Contents lists available at: IJS

International Journal of Surgery

Journal homepage: ijsopen.org

Review Article

Remote Robotic Surgery: A Systematic Review

Yi Liu[1], Zhiping Ma[1], Pei Liu[1], Xiaowei Zhu[1], Long Zhao [1], Zhengjie Xu[1], Yuntao Ma[2,3] and Jing Yang[1,2,3*]

[1]*First Clinical Medical College, Gansu University of Chinese Medicine, Lanzhou, China*
[2]*Department of General Surgery I, Gansu Provincial People's Hospital, Lanzhou, China*
[3]*NHC Key Laboratory of Diagnosis and Therapy of Gastrointestinal Tumor & Key Laboratory of Molecular Diagnostics and Precision Medicine for Surgical Oncology in Gansu Province, Gansu Provincial Hospital, Lanzhou, China*

A R T I C L E I N F O

Keywords:
Human
remote
robotic surgery
systematic review

A B S T R A C T

Aim: To assess the clinical effectiveness, safety, technical feasibility, and challenges of remote robotic surgery in general surgery, gynecology, orthopedics, and urology, focusing on issues like communication technology, ethics, and cost.

Methods: Relevant reports on remote robotic surgery were retrieved from databases such as PubMed, Embase, Web of Science, Cochrane Library, VIP, CNKI, and Wanfang (2001-2025). Literature quality was evaluated using tools from the Joanna Briggs Institute (JBI).

Results: A total of 24 articles were included (13 in Chinese, 11 in English) covering general surgery, gynecology, orthopedics, urology, and thyroid surgery. The findings showed high success rates and accuracy in remote robotic surgery, with controllable network latency, demonstrating its potential to expand medical resource access, particularly in remote areas. However, challenges such as network stability, equipment cost, operational precision, data privacy, and ethical concerns remain.

Conclusion: Despite challenges, remote robotic surgery shows promise in overcoming geographical and resource limitations. With continuous technological advancements, it is expected to play an increasingly significant role in global healthcare.

1. Introduction

With the continuous advancements and widespread adoption of robotic surgical systems, robotic surgery technology has progressively expanded across multiple disciplines and medical specialties [1]. With the rapid advancement of medical technology, remote robotic surgery systems have emerged as a revolutionary breakthrough in surgical techniques and have become a key focus in medical research. By integrating advanced communication technologies, robotics, and artificial intelligence, these systems enable surgeons to perform operations on patients from a distance. They demonstrate significant application potential, particularly in addressing uneven distribution of medical resources and providing emergency medical assistance in challenging environments [2, 3]. The concept of remote surgery can be traced back to the 1950s when NASA proposed it to ensure the medical needs of astronauts in space [4]. Owing to the limitations of communication and automation technologies at the time, this vision could not be realized immediately [5]. However, with the rapid advancement of 5G network technology, remote surgery systems are encountering new opportunities. The low-latency and high-bandwidth characteristics of 5G networks offer more stable and efficient technical support for remote surgical procedures [6].

For instance, in remote areas or during emergency scenarios such as earthquakes, physicians can perform complex surgical procedures by remotely operating robots via 5G networks in real time, thereby substantially enhancing the accessibility and efficiency of medical services [6]. Furthermore, the widespread adoption of 5G technology has facilitated the implementation of multi-center collaboration and real-time data transmission, thereby significantly enhancing the safety and reliability of remote surgical procedures [7]. This systematic review aims to assess the current status of telerobotic surgery in clinical practice, with a focus on its developmental trajectory and practical applications

[*]*Corresponding author: First Clinical Medical College, Gansu University of Chinese Medicine, Department of General Surgery I, Gansu Provincial People's Hospital, NHC Key Laboratory of Diagnosis and Therapy of Gastrointestinal Tumor & Key Laboratory of Molecular Diagnostics and Precision Medicine for Surgical Oncology in Gansu Province, Gansu Provincial Hospital, Lanzhou 730000, China; E-mail: 21634604@qq.com* (Jing Yang)

10.60122/j.IJS.2025.50.01
Received 13 November, 2025; Accepted 17 December, 2025
Available online 23 February, 2026

within the medical field. By synthesizing research advances and technological breakthroughs both domestically and internationally, the study further examines existing challenges, including high equipment costs, insufficient network coverage, evolving ethical oversight, and regulatory framework limitations [8], and propose corresponding solutions.

2. Methods

2.1. Literature Search Strategy

We conducted a systematic review of existing literature published between 2001 and 2025 across multiple databases, including PubMed, Embase, Web of Science, Cochrane Library, VIP, CNKI, and Wanfang. The search strategy incorporated a combination of Medical Subject Headings (MeSH) and text words, integrating terms such as "telemedicine," "telerobotic surgery," and their synonyms to ensure comprehensive coverage and minimize the likelihood of omitting relevant studies. Boolean operators ("AND" and "OR") were employed to further refine the search process.

2.2. Inclusion and Exclusion Criteria for Literature

2.2.1. Inclusion Criteria

i) The study population comprises human clinical cases (excluding cadaveric specimens). ii) Included publications were issued between 2001 and 2025. iii) Surgical procedures were performed through direct remote manipulation of robotic systems by surgeons.

2.2.2. Exclusion Criteria

i) Articles specifically involving animal experimentation. ii) Review articles and news reports. iii) Publications focusing on telemedicine services without specific data. iv) Studies not related to remote surgery. v) Literature for which full text is unavailable. vi) Articles reporting cases converted to open or laparoscopic procedures during intervention were excluded.

2.3. Literature Screening and Data Extraction

During the screening process, an initial assessment of article relevance was conducted based on titles, abstracts, and keywords. Subsequently, cross-referencing was performed to identify additional relevant studies, followed by full-text reviews of articles meeting the inclusion criteria. Two researchers independently extracted data from the included literature using the Cochrane data extraction tool, capturing details such as authorship, publication year, sample size, surgical distance, network establishment, economic outcomes, and safety profiles. All stages were independently evaluated by both authors, with any discrepancies resolved through consensus discussions.

2.4. Literature Quality Assessment

Two researchers independently assessed the quality of the included studies using the Case Report Quality Appraisal Tool (or the Cross-Sectional Study Quality Appraisal Tool, as applicable) provided by the Joanna Briggs Institute (JBI) Centre for Evidence-Based Health Care in Australia. The appraisal tool comprises eight items, each evaluated as "Yes," "No," or "Unclear." Any discrepancies arising during the evaluation process were resolved through discussion or consultation with a third researcher.

3. Results

3.1. Literature Search Results

A preliminary search identified 19,662 potentially relevant publications. After removing duplicates, screening titles and abstracts, and conducting full-text reviews, 24 studies met the eligibility criteria for inclusion in the systematic review. The literature selection process and results are illustrated in (Figure 1).

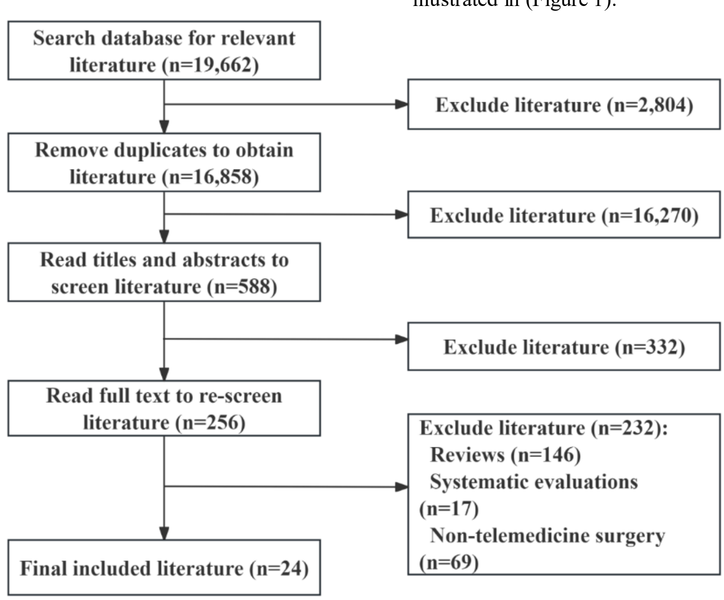

Fig. 1. Flowchart of literature screening process.

3.2. Baseline Characteristics of Included Studies and Methodological Quality Assessment

Among the 24 included studies, 13 were published in Chinese and 11 in English, with publication dates spanning from 2001 to 2025. The baseline characteristics of the included studies are presented in (Table 1). All reports indicated uneventful surgical procedures and absence of serious postoperative complications. The methodological quality assessment results, based on the JBI Critical Appraisal Tool for Case Reports, are summarized in (Table 2). Overall, the studies demonstrated satisfactory reporting in clearly documenting the surgical intervention process (Item 5), short-term postoperative outcomes (Item 6), and absence of severe complications (Item 7). However, descriptions of patients' baseline comorbidities (Item 2) were generally insufficient, and most studies lacked medium- to long-term follow-up data (depth of Item 6). Furthermore, monitoring and reporting standards for technology-specific adverse events inherent to telesurgery—such as communication interruptions and data packet loss—were inconsistent across studies.

Table. 1. Baseline characteristics of the included studies.

Included Study (Author, Year)	Surgical Procedure	Sample Size (n)	Surgeon-Patient Distance (km)	Reported Latency (ms)	Communication Method	Robotic System	Regulatory & Ethical Oversight	Surgical Outcomes & Complications	Economic Aspects
Wassilios Bentas et al. (2002)	Laparoscopic Transperitoneal Adrenalectomy	4	Not Reported	Not Reported	Not Reported	da Vinci™ Surgical System	Not Reported	Three right-sided and one left-sided adrenal tumor were successfully resected. No complications occurred, with excellent clinical outcomes. Procedures were completed laparoscopically with minimal blood loss and rapid patient recovery.	The da Vinci Surgical System incurs high costs, at least at present.
Ezio Caratozzolo et al. (2005)	Telerobotic-Assisted Laparoscopic Cholecystectomy (TLAC)	29	Not Reported	Not Reported	Not Reported	Zeus and Aesop Systems	Approved by the European Professional Ethics Committee.	Mean operative time: 75 min; setup time: 45 min; 2 cases required conversion to open surgery. No TLAC-related complications. Limitations included lack of tactile feedback, increased operative time, and high cost.	System cost: 1.3 million Euros.
Han-Xin Zhou et al. (2005)	Telerobotic-Assisted Laparoscopic Cholecystectomy using the Zeus System	40	Not Specified	Not Specified	Not Specified	Zeus Robotic Surgical System	Not Specified	All 40 procedures were completed successfully without postoperative complications.	Not Specified
F. Marchal et al. (2005)	Telerobotic-Assisted Laparoscopic Hysterectomy	30	>0 (Remote Operation)	Not Explicitly Reported	Not Explicitly Described	da Vinci Surgical System	Approved by the institutional review boards of both participating institutions.	Operative time ranged from 43-315 min (mean 185 min). Procedure-related complication rate was 17%; no complications were related to the robotic system itself.	System cost approximately 1 million Euros; disposable supply cost per procedure ~200 Euros. A comprehensive cost-effectiveness analysis was not performed.
Wei Tian et al. (2019)	Spinal Internal Fixation Surgery	5	One-to-Multiple Sites	Not Reported	Not Reported	TiRobot Orthopaedic Surgical Robot	Not Reported	Operative time: (122.0±33.5) min; guide pin insertion time: (44.0±8.2) min; excellent screw placement accuracy: 96.7%; VAS score decreased from preoperative (4.6±1.5) to postoperative (2.6±0.5).	Not Reported
Xiangpeng Kong et al. (2020)	Robot-Assisted Total Hip Arthroplasty with 5G Remote Guidance	2	Case 1: 3000; Case 2: 1200	Not Explicitly Reported	5G Communication	Mako Robot (Stryker, USA)	Study protocol approved by the Medical Ethics Committee of PLA General Hospital (S2019-052-01).	Procedures proceeded smoothly with fluid intraoperative communication. The robotic arm and software functioned well, yielding satisfactory short-term follow-up outcomes.	Not Reported
Wei Tian, Mingxing Fan, et al. (2020)	Telerobotic Spinal Surgery	12	Not Explicitly Stated	28	5G Network	TiRobot System	Approved by the Bioethics Committee (ID: 20181106).	Cases included 4 thoracolumbar fractures, 6 lumbar spondylolisthesis, and 2 lumbar spinal stenosis.	Not Explicitly Stated
Hang Yuan et al. (2022)	Telerobotic-Assisted Nephrectomy using a Domestic Robot	3	82.5, 141.0, 229.0	Mean: 27.3; Total Avg: 177.3	5G Wireless Communication	Domestic MicroHand S Surgical Robot System (Model WG-NST600S)	Approved by the Medical Ethics Committee of the Affiliated Hospital of Qingdao University and registered for clinical trial.	All three telerobotic procedures were completed successfully. No network-related adverse events occurred. Occasional robot-related minor issues did not impact procedure progression. No postoperative complications.	Not Reported
Xiang Zhou et al. (2022)	Telerobotic-Assisted High Ligation of the Spermatic Vein via 5G	2	3800	130	Public 5G Wireless Network	Domestic 'Tumai' Surgical Robot System	Approved by the Ethics Committee of Xinjiang Kizilsu Kirghiz Prefecture People's Hospital.	Total operative times were 45 min and 40 min, respectively; blood loss <5ml for both. Postoperative recovery was uneventful with no complications.	The domestic robot reduced costs, being approximately one-third cheaper than imported robotic equipment.
Daqi Zhang et al. (2023)	Robotic Bilateral Axillo-Breast Approach (BABA) Thyroidectomy (RT-BABA) vs. Endoscopic BABA Thyroidectomy (ET-BAA)	757	Not Reported	Not Reported	Not Reported	RT-BABA: da Vinci® Surgical System; ET-BAA: Olympus Endoscopic Surgery System	Not Reported	Compared to ET-BAA, RT-BABA was associated with shorter operative time, shorter postoperative hospital stay, and a lower incidence of temporary vocal cord dysfunction, albeit at a higher cost.	Although associated with higher costs, RT-BABA provided superior surgical outcomes in certain aspects.
Chenglei Gu et al. (2023)	5G Telerobotic-Assisted Laparoscopic Total Hysterectomy	1	4000	Average: 161.959	5G Wireless Network (China Telecom) and 5G CPE	Domestic Tumai Four-Arm Laparoscopic Surgical Robot System	Approved by the Ethics Committees of the Seventh Medical Center of PLA General Hospital and Pishan County People's Hospital, with patient informed consent obtained.	Operative time: 62 min; blood loss: 5ml. Patient passed flatus and initiated oral intake on postoperative day 1, urinary catheter removed on day 2, and discharged on day 3. No postoperative complications.	Not Reported
Yan Ke et al. (2023)	5G Telerobotic-Assisted Total Hip Arthroplasty	55	1985	172.28±36.58	5G Wireless Cellular Network	MAKO Smart Robotic-Arm Assisted System	Remote guidance from Beijing experts, with the procedure performed by local surgeons.	Operative time was significantly longer in the robotic group (126.41±12.78 min) compared to the conventional group (88.81±8.83 min) (t=13.31, P<0.001).	Not Reported

Included Study (Author, Year)	Surgical Procedure	Sample Size (n)	Surgeon-Patient Distance (km)	Reported Latency (ms)	Communication Method	Robotic System	Regulatory & Ethical Oversight	Surgical Outcomes & Complications	Economic Aspects
Yuxin Fan, Chao Ma, Xinyu Wu (2024)	Hepato-pancreato-biliary surgery	5	4670.2	73 (70.25–126.10)	5G Network	Tumai Four-Arm Robot	Approved by the Ethics Committee of Sir Run Run Shaw Hospital, Alar Hospital, Zhejiang University School of Medicine	Successfully completed five ultra-remote robot-assisted hepato-pancreato-biliary surgeries.	Optimizes allocation of medical resources, reduces treatment costs, improves efficiency, and enhances patient convenience.
Yu Tian, Huibin Lv, Adilijiang Jumai (2024)	Ultra-remote robot-assisted right upper lobectomy	1	5000	Average 100 ms	Dedicated network and 5G mobile communication	Minimally Invasive Tumai® Laparoscopic Surgical Robot System	Approved by the Institutional Review Boards of Shanghai Chest Hospital and the Second People's Hospital of Kashi Prefecture	Successful surgery; patient recovered well postoperatively.	Facilitates the transfer of medical resources from developed to underdeveloped regions.
Fenghai Zhou, Baihong Guo, Haidi Lv (2024)	Adrenal tumor resection, nephrectomy, partial nephrectomy, partial cystectomy, ureteral reimplantation, radical prostatectomy	14	52	Average max latency 129.3 ms, Average min latency 20.7 ms	5G Network	Domestic Tumai Surgical System	Approved by the central medical ethics committee; patients or authorized representatives signed informed consent.	Completed 14 surgeries. Average operation time 83.3 min, average blood loss 23 ml; no conversions to open surgery; no complications.	Optimizes rational distribution of medical resources, expands telemedicine applications, aids emergency response, supports decentralization/sharing of high-quality resources, reduces economic costs.
Honghai Guo, Yuan Tian, Jia Shi (2024)	Robot-assisted remote radical distal gastrectomy for gastric cancer	1	Surgeon at branch hospital, Patient at main hospital	Average total intraoperative latency 225 ms, Average round-trip delay 30 ms	5G wireless network (China Mobile) and 5G CPE	Tumai Robotic Surgical System	Approved by the Ethics Committee of the Fourth Hospital of Hebei Medical University	Successful surgery; no postoperative complications.	Application of 5G technology in remote surgery marks significant progress; addresses key challenges in medical resource distribution, especially in resource-limited areas.
Juyuan Huang, Li'an Li, Jing Cheng (2024)	Ultra-remote robot-assisted laparoscopic total hysterectomy	1	1200	19	5G communication technology combined with wired network	Edge MP1000 Multi-port Endoscopic Surgical Robot	Approved by the hospital ethics committee.	Successful surgery; no complications; intraoperative blood loss ~20 ml; duration ~70 min.	Breaks geographical barriers, delivers quality medical resources to underserved areas, promotes homogenization of diagnosis/treatment levels.
Li Songyan, Wen Wei, Dai Feixiang, et al. (2024)	Ultra-remote robot-assisted radical resection of rectal cancer	1	3000	170	5G network and public internet dedicated line	Domestic MP Surgical Robot System	Approved by the Ethics Committee of Chinese PLA General Hospital.	Smooth procedure; no noticeable latency; no complications; blood loss 20mL; operation time 90 min; smooth postoperative recovery.	Not Reported
Tian Wen, Wang Bing, Yao Jing, et al. (2024)	Remote robot-assisted hiatal hernia repair and fundoplication	1	2200	Average latency: 39, Total average latency: 159	Wired network (100 Mb/s public internet) & China Telecom 5G; both encrypted, pre-debugged with new-gen firewall.	Jingfeng MP1000 Surgical Robot System, Software v1.3.4.0	Approved by Chinese PLA General Hospital Ethics Committee (No. S2024-488-01); patient/family signed informed consent.	Surgery successful; no complications; blood loss 10 mL; op time 78 min. Flatus/defecation at 23h, eating at 2d, discharge at 6d.	High communication, procurement, maintenance costs limit adoption in poor areas. Costs expected to decrease with domestic robots, easing patient burden.
Tian Wen, Yao Jing, Wang Bing, et al. (2024)	5G remote robotic-assisted radical thyroidectomy for thyroid cancer	1	2200	39	Dedicated line network and 5G wireless network	Shenzhen Jingfeng Medical MP1000 Surgical Robot System	Approved by the Ethics Committee of Chinese PLA General Hospital.	Smooth procedure; no complications; duration 1h 55min; blood loss ~10 mL. Smooth recovery; PTH 15.25 ng/L; discharged on day 5.	Not Reported
Tong Guoyu, Zhang Yinan, Wu Shao, et al. (2024)	Domestic robot 5G remote bilateral gonadectomy	1	2274	Not explicitly reported	5G Network	Tumai® Four-Arm Laparoscopic Surgical Robot	Approved by the hospital ethics committee.	Successful surgery; duration 40 min; blood loss ~2 mL; no transfusion; good recovery.	Not Reported
Wang Xiaopeng, Wang Yan, Ma Yuntao, et al. (2025)	5G remote robot-assisted sleeve gastrectomy	1	75.6	55.16 ± 25.33	5G signal network system	Minimally Invasive Tumai Laparoscopic Surgical Robot System (MT-1000)	Approved by Gansu Provincial Hospital Medical Ethics Committee; patient informed consent; detailed surgical plan/contingencies; monitoring roles/secondary console.	Successfully completed; total duration 120 min; blood loss 20 ml; good recovery; no complications.	Not Reported
Zhan Weipeng, Ma Yuqi, Hu Ming, et al. (2025)	5G remote robot-assisted radical distal gastrectomy for gastric cancer	1	70	43	Public 5G wireless network, VPN encrypted via intelligent firewall	Tumai® Laparoscopic Surgical Robot	Compliant with laws/ethics/Helsinki Declaration; approved by Gansu Provincial Hospital Med. Ethics Comm. (No. 2023-328).	Smooth procedure; total time 250 min; master-slave control 190 min; blood loss ~50mL. Good recovery, discharged day 10. Pathology: mod. diff. adenocarcinoma (T3N2M0); 6 chemo sessions; no recurrence/metastasis.	Aids decentralization of resources, addresses supply-demand imbalance, narrows regional gaps, reduces expenses/patient burden.
Zhang Wentao, Miao Changfeng, Hu Ming, et al. (2025)	5G remote robot-assisted radical colectomy for colon cancer	1	70	Max latency 84.2ms, range 20-100ms	5G Network	Domestic Tumai® Robotic Surgical System (MT1000)	Not Reported	Smooth procedure; no network interruption/robot-related adverse events; total time 250min; blood loss 10mL; good recovery; no complications.	Not Reported

Table. 2. Methodological quality assessment of included studies.

Included Study (Author, Year)	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩
Bentas W, Wolfram M, et al. (2002)	Yes	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Unclear
Caratozzolo E, Recordare A, et al. (2005)	Yes	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Unclear
Zhou HX, Guo YH, Yu XF, et al. (2005)	Yes	Yes	Unclear	Unclear	Yes	Yes	Yes	Yes	Yes	Unclear
Marchal F, Rauch P, Vandromme J, et al. (2005)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	Unclear
Tian W, Zhang Q, Li ZC, et al. (2019)	Yes	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes
Kong XP, Fu J, Chen JY, et al. (2020)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tian W, Fan MX, Zeng C, et al. (2020)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Yuan H, Yang XC, Luo L, et al. (2022)	Yes	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes
Zhou X, Wang JY, Zhu X, et al. (2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	Yes
Zhang DQ, Wang C, Sui CQ, et al. (2023)	Yes	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes
Gu CL, Li LA, Wang N, et al. (2023)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	Yes
Ke Y, Li ZC, Luo SQZ, et al. (2023)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fan YX, Ma C, Wu XY, et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear
Tian Y, Lv HB, Jumai A, et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear
Zhou FH, Guo BH, Lv HD, et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Guo HH, Tian Y, Shi J, et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear
Huang JY, Li LA, Cheng J, et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear
Li SY, Wen W, Dai FX, et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	Unclear
Tian W, Wang B, Yao J, et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear
Tian W, Yao J, Wang B, et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear
Tong GY, Zhang YN, Wu S, et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear
Wang XP, Wang Y, Ma YT, et al. (2025)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear
Zhan WP, Ma YQ, Hu M, et al. (2025)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear
Zhang WT, Miao CF, Hu M, et al. (2025)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	Unclear

Notes: ① Were there clear criteria for inclusion? ② Was the condition measured in a standard, reliable way? ③ Were valid methods used for identification?④ Did the study use consecutive inclusion? ⑤ Was complete inclusion achieved? ⑥Were clear demographics reported? ⑦ Were clinical information features clear?⑧ Were outcomes or follow-up results clear? ⑨ Was there clear reporting of adverse events? ⑩ Were statistical analyses appropriate?

4. Discussion

4.1. Surgical Efficacy and Safety

This systematic review demonstrates that, based primarily on current evidence from case reports, telerobotic surgery exhibits favorable short-term safety and feasibility. For instance, the study by Kong Xiangpeng *et al.* on 5G communication technology-guided telerobotic total hip arthroplasty reported uneventful procedures and satisfactory short-term follow-up outcomes [9]; Yuan Hang *et al.* successfully performed three cases of remote nephrectomy using domestically produced robotic systems, with no postoperative complications reported in any instance [10]. Some problems also exist in certain studies. For instance, in the 5G remote robot-assisted total hip arthroplasty conducted by Ke Yan *et al.*, the operation time of the robot group was longer than that of the conventional group [11]. This may be attributed to the operational complexity of robotic systems and the associated learning curve. The maintained safety and efficacy of surgical procedures indicate that remote robotic surgery holds broad application potential across various surgical types. However, further optimization of operational protocols and enhanced surgeon training are required to improve procedural efficiency [12].

Nevertheless, the interpretation of these optimistic findings must be contextualized within the methodological limitations inherent in the included studies. These investigations were predominantly conducted at leading medical centers, involved rigorously selected patient cohorts, and emphasized the reporting of successful outcomes, which may lead to an overestimation of therapeutic efficacy and an underestimation of rare adverse events. Consequently, the reported 100% success rate should be regarded as a "proof-of-concept" performance under idealized conditions rather than as an indicator of real-world effectiveness in broader clinical practice.

4.2. Evolution of Communication Technologies

Research on telesurgery commenced at a relatively early stage, with the earliest documented case dating back to 2001. During that period, Marescaux *et al.* performed a remote laparoscopic cholecystectomy by controlling a robotic system via high-speed optical fiber cables, reporting an overall latency of approximately 155 milliseconds [13]. By 2006, the "one-to-many" master-slave remote surgical robot-assisted tibial intramedullary nailing internal fixation surgery system independently developed by Beijing Jishuitan Hospital based on the ASDL/ISDN network platform had a successful operation. However, due to the bandwidth limitations of ASDL at that time, only image transmission could be guaranteed. Moreover, due to the lack of security, the operation was also attacked by viruses during the process [14]. This fully demonstrates that under previous communication conditions, the safety and reliability of remote robotic surgery could not be adequately guaranteed. Subsequently, with the rapid advancement of communication technologies, the emergence of 5G network technology has provided new possibilities for the further expansion of remote surgery. For instance, Liu Rong and colleagues preliminarily validated the feasibility of 5G-enabled remote surgery through animal experiments [15]. The official deployment of 5G networks in 2018, characterized by high-speed data transmission and low latency, has provided robust technical support for ensuring the successful execution of surgical procedures [16]. Against this backdrop, remote surgery has been progressively implemented across various specialized fields, including neurosurgery, orthopedics, and urology [17]. With the continuous advancement of communication technologies, the geographical limitations for surgical procedures are being progressively overcome.

For instance, in January 2024, China successfully performed its first transcontinental robot-assisted radical resection of rectal cancer over a distance of 3,000 kilometers [18], this achievement marks a significant milestone in the field of remote robotic surgery in China. It is noteworthy that the majority of studies employ 5G communication technology. For instance, research by Zhou Xiang *et al.* on ultra-remote 5G robot-assisted laparoscopic high ligation of the spermatic vein demonstrated that utilizing public 5G wireless networks resulted in shorter total operative duration, favorable postoperative recovery, and absence of complications [19]. Furthermore, several studies have integrated wired networks with 5G technology, as exemplified by the remote robot-assisted hiatal hernia repair and fundoplication procedure conducted by Tian Wen *et al.* Through encryption protocols and firewall implementation, these approaches ensured secure data transmission, resulting in successful surgical completion without complications [20]. However, communication latency remains a non-negligible issue, as exemplified by Zhan Weipeng *et al.*'s 5G-enabled remote robot-assisted radical gastrectomy, which exhibited an average latency of 43ms [21], n their study on 5G-enabled remote robot-assisted radical colectomy, Zhang Wentao and colleagues reported a maximum latency of 84.2 ms, with latency fluctuations ranging between 20 and 100 ms [22]. Despite breakthroughs in 5G network technology for latency reduction, which have not yet substantially impacted surgical procedures, this underscores the persistent need for further optimization of network stability and security—particularly in long-distance transmissions and complex network environments [23]. In the future, with the deployment of next-generation wireless communication technologies such as 6G and satellite communications [16, 24], this advancement holds the potential to significantly reduce latency while enhancing the stability and reliability of communications, thereby providing a more robust technical foundation for the widespread adoption of remote robotic surgery.

4.3. Regulatory and Ethical Considerations

Remote robotic surgery involves complex regulatory and ethical considerations, with the majority of studies having obtained approval from relevant ethics committees and secured informed consent from patients [25, 26]. The 5G remote robot-assisted total laparoscopic hysterectomy performed by Gu Chenglei *et al.* was approved by the Ethics Committee of the Seventh Medical Center of the PLA General Hospital and the Medical Ethics Committee of Pishan County People's Hospital, with informed consent obtained from the patient [27]. This ensures the legality and regulatory compliance of the surgical procedures, thereby safeguarding patients' rights and interests. Meanwhile, regulatory guidelines for remote surgery are being continuously refined. Research by scholars such as Yuma Ebihara indicates that Japan is currently developing guidelines for optimal communication systems in the clinical application of telerobotic surgery, which will establish a critical foundation for standardizing the advancement of remote robotic surgical practices [28]. Finally, data security and privacy protection represent critical considerations that warrant due attention [29, 30]. The surgical process involves a large amount of sensitive patient information. How to ensure the security of data during transmission and storage and prevent information leakage or tampering is a difficult problem that must be solved in the development of remote robotic surgery technology [31, 32]. Strengthening ethical oversight to ensure the steady advancement of remote robotic surgery requires further enhancing the regulatory framework, clarifying the responsibilities and obligations of all stakeholders, and establishing relevant laws and regulations. These measures are essential to prevent cybersecurity threats, such as hacker intrusions, from compromising surgical safety, thereby guaranteeing that remote robotic surgeries are conducted securely, effectively, and in compliance with established standards [33].

4.4. Benefits and Costs

The implementation of remote robotic surgery entails substantial costs, encompassing equipment procurement expenditures, communication infrastructure fees, as well as ongoing expenses for line maintenance and system diagnostics [34]. As highlighted in the study by Tian Wen *et al.* on telerobotic-assisted hiatal hernia repair and fundoplication, the elevated costs associated with telecommunication infrastructure pose significant barriers to the widespread adoption of remote surgical systems in resource-limited healthcare settings [20]. However, with the continuous advancement of domestically produced surgical robots such as the Toumai robotic system, associated costs are expected to gradually decrease. As indicated by studies conducted by Zhou Xiang *et al.*, domestically manufactured robotic systems have reduced operational expenses, with costs nearly one-third lower than imported robotic equipment. This contributes to alleviating the financial burden on patients and enhances the accessibility of surgical procedures [35]. Furthermore, remote robotic surgery demonstrates potential economic benefits in optimizing healthcare resource allocation, reducing treatment costs, and enhancing operational efficiency [6]. As noted in the urological surgery literature by Fenghai Zhou *et al.*, the implementation of telerobotic surgery optimizes the rational distribution of medical resources, extends the scope of telemedicine applications, enhances emergency response capabilities during crises, facilitates the decentralization and collaborative sharing of high-quality medical resources, and reduces economic costs [36]. Consequently, remote robotic surgery demonstrates considerable long-term potential in terms of both economic efficiency and societal benefits.

4.5. Future Outlook

Future research and technological advancements in telerobotic surgery should prioritize the following key areas: first, enhancing network technologies to not only minimize latency but also improve stability and interference resistance, thereby ensuring seamless connectivity and real-time communication in complex operational environments. Furthermore, it is imperative to explore efficient network architectures and transmission protocols to meet the stringent requirements for high-speed, low-latency data transmission in remote surgical procedures [29]. Second, reducing the cost of surgical robotic systems constitutes a critical factor in promoting their widespread adoption. Through technological innovation, scaled production, and optimized supply chains, manufacturing and maintenance expenses can be minimized, thereby enhancing healthcare institutions' accessibility to these technologies and ultimately benefiting a larger patient population. Third, optimize the surgical robotic system to enhance its operational precision

[37], flexibility, and adaptability to address more complex surgical demands [38, 39].

Concurrently, investigate collaborative models between surgeons and robotic systems to leverage the respective strengths of both, thereby improving overall surgical outcomes [40]. Finally, it is imperative to enhance data security and privacy protection, establish a comprehensive management framework, strengthen ethical oversight, and refine relevant laws and regulations to ensure the security of patient information [41, 42]. Extensive clinical trials should be carried out to accumulate data and experience, providing a basis for the standardization and normalization of remote robotic surgery. At the same time, the application of technologies such as satellite communication in remote areas should be explored to address the issue of insufficient network coverage and further expand the application scenarios of remote surgery [43].

5. Conclusion

Remote robotic surgery represents an emerging surgical technique with substantial potential and increasing maturity. Despite challenges such as network stability, equipment costs, operational precision, data security, ethical oversight, and regulatory compliance, continuous technological innovation and in-depth research are expected to gradually address these issues. In the future, remote robotic surgery will play an increasingly vital role in the medical field and contribute significantly to the advancement of global healthcare.

Conflicts of Interest

None.

Acknowledgments

We extend our sincere gratitude to Professor Yang Kehu, Dean of the Evidence-Based Medicine Institute at Lanzhou University, for his invaluable methodological guidance on this article.

Author Contributions

Liu Yi and Ma Zhiping made substantial contributions to the conception and design of the study, conducted data analysis and interpretation, and were responsible for manuscript preparation. Liu Pei, Zhu Xiaowei, Zhao Long, and Xu Zhengjie were in charge of data acquisition and provided administrative, technical, and material support. Yang Jing and Ma Yuntao were responsible for manuscript revision and editing.

Availability of Data and Materials

Not applicable.

Financial Support and Sponsorship

None.

Ethical Approval and Consent to Participate

Not applicable.

Funding Project

Gansu Province Longyuan Talent Project.

References

[1] Wang Y, Ai Q, Li H. Z., et al. "Evolution and Research Progress of Remote Surgery." *Journal of Minimally Invasive Urology*, vol. 12, no. 2, pp. 73-76, 2023.

[2] Juyuan Huang, Li'an Li, Jing Cheng, et al. "Feasibility and safety evaluation of ultra-remote robot-assisted laparoscopic hysterectomy." *Intelligent Surgery*, vol. 7, pp. 74-79, 2024. View at: Publisher Site

[3] Sima Ajami, Parisa Lamoochi "Use of telemedicine in disaster and remote places." *J Educ Health Promot*, vol. 3, no. 1, pp. 26, 2014. View at: Publisher Site | PubMed

[4] Bai Jing. *Introduction to Telemedicine* [M]. *Tsinghua University Press Co.*, Ltd., 2000.

[5] Frederick Godley 4th, Danyal Fer, Ankit D Patel, et al. "Remote robotic surgery: implementing a technology 20 years in the making." *Surg Endosc*, vol. 39, no. 4, pp. 2743-2747, 2025. View at: Publisher Site | PubMed

[6] Diao S. W., Zhang J. B., Zhu P. "Research Progress of Telemedicine in Surgery." *Advances in Clinical Medicine*, vol. 15, pp. 2184, 2025.

[7] He Bingwei, Zhang Yue, Deng Zhen, et al. "Research Progress in Medical Robotics and Medical-Engineering Integration Technologies." *Journal of Fuzhou University*, vol. 49, no. 5, 2021.

[8] Shady Saikali, Marcio Covas Moschovas, Ahmed Gamal, et al. "Telesurgery: humanitarian and surgical benefits while navigating technologic and administrative challenges." *J Robot Surg*, vol. 18, no. 1, pp. 393, 2024. View at: Publisher Site | PubMed

[9] Xiang Pengkong, Jun Fu, Chen Jiying, et al. "Two Cases of Robot-Assisted Total Hip Arthroplasty Remotely Guided via 5G Communication Technology." *Chinese Journal of Reparative and Reconstructive Surgery*, vol. 34, no. 11, pp. 1492, 2020.

[10] Lin Yuanhang, Yang Luo, Lei Jiao, et al. "Preliminary Analysis of Indigenous Robot-Assisted Remote Nephrectomy Utilizing 5G Communication Technology." *Chinese Journal of Urology*, 2022.

[11] Ke Yan, Li Zhichang, Luo Songquzhu, "Robotic-assisted total hip arthroplasty via 5G remote technology for hip joint lesions induced by Kashin-Beck disease." *Chinese Journal of Orthopaedics*, 2023.

[12] Wang Y, Yan S, Chang YF, et al. "Current status and advances in telesurgical innovation." *Journal of Naval Medical University*, vol. 44, no. 5, pp. 627-630, 2023.

[13] J Marescaux, J Leroy, M Gagner, et al. "Transatlantic robot-assisted telesurgery." *Nature,* vol. 168, no. 2, pp. 873-874, 2001. View at: Publisher Site | PubMed

[14] Wang JQ, Zhao CP, Hu L, et al. "Preliminary Application of a Remote

Surgical Robotic-Assisted System for Tibial Intramedullary Nail Fixation.” *Chinese Journal of Orthopaedics*, no. 10, pp. 682-686, 2006.

[15] Liu R, Zhao GD, Sun YN, et al. “Experimental study on 5G-enabled telerobotic surgery in animal models.” *Chinese Journal of Laparoscopic Surgery (Electronic Edition)*, vol. 12, no. 1, pp. 45-48, 2006.

[16] Mischa Dohler, Shady Saikali, Ahmed Gamal, et al. “The crucial role of 5G, 6G, and fiber in robotic telesurgery.” *J Robot Surg*, vol. 19, no. 1, pp. 4, 2024. View at: Publisher Site | PubMed

[17] Jianmin Li, Xuecheng Yang, Guangdi Chu, et al. “Application of Improved Robot-assisted Laparoscopic Telesurgery with 5G Technology in Urology.” *Eur Urol*, vol. 83, no. 1, pp. 41-44, 2023. View at: Publisher Site | PubMed

[18] Li Songyan, Wen Wei, Dai Feixiang, et al. “Preliminary Clinical Study on Robot-Assisted Radical Resection of Rectal Cancer via Ultra-Remote Surgery.” *Chinese Journal of Practical Surgery*, vol. 44, no. 3, pp. 308-311, 2024.

[19] Tian Jinyong, Zhou Xiang, Wang Shao, et al. “Two Cases of Ultra-Remote 5G Robot-Assisted Laparoscopic High Ligation of Varicocele with Literature Review.” *Chinese Journal of Andrology*, 2022.

[20] Tian Wen, Wang Bing, Yao Jing, et al. Preliminary Clinical Study on 5G-Enabled Remote Surgical Robot-Assisted Hiatal Hernia Repair and Fundoplication. *Chinese Journal of Practical Surgery*, vol. 44, no. 10, pp. 1171-1173, 2024. View at: Publisher Site

[21] Zhan Weipeng, Ma Yuqi, Hu Ming, et al. “A Case Report of 5G-Enabled Telerobotic-Assisted Distal Gastrectomy for Gastric Cancer (with Surgical Video).” *Journal of Robotic Surgery (Chinese and English)*, vol. 6, no. 1, pp. 18-23, 2025.

[22] Zhang Wentao, Miao Changfeng, Hu Ming, et al. “A Case Report of 5G Remote Robot-assisted Radical Colectomy with Literature Review (with Surgical Video).” *Journal of Robotic Surgery (Chinese and English)*, vol. 6, no. 1, pp. 28-32, 2025.

[23] Xu Yafang. “Characteristics of 5G Communication Technology and Its Application in Telemedicine.” *Electronic Production*, no. 2, pp. 87-89, 2020.

[24] Zhao Junhui, Ren Ruixing, Liu Congcong, et al. “Key Technologies for Ultra-Reliable Low-Latency Communications Oriented to 6G: Research Progress and Prospects.” *Mobile Communications*, vol. 48, no. 10, pp. 49-57, 2024.

[25] Xiaoguang Han, Xiaolong Zhu, Yuzhen Jiang, et al. “Research on the Development of Artificial Intelligence and Robot-Assisted Medicine.” *Engineering Science in China*, vol. 25, no. 5, pp. 43-54, 2023.

[26] Masaki Mori, Satoshi Hirano, Kenichi Hakamada, et al. “Clinical practice guidelines for telesurgery 2022.” *Surgery Today*, vol. 54, no. 8, pp. 817-828, 2024. View at: Publisher Site | PubMed

[27] Gu Chenglei, Li Li'an, Wang Ning, et al. “First Report of 5G Remote Robot-assisted Laparoscopic Total Hysterectomy.” *Chinese Journal of Minimally Invasive Surgery*, vol. 23, no. 8, pp. 610-615, 2023.

[28] Hajime Morohashi, Kenichi Hakamada, Takahiro Kanno, et al. “Construction of redundant communications to enhance safety against communication interruptions during robotic remote surgery.” *Sci Rep*, vol. 13, no. 1, pp. 10831, 2023. View at: Publisher Site | PubMed

[29] Zhang Z P, Li Z X, Qiao J L, et al. “Current Applications and Future Prospects of 5G-Enabled Telesurgery in Robotic Operations.” *Chinese Journal of Practical Surgery*, vol. 44, no. 7, pp. 836-840, 2024.

[30] George Moustris, Costas Tzafestas, Konstantinos Konstantinidis “A long distance telesurgical demonstration on robotic surgery phantoms over 5G.” *Int J Comput Assist Radiol Surg*, vol. 18, no. 9, pp. 1577-1587, 2023. View at: Publisher Site | PubMed

[31] Vipul Patel, Shady Saikali, Marcio Covas Moschovas, et al. “Technical and ethical considerations in telesurgery.” *J Robot Surg*, vol. 18, no. 1, pp. 40, 2024. View at: Publisher Site | PubMed

[32] Chukwuka Elendu, Dependable C Amaechi, Tochi C Elendu, et al. “Ethical implications of AI and robotics in healthcare: A review.” *Medicine (Baltimore)*, vol. 102, no. 50, pp. e36671, 2023. View at: Publisher Site | PubMed

[33] Lin Yujia, Li Jinhai, Ning Huansheng, et al. “A Review of Digital Twin Technology in Smart Healthcare and Wellness: Techniques, Applications, and Challenges.” *Chinese Journal of Engineering Science*.

[34] TIAN D, NIU H. “History and current situation of telesurgery.” *Chinese Journal of Robotic Surgery*, vol. 3, no. 5, pp. 343-350, 2022.

[35] Xiang Zhou, Jia-Yin Wang, Xiang Zhu, et al. “Two cases of ultra-long-distance 5G robot-assisted laparoscopic high ligation of the spermatic vein and literature review.” *Zhonghua Nan Ke Xue*, vol. 28, no. 8, pp. 696-701, 2022. View at: PubMed

[36] ZHOU F, GUO B, LV H, et al. “Reply to Letter to the Editor on "Application of 5G Remote Robotic-assisted Laparoscopy in Urological Surgery: A Small Sample Analysis".” *Urology*, vol. 197, pp. 117-118, 2025.

[37] Helen Mi, Robert E MacLaren, Jasmina Cehajic-Kapetanovic “Robotising vitreoretinal surgeries.” *Eye (Lond)*, vol. 39, no. 4, pp. 673-682, 2025. View at: Publisher Site | PubMed

[38] Li Jinquan, Wang Jiulong, Luo Yangyu. “Research Progress and Development Prospects of Orthopedic Surgical Robots.” *Chinese Medical Equipment Journal*, vol. 44, no. 6, 2023.

[39] Xunjun Ma, Jun Yu, Haitao Liu, et al. “Review and Optimization Discussion on Key Technologies of Surgical Robots.” *Chinese Journal of Medical Instrumentation*, vol. 48, no. 5, pp. 505-511, 2024. View at: Publisher Site | PubMed

[40] Bai Xue, Li Chunyang, Pu Jian, et al. “Exploration and Practice of the "Multidisciplinary Team-based" Medical and Health Aid Xinjiang Model in West China Hospital, Sichuan University.” *West China Medical Journal*, vol. 34, no. 12, 2019.

[41] Wang Xiaojun, Zhou Xiangyu “Research on the Privacy and Security of Health Records in the "Artificial Intelligence + Healthcare" Environment.” *Journal of Medical Informatics*, vol. 42, no. 2, pp. 22-24, 2021.

[42] Chen Lei, Wang Bacun, Huang Sihan, et al. “Ethical Guidelines and Governance System for Artificial Intelligence: Current Development

Status and Strategic Suggestions." *Science and Technology Management Research*, vol. 41, no. 6, pp. 193-200, 2021.

[43] Ni Jian, Cao Baogen, Luo Xingjiu, et al. "Research on Remote Medical Information System of Large-scale Medical Rescue Platform at Sea." *Medical Equipment*, vol. 40, no. 8, pp. 16-19, 2019.