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Evaluation of the Toumai robotic system in partial nephrectomy and key system features

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Robotic partial nephrectomy is a standard procedure in urology, but its widespread use is limited by the high cost and technical constraints of current systems. New robotic systems are being developed to enhance affordability and accessibility, expanding the availability of advanced robotic surgery to a broader range of healthcare facilities and patients. This study evaluates the feasibility and safety of the Toumai system in partial nephrectomy, examining its advanced features and their potential impact on surgical precision and operational efficiency. In this single center study, eleven patients underwent partial nephrectomy using Toumai. Primary endpoints were feasibility and safety, while secondary outcomes included perioperative outcomes. All surgeries were completed successfully without conversion, minimal complications, and no major equipment failures. The median operative time was 107 min, docking time was 8 min, and estimated blood loss was 50 ml. One off-clamp partial nephrectomy was successfully performed and median warm ischemia time was 9 min in the remaining cases. Postoperatively, renal function remained stable, and surgical margins were negative in all cases. These preliminary results suggest that partial nephrectomy can be safely performed using the Toumai robotic system. The system's advanced features, including sensory feedback, high-frequency response, and enhanced imaging technologies, likely contributed to favorable surgical outcomes with minimal complications. However, these initial findings warrant further validation through larger studies and longer follow-up.

Keywords Robotic surgery, Novel robot, Toumai robotic system, Urology, Partial nephrectomy

Robot-assisted surgery (RAS) has significantly advanced urology, offering superior precision, reduced invasiveness, and improved clinical outcomes compared to traditional techniques[1,2]. Robotic systems, such as the da Vinci platform, have become essential tools in complex urological procedures, including partial nephrectomy, balancing oncologic efficacy with nephron preservation[3]. This approach is particularly valuable for complex hilar or posterior tumors, where access and resection are challenging with traditional techniques, potentially leading to suboptimal outcomes[4]. Despite the advantages, current robotic systems have limitations, including high acquisition and maintenance costs, suboptimal haptic feedback, and ergonomic challenges[5,6]. New robotic platforms are being developed with a focus on improving adaptability, accessibility, and affordability[7,8]. The Toumai system, recently CE-approved, integrates advanced functionality such as force sensing, high-frequency response capabilities, and *telerobotic surgery capabilities*[9].

Recent studies have demonstrated safety and procedural efficacy of Toumai across diverse surgical disciplines, including urology, gastrointestinal surgery, and vascular oncology. Our prior work established its feasibility in range of urological procedures[9]. The successful resection of inferior vena cava (IVC) hemangiomas highlighted the system's potential in managing rare and complex vascular tumors[10]. Early gastrointestinal applications, including gastric and colorectal resections, further highlight its versatility, with favorable outcomes observed in initial clinical evaluations[11]. This study aims to evaluate the safety and efficacy of the Toumai robotic system in partial nephrectomy. It also explores the system's advanced functionality and discuss their potential impact on surgical precision and operational efficiency.

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Material and method

Study design

This study was conducted at the first affiliated hospital of Zhengzhou university and performed by a single surgeon with extensive experience in both laparoscopic and robotic partial nephrectomy. Eleven patients planned for partial nephrectomy were consecutively enrolled between April 2023 and February 2024 at our institution. All the participant were well informed about the novel system and a written informed consent was taken after the approval to undergo the surgery. The study was approved by the institutional review board (2023-KY-0260–003) of first affiliated hospital of Zhengzhou university and was conducted in compliance with the ethical guidelines of the Helsinki Declaration of 1975.

Patient selection and evaluation

Standardized preoperative and postoperative protocols were applied across all procedures. Patients with renal masses suspicious for malignancy and suitable for nephron-sparing surgery underwent partial nephrectomy. Exclusion criteria included refusal to provide informed consent, incomplete data, significant comorbidities contraindicating surgery, and metastatic disease.

Outcome measures

The primary outcome measures were the feasibility and safety of the novel robotic system during partial nephrectomy. Feasibility was measured by successful completion of surgeries without the need for conversion to conventional techniques. Safety was evaluated by recording perioperative complications and thirty-day readmission. Secondary outcome measures included docking time, operative time, blood loss, warm ischemia time and oncological and functional outcomes. Postoperative complications were graded according to the Clavien-Dindo classification, with complications categorized as major (Grade ≥ 3) or minor (Grade ≤ 2).

Statistical analysis

Descriptive statistics were used to summarize the key variables of the study. Continuous variables, including operative time and surgical margins, were summarized using medians and ranges to provide an overview of the central tendency and variability within the data. Categorical variables, such as patient demographics, complications, and other procedural outcomes, were reported as frequencies and percentages.

The Toumai robotic system

The Toumai robotic system operates as a master–slave system, consisting of a four-arm patient cart, a closed surgeon console, and a high-definition vision cart[9]. It is the first China-built robotic system to acquire CE approval.

Key features of the system include advanced force sensing and feedback technology, which allows for accurate tactile sensation during procedures. The system's high-frequency response capability (4000 Hz) and rapid response time (250 μs) are designed to enhance precision in delicate surgical tasks. The Field-Programmable Gate Array (FPGA) real-time image processing, combined with dual fiber optic transmission, reduces latency to less than 50 ms, facilitating timely and clear visualization of the surgical field. Additionally, the integrated 3D electronic endoscope provides a comprehensive and realistic view, supported by visual enhancement technologies such as the Intelligent Smoke Removal Algorithm and the Vascular Enhancement Algorithm, which improve the clarity of the surgical field.

The system's wrist technology offers seven degrees of freedom, enhancing instrument dexterity and flexibility, which is critical in performing complex surgical maneuvers. The robotic instruments, with a diameter of ≤ 8.4 mm and 540 degrees of rotation, allow for stable grip and precise energy delivery, crucial for maintaining control and safety during procedures. Safety features, including an immersive protection mechanism that locks automatically when the operator's head is not in the viewing position and a foot pedal with safeguards against inadvertent activation, are integrated to enhance operational safety.

Surgical procedures

All surgeries were performed by a highly experienced robotic surgeon (XPZ), with over 4,000 robotic procedures. Partial nephrectomy was performed using the standard robotic technique[12], which included key steps such as transperitoneal access, renal artery clamping, tumor excision, and renorrhaphy. All procedures were conducted using the Toumai robotic system, ensuring precision and consistency throughout the surgery (Fig. 1).

Results

A total of eleven patient underwent partial nephrectomies with the Toumai robotic system. Seven men and four women (median age, 55 yr) with a median body mass index of 25 (22.87–27.32) were included. Five masses were located on the right kidney and six on the left. Tumor complexity was stratified using the RENAL Nephrometry Score, with 8 cases classified as low complexity (scores 4–6: 4P [n = 2], 4X [n = 1], 6P [n = 4], 6A [n = 1]) and 3 cases as moderate complexity (scores 7–9: 7A [n = 1], 7X [n = 1], 8X [n = 1]). The patient demographics and preoperative parameters are shown in Table 1.

All surgeries were successfully completed without conversions to alternative surgical approaches. No major robotic malfunction was encountered and there were no 30-days readmission. The median operative time was 107 (77.93–120.80) minutes, median docking time was 8 (7.42–12.39) minutes, and estimated blood loss was 50 (8.78–63.04) ml (Fig. 2). Off clamp partial nephrectomy was successfully performed in one case, with a median warm ischemia time was 9 (6.94–14.16) minutes in the remaining cases. Postoperative period was uneventful and no major complications were observed. Final histopathology confirmed clear cell carcinoma

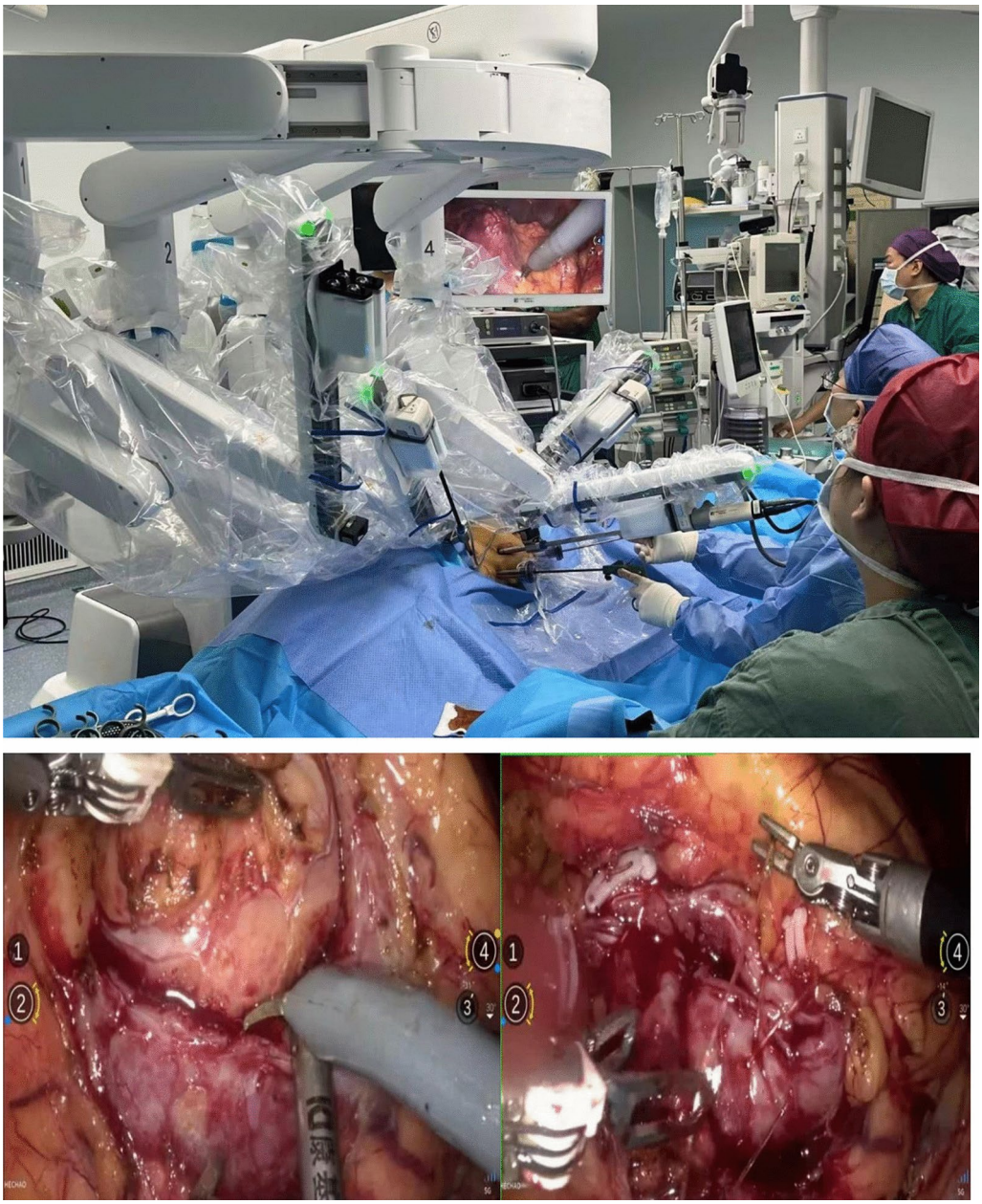

Fig. 1. Intraoperative robotic setup and docking of the Toumai robotic system during partial nephrectomy showing robotic arm configuration and key surgical steps during partial nephrectomy. Intraoperative robotic setup and docking of the Toumai robotic system (upper panel) demonstrating the robotic arms positioned and docked on the patient, preparing for partial nephrectomy. The lower image panel demonstrates key stages in the robotic-assisted partial nephrectomy, the precise resection of the renal tumor (left), and renorrhaphy (right).

with negative surgical margins in all specimens. At three months follow-up renal function remained stable and was 97.74(85.91–101.44) ml/min.

Discussion

Robot-assisted partial nephrectomy (RAPN) is well-established as a standard treatment modality, with its applications expanding from small renal masses to more complex and anatomically challenging tumors[1,13]. The expiration of several da Vinci patents opened opportunities for the development and introduction of new robotic systems. The Toumai Robotic System, the first Chinese surgical robotic system to acquire the CE mark, has shown promising outcomes in clinical applications across urology, general surgery, thoracic and vascular surgery[9–11,14].

This study demonstrates favorable early trifecta outcomes, which are comparable to RAPN series from multicenter study[13]. The median operative time in our series was comparable to, and in some cases efficient

Basic characteristics	
Age	55 (48.78–63.04)
Sex, male/female	7/4
BMI (kg/m^2)	25.01 (22.87–27.32)
Laterality, left/right	6/5
R.E.N.A.L. score, *n* (%)	
4–6	8(72.7)
7–9	3(27.27)
Preoperative evaluation	
Hb (g/L)	131.00(119.72–149.19)
Cr (μmol/L)	65(58.25–103.20)
eGFR (ml/min)	100.55(90.34–105.16)
Intraoperative parameters	
Docking time(min)	8(7.42–12.39)
Operating Time(min)	107(77.93–120.80)
EBL (ml)	50.00(48.78–63.04)
WIT (min)	9.00(6.94–14.16)
Postoperative parameters	
Hb (g/L)	110.00(107.61–135.02)
Cr (μmol/L)	66.00(58.49–82.96)
eGFR (ml/min)	97.48(85.50–102.27)
Histology	CC
Surgical margins, *n* (%)	
Positive margin	0 (0)
Negative margin	11 (100)
eGFR(3 months)	97.74(85.91–101.44)

Table 1. Demographic, preoperative, intraoperative and postoperative parameters of 11 patients undergoing Toumai assisted partial nephrectomy. Continuous variables are shown as medians (IQR). *BMI* Body Mass Index; *eGFR* Estimated Glomerular Filtration Rate; *Hb* Hemoglobin; *Cr* Creatinine; *EBL* estimated blood loss; *WIT* Warm Ischemia Time. *CC* Clear Cell Carcinoma.

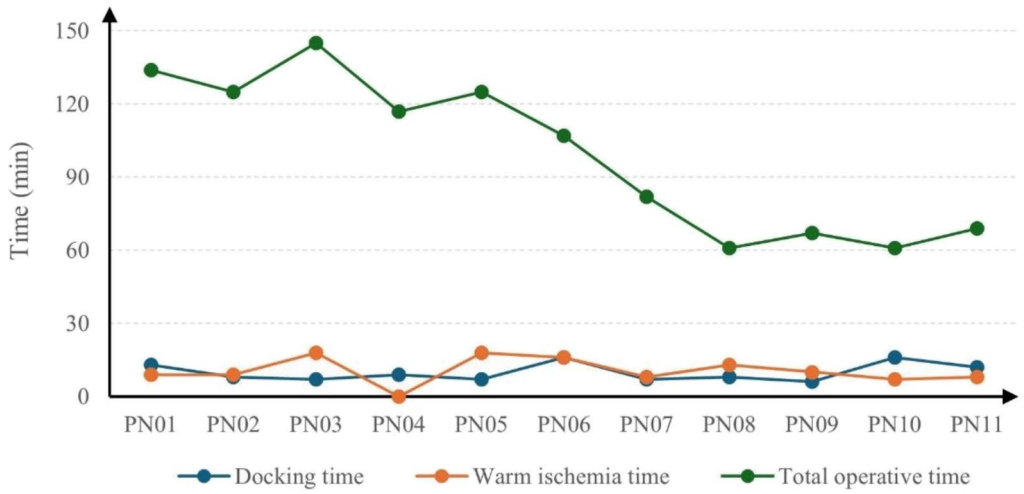

Fig. 2. Variation in Docking Time, Warm Ischemia Time, and Total Operative Time for Partial Nephrectomies demonstrating an efficient workflow with stable docking and ischemia times. The figure illustrates the variation in docking time (blue), warm ischemia time (orange), and total operative time (green) for each partial nephrectomy (PN) performed using the Toumai robotic system and demonstrates an efficient workflow with stable docking and ischemia times.

than, that reported in other series[15,16]. This is particularly notable considering the consecutive enrollment of patients without specific selection criteria. Warm ischemia time (WIT) is a critical modifiable factor influencing functional outcomes in partial nephrectomy, and the robotic approach has been shown to significantly reduce WIT[17]. The median WIT of 9-min compares favorably to prior robotic series[18]. Moreover, successful completion of a single off-clamp partial nephrectomy in 117 min and blood loss of 50 ml suggest encouraging early findings[19] for the system's responsive instrumentation and enhanced visual field stability during vascular control. However, this finding should be interpreted cautiously due to the single case performed, and further studies are needed to assesses the systems efficacy regarding off clamp partial nephrectomy.

All patients had negative surgical margins, and postoperative renal function was well-preserved, indicating both complete tumor resection and renal function preservation. Additionally, the absence of readmissions within 30 days reflects successful early surgical outcomes and adherence to high safety standards. The completion of all surgery without conversion and major machine related malfunction further supports the safety and efficacy of the system and its potential clinical application.

The Toumai robotic system incorporates features aimed at improving workflow efficiency, surgical precision, and safety. One of the major concerns in RAS is prolonged operative time, often influenced by docking procedures[20]. The system's four-arm suspension design, mounted on a movable overhead boom, allows maximum rotation and docking from any quadrant, improving docking times and overall surgical workflow. The suspension design also minimized physical interference with bedside assistants, optimizing workspace ergonomics. Laser crosshairs facilitate precise alignment of the patient cart with the camera port, helping streamline the docking process. The median docking time of eight minutes suggests the system's potential to optimize the surgical setup and improve procedural efficiency[19].

The ergonomic console design and instrument controls, appear beneficial during prolonged procedures by potentially reducing surgeon fatigue. Its wrist articulation technology provides enhanced instrument dexterity through seven degrees of freedom, while robotic instruments (diameter of 8.4 mm or smaller) offer 540 degrees of rotation and stable energy output. The system's master slave configuration, analogous to conventional robotic interfaces, enabled adaptation without observed disruptions to surgical performance or patient outcomes[21,22]. Operational safety features include automated collision detection, foot pedal safeguards and force feedback sensitivity as low as 0.1 N. Notably, no major machine-related malfunctions were observed in this cohort, suggesting its consistent and reliable performance. While these features may contribute to procedural safety and efficacy, their impact on workflow efficiency requires validation through larger comparative studies.

Current robotic systems are frequently limited by inadequate sensory feedback during tissue manipulation[23,24] The Toumai robotic system integrates haptic feedback technology, enabling surgeons to perceive real-time force interactions between instruments, tissues, and suture lines. This system achieves sensitivity thresholds as low as 0.1 N (Fig. 3), paired with self-compensating calibration to maintain accuracy during challenging and delicate procedures. Such features may enhance intraoperative decision making particularly in vascular dissection or suturing, by providing tactile cues to modulate instrument force and reduce inadvertent tissue strain[25,26]. Compared to the da Vinci robotic platform the Toumai advanced force feedback offers superior tactile feedback, enabling surgeons to feel the force exerted on tissues and make real-time adjustments. This enhanced sensitivity provides an additional layer of control, improving surgical precision and minimizing the risk of tissue damage (Table 2). While direct evaluation of haptic efficacy (e.g., force measurements during critical steps) was not performed, the lack of major intraoperative complication in this cohort aligns with the system's proposed technical advantages.

The robotic system integrates imaging innovations designed to enhance intraoperative visualization. The FPGA real-time image processing reduces latency to below 50 ms, enabling near-instantaneous visual feedback during instrument manipulation (Fig. 3). A dual-channel optical transmission system ensures stable data flow, while a 3D endoscope provides a wide, high-resolution field of view. Additional software algorithms including the Vascular Enhancement Algorithm and Intelligent Smoke Removal Algorithm automatically enhance vascular structures and filter surgical smoke, improving clarity during critical steps like vessel dissection[27,28]. While these features may support precision in complex anatomical settings, their direct impact on clinical outcomes requires further procedural validation.

This study has several limitations. First, the single center experience, small cohort, and short follow-up period restrict assessment of long-term outcomes, including delayed complications or cancer recurrence. Second, all procedures were performed by surgeons with extensive robotic expertise, which limits insights into the learning curve for less experienced teams and generalizability to low-volume centers. Third, while advanced features such as haptic feedback and imaging enhancements were utilized, their technical performance (e.g., force feedback precision, algorithm reliability) was not objectively quantified. Finally, cost comparisons with established systems and broader workflow efficiency were not directly evaluated. Larger studies, longer follow-up, and comparisons with established robotic systems are necessary to provide a more comprehensive understanding of its clinical applicability and validate the system's innovations.

Conclusion

In conclusion, the preliminary results of this study suggest that partial nephrectomy can be safely performed using the Toumai robotic system. The system's advanced features, including sensory feedback, high-frequency response, and enhanced imaging technologies likely contributed to favorable surgical outcomes with minimal complications. However, further research, including comparative studies with established systems is needed to validate these results and fully assess the clinical value of the system's advanced features.

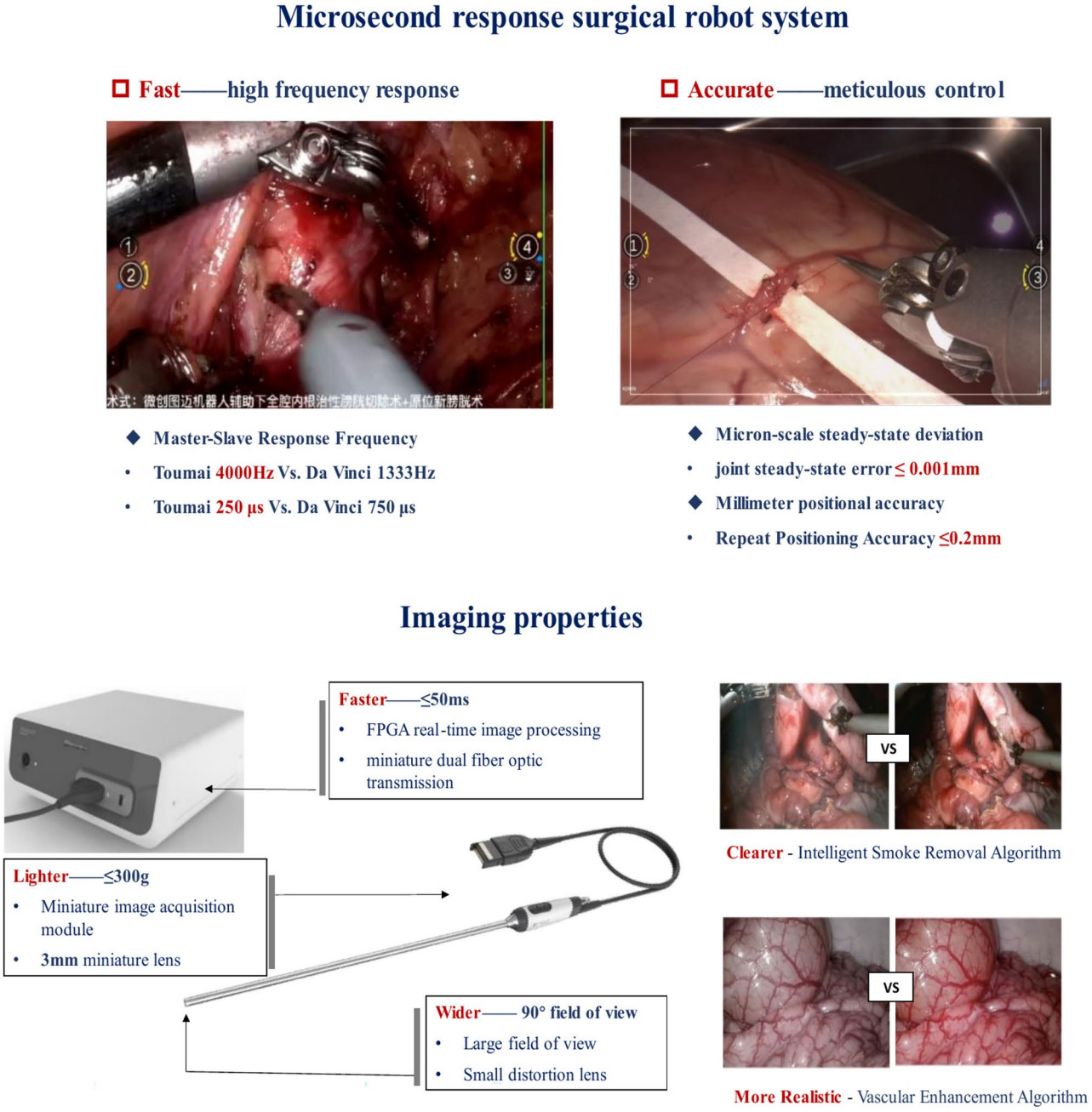

Fig. 3. Sensory feedback and advanced imaging features of Toumai robotic demonstrating high-response master slave response, advanced imaging technologies include the FPGA real-time image processing and Visual enhancement technologies. The Toumai robotic system incorporates advanced force sensing and feedback technology, with a masterslave frequency of 4000 Hz and a response time of 250 μs to enhanced high-response master slave response (upper panel). Advanced imaging technologies include the FPGA real-time image processing and dual fiber optic transmission with faster image acquisition and transmission, reducing latency to less than 50 ms. Visual enhancement technologies, including the Vascular Enhancement Algorithm and Intelligent Smoke Removal Algorithm (lower panel).

	Toumai	da Vinci Xi
Features		
Indication	Urology, Gynecology, Thoracic Surgery, General Surgery	Urology, Gynecology, Thoracic Surgery, General Surgery
Surgeon console		
Control scale	≥ 3 kinds	≥ 3 kinds
Operating force	0.1N	0.1N
Dual surgeon console	Yes	Yes
Resolution (HZ)	≥ 1920X1080, 60 Hz	≥ 1280X1024, 60 Hz
Optical device		
Image digital amplification ratio adjustment ≥ 3 types	Yes	Yes
Angle automatic 180° reversal function	Yes	Yes
Instrument		
Ultrasonic shears	Yes	Yes
Force sensing	Yes, ≤ 0.1N	No
Control Latency	≤ 50 ms	≤ 80 ms
Product life		
System	10 years	5 years
Endoscope image processor	5 years	5 years
5G telesurgery		
Industry position	Leading telesurgery technology in China	Non
Network-compatible	6 types: dedicated line, 5G, fiber, wifi, 4G, wired and other hospital network systems	Does not support
Longest distance	12,950 km	Non
Support for cross-border surgeries	Yes	Non
Number of surgeries	120 +	Non

Table 2. Comparison of the major features of the Toumai and da Vinci robotic surgical platforms.

Data availability

The datasets used and/ or analyzed during the current study available from corresponding author on reasonable request.

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References

1. Zahid, A. et al. Robotic surgery in comparison to the open and laparoscopic approaches in the field of urology: A systematic review. *J. Robot. Surg.* **17**, 11–29 (2023).
2. Sheetz, K. H., Claflin, J. & Dimick, J. B. Trends in the adoption of robotic surgery for common surgical procedures. *JAMA Netw. Open.* **3**, e1918911 (2020).
3. Pal, R. P. & Koupparis, A. J. Expanding the indications of robotic surgery in urology: A systematic review of the literature. *Arab. J. Urol.* **16**, 270–284 (2018).
4. Lv, Z. et al. Open versus robot-assisted partial nephrectomy for highly complex renal masses: A meta-analysis of perioperitive and functional outcomes. *J. Robot. Surg.* **17**, 1955–1965 (2023).
5. Chatterjee, S., Das, S., Ganguly, K. & Mandal, D. Advancements in robotic surgery: Innovations, challenges and future prospects. *J. Robot. Surg.* **18**, 28 (2024).
6. Yu, H. Y., Hevelone, N. D., Lipsitz, S. R., Kowalczyk, K. J. & Hu, J. C. Use, costs and comparative effectiveness of robotic assisted, laparoscopic and open urological surgery. *J. Urol.* **187**, 1392–1398 (2012).
7. Kallidonis, P. et al. Novel robotic platforms for robot-assisted laparoscopic surgery in urology: A narrative review. *J. Endourol.* **38**, 652–660 (2024).
8. Sarin, A. et al. Upcoming multi-visceral robotic surgery systems: A SAGES review. *Surg Endosc.* **38**, 6987–7010 (2024).
9. Pokhrel, G. et al. Assessing the feasibility and safety of the Toumai((R)) robotic system in urologic surgery: Initial experience. *J. Endourol.* **38**, 552–558 (2024).
10. Sunyi, Y. et al. Inferior vena cava hemangioma resected using a novel Toumai robotic surgical platform. *J. Vasc. Surg. Cases Innov. Tech.* **10**, 101403 (2024).
11. Zhang, Z. et al. An initial exploratory clinical study and outcome assessment of gastrointestinal surgeries using advanced robotic-assisted techniques. *Surg. Endosc.* **39**, 766–775 (2025).
12. Wang, Z. Y. et al. The efficacy of modified binding technique for renorrhaphy during robotic partial nephrectomy: Surgical and functional outcomes from single-center experience. *Surg. Endosc.* **37**, 391–401 (2023).
13. Mari, A. et al. Perioperative and mid-term oncological and functional outcomes after partial nephrectomy for complex (PADUA Score >/=10) renal Tumors: A prospective multicenter observational study (the RECORD2 project). *Eur. Urol. Focus.* **7**, 1371–1379 (2021).

14. Huang, J. et al. Comparison of lobectomy performed through Toumai((R)) surgical robot and da Vinci surgical robot in early-stage non-small cell lung cancer: A retrospective study of early perioperative results. *Transl. Lung Cancer Res.* **12**, 2219–2228 (2023).
15. Xu, W. et al. Robot-assisted partial nephrectomy with a new robotic surgical system: Feasibility and perioperative outcomes. *J. Endourol.* **36**, 1436–1443 (2022).
16. Garcia Rojo, E. et al. Da Vinci and Hugo RAS Platforms for robot-assisted partial nephrectomy: A preliminary prospective comparative analysis of the outcomes. *Minerva Urol. Nephrol.* **76**, 303–311 (2024).
17. Ingels, A. et al. Comparison of open and robotic-assisted partial nephrectomy approaches using multicentric data (UroCCR-47 study). *Sci. Rep.* **12**, 18981 (2022).
18. Kaul, S. et al. da Vinci-assisted robotic partial nephrectomy: Technique and results at a mean of 15 months of follow-up. *Eur. Urol.* **51**, 186–91 (2007).
19. Prata, F. et al. Robot-assisted partial nephrectomy using the novel Hugo RAS system: Feasibility, setting and perioperative outcomes of the first off-clamp series. *Urologia* **91**, 372–378 (2024).
20. van der Schans, E. M., Hiep, M. A. J., Consten, E. C. J. & Broeders, I. From Da Vinci Si to Da Vinci Xi: Realistic times in draping and docking the robot. *J. Robot. Surg.* **14**, 835–839 (2020).
21. Prata, F. et al. Skill transfer from laparoscopic partial nephrectomy to the Hugo RAS system: A novel proficiency score to assess surgical quality during the learning curve. *J. Clin. Med.* **13**(8), 2226 (2024).
22. Wee, I. J. Y., Kuo, L. J. & Ngu, J. C. A systematic review of the true benefit of robotic surgery: Ergonomics. *Int. J. Med. Robot.* **16**, e2113 (2020).
23. Bergholz, M., Ferle, M. & Weber, B. M. The benefits of haptic feedback in robot assisted surgery and their moderators: A meta-analysis. *Sci Rep.* **13**, 19215 (2023).
24. Lim, S. C., Lee, H. K. & Park, J. Role of combined tactile and kinesthetic feedback in minimally invasive surgery. *Int. J. Med. Robot.* **11**, 360–374 (2015).
25. Abdi, E., Kulic, D. & Croft, E. Haptics in teleoperated medical interventions: Force measurement, haptic interfaces and their influence on user's performance. *IEEE Trans. Biomed. Eng.* **67**, 3438–3451 (2020).
26. Awad, M. M., Raynor, M. C., Padmanabhan-Kabana, M., Schumacher, L. Y. & Blatnik, J. A. Evaluation of forces applied to tissues during robotic-assisted surgical tasks using a novel force feedback technology. *Surg. Endosc.* **38**, 6193–6202 (2024).
27. Wong, S. W. & Crowe, P. Visualisation ergonomics and robotic surgery. *J. Robot. Surg.* **17**, 1873–1878 (2023).
28. Wang, F., Sun, X. & Li, J. Surgical smoke removal via residual Swin transformer network. *In. J. Comput. Assist. Radiol. Surg.* **18**, 1417–1427 (2023).

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Declarations

Competing interest

The authors declare no competing interests.

Ethical approval

This study was approved by Institutional review board of first affiliated hospital of Zhengzhou University (2023-KY-0260-003). All the participant were well informed about the novel system and a written consent was taken after the approval to undergo the surgery.

Additional information

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