advanced endoscopic skills
Initial cost	USD 1.5–2.5 million + USD 100–200k/year maintenance	Much lower: laser generator + integration with operating room
Learning curve	20–40 cases for basic proficiency, >100 cases for optimal outcomes	30–50 cases (HoLEP)
Level of evidence	High for RARP, RPN, RARC (RCTs, meta-analyses)	High for HoLEP and PVP (RCTs, meta-analyses)
Complication risk	Low: nerve injury, port-site hernia, device malfunction (1–2%)	Low: transient dysuria, hematuria, rare capsular perforation or ureteric injury
Availability	Mainly in large academic and specialized centers	More widely available, including smaller hospitals

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Komentarz:

„Robotic and Laser-Assisted Techniques in Urologic Surgery" is a well-structured and insightful review that highlights the transformative impact of modern minimally invasive technologies. The authors present a thorough analysis of current applications, clinical outcomes, and future directions, combining scientific rigor with practical relevance. This paper is a valuable resource for both practicing urologists and researchers exploring the evolution of surgical innovations.

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This article delivers a comprehensive and up-to-date overview of robotic and laser-assisted techniques in modern urologic surgery. The authors skillfully balance technical detail with clinical relevance, making the review both informative and accessible. It stands out as a valuable reference for clinicians seeking to integrate innovative surgical technologies into practice.

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