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Review

Telemedicine and Robotic Surgery: A Narrative Review to Analyze Advantages, Limitations and Future Developments

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Abstract: Today, the introduction and application of telemedicine are leading to a radical transformation in healthcare systems all over the world. In particular, the use of information and communication technologies (ICT) can have a positive impact on the containment of healthcare costs. The concept of telemedicine has also been applied to surgery, defining telesurgery as the use of robotic systems composed of one or more arms controlled via a console located in a remote position from the patient, where the surgeon sits and performs the surgical tasks. This revolution—made possible by technological advances in robotic systems and ICT—allows surgical care to be provided to patients in remote locations. Telesurgery, therefore, adds to the advantages of minimally invasive robotic surgery by overcoming geographical barriers and allowing patients to avoid traveling. Although there has been a rapid increase in interest and demand for telesurgery, its use in clinical practice is still rare. The purpose of this article is to review the advantages and benefits of the use of telesurgery, to identify the limitations that do not yet allow its use in current clinical practice, and to describe the existing challenges and possible solutions that are being explored by research.

Keywords: telesurgery; telerobotic surgery; remote surgery; telemedicine

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1. Introduction

Since the 1970s, the term 'telemedicine' has been employed to delineate a paradigm shift in healthcare services, facilitating remote physician–patient interactions through the integration of telecommunication technologies [1,2]. Subsequent to its inception, telemedicine has undergone remarkable advancements, spanning both widespread adoption and technological evolution. The National Health Institute provides a definition for telemedicine, emphasizing its reliance on "utilizing electronic information and communication technologies to deliver and facilitate healthcare when participants are physically separated" [3]. This strategic approach holds particular significance in enhancing healthcare service accessibility, effectively managing chronic conditions, and addressing healthcare challenges prevalent in remote or underserved areas [4]. Presently, there exists a universally acknowledged understanding that harnessing information and communication technologies is a pivotal asset in achieving the transformative objectives necessitated by global healthcare systems.

The extension of the telemedicine concept into the surgical domain has given rise to telesurgery, also known as robotic surgery, wherein robotic systems are leveraged to execute surgical procedures in distant locations [5–7]. Telesurgery intricately integrates surgical robotic systems with state-of-the-art communication technology, constituting remotely conducted surgical procedures with rapid data transmission across networks. Within the realm of telesurgery, the robotic system maintains direct contact with the patient while the surgeon orchestrates the surgical procedure from a remote console [8]. In this innovative approach, medical data, encompassing imaging, audio, and video components, undergoes digitization and is swiftly transmitted through either wired or wireless telecommunication networks [9].

In telerobotic systems, the remote manipulator is controlled from the operator's site by sending position commands while receiving visual and other sensory feedback information. The systems situated both locally and remotely are commonly denoted as the "master" and "slave" systems, respectively, constituting an overarching "master–slave system." The remote manipulator is programmed to mirror the operator's controls [10].

Numerous medical robotic systems predominantly utilize teleoperation as their primary mode of operation. However, it is noteworthy that the master, also known as the expert site, and the slave remote manipulator, referred to as the patient site, are frequently situated in the same room [11,12]. This type of surgery is categorized as short-distance telesurgery, even when the master and slave components are in close proximity. In such cases, telerobotic systems are effectively divided into two sites: the local site, encompassing the human operator and all essential components for remote system operation (such as monitors, keyboards, joysticks, and other input/output devices), and the distant site, housing the robotic manipulation system and the patient along with the necessary support personnel [10]. When applied to surgical interventions, this approach is commonly known as telesurgery [10].

On the other side, using a robotic platform, there exists the possibility to perform long-distance telesurgery in which the principal surgeon performs a surgical procedure on a patient situated at a remote location [13], such as in a different hospital or in a different country. This form of surgical practice is frequently referred to as telesurgery or remote ttelesurgery.

Thus, there is no clear distinction in the literature between the use of terms referring to short-distance telesurgery and long-distance telesurgery.

In recent years, a burgeoning global trend has emerged, with heightened interest in the adoption and utilization of remote telesurgery. This surge is attributed to its demonstrated efficacy in addressing challenges associated with trauma treatment and elevating the standard of healthcare delivery, particularly in unique geographical and environmental contexts. Positioned as an emerging field, telesurgery holds the promise of reshaping conventional medical practices and possesses the potential to provide remote surgical interventions on a global scale [5].

Despite the rapid increase in interest and demand for long-distance telesurgery, its integration into clinical practice remains relatively rare.

This narrative review endeavors to explore the multifaceted dimensions intrinsic to long-distance telesurgery, tracing its development and clinical applications, identifying its benefits and limitations, and describing the challenges and opportunities it presents.

2. Materials and Methods

To provide a comprehensive overview of long-distance telesurgery applications, a narrative literature review was performed to evaluate clinical experiences of telesurgery. An electronic search was conducted on Pubmed, Scopus, and Web of Science databases. The following words were used to perform the research: "telesurgery", "tele robotic surgery", and "remote surgery", "robotic-assisted telesurgery".

The following criteria for inclusion were employed in the article selection process:

1. Written in English language.
2. Full articles written in English, excluding reviews, perspectives, communications, and case studies.
3. Full text available.
4. Published from 2001 to 2023.
5. The operating surgeon and the patient must be located in different hospitals.
6. The clinician located off-site must act as the primary surgeon.

7. The paper reports information about latency time, robotic platform, and communication network used.

Otherwise, the following exclusion criteria were considered:

1. Articles that contained simulation and tests about telesurgery.
2. Papers centered on telementoring or telepresence.
3. Studies which perform telesurgery in the same hospital.

The review's references were checked to find relevant papers that were included in the research.

Article titles and abstracts underwent screening to assess their relevance according to the inclusion and exclusion criteria.

3. Results

A total of 2390 articles was obtained from the electronic research databases previously mentioned, while the records identified through snowballing were 106. After duplicates were removed, 1946 papers remained. The screening of the titles and abstracts resulted in the exclusion of 1924 items. Among the remaining 22 articles, 15 papers did not meet the inclusion criteria.

The selection process is reported in the PRISMA flowchart (Figure 1).

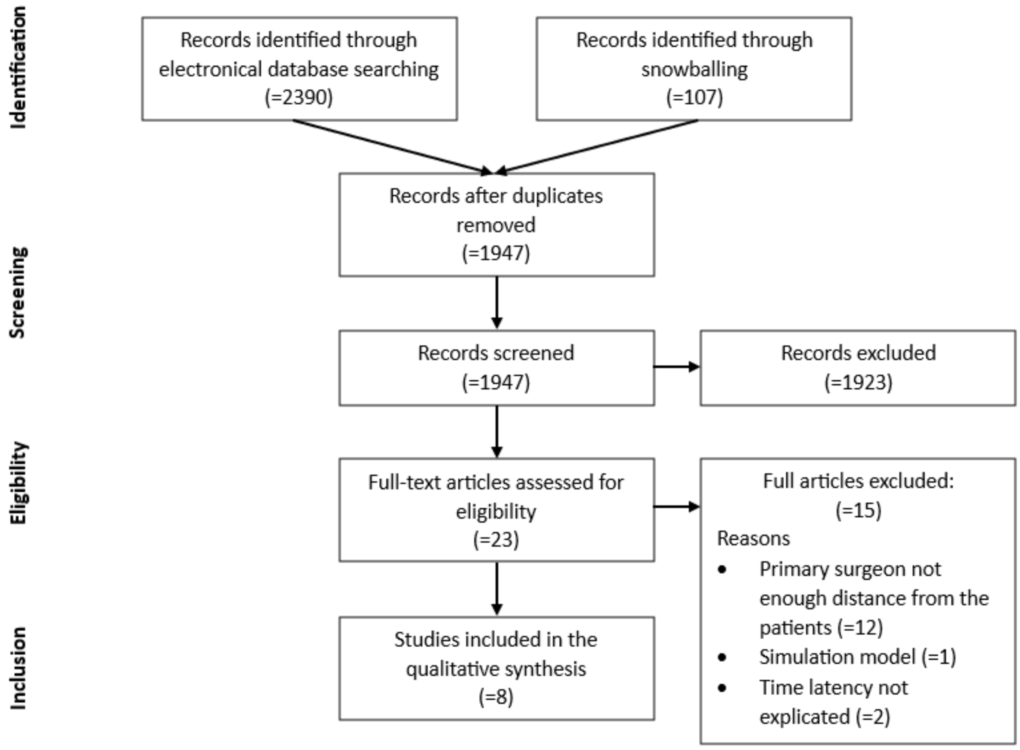

Figure 1. Prisma flowchart.

Table 1 presents the 8 papers included in the review together with their main characteristics: type of procedure, surgical platform used, connection methods, latency time, type, and number of subjects.

This section reports the review's findings. The first paragraph provides information about the evolution of telesurgery (Section 3.1), describing the main aspects of the papers included in the review. The following paragraphs present the advantages (Section 3.2), the constraints (Section 3.3), and the forthcoming directions in the advancement of this research domain (Section 3.4).

Table 1. Studies included in the final review and key characteristics.

Source	Year	Type of Procedure	Surgical Platform	Connection Methods	Latency	Type of Subjects	Number of Subjects
Marceaux, J., et al. [14]	2001	Cholecystectomy (gall-bladder removal)	ZEUS, Computer Motion	Optical-fibre network that transports data through dedicated connections using asynchronous transfer mode (ATM) technology	155 ms	Animal	6
Marceaux, J., et al. [15]	2001	Cholecystectomy	ZEUS, Computer Motion	ATM network connected via fiber optic cables	155 ms	Human	1
Anvari, M., et al. [16]	2005	Laparoscopic Nissen fundoplication, laparoscopic right hemicolectomy, laparoscopic sigmoid/anterior resection, laparoscopic hernia repair	Zeus TS robotic platform, Computer Motion	IP/VPN network	140 ms	Human	21
Anvari, M. [17]	2007	Laparoscopic Nissen fundoplication, laparoscopic right hemicolectomy, laparoscopicsigmoid/anterior resection, laparoscopic hernia repair	Zeus TS robotic platform, Computer Motion	IP/VPN network	150 ms	Human	22
Patel, T. M., et al. [18]	2019	Robotic-assisted percutaneous coronary intervention with balloon angioplasty and stent deployment	CorPath GRX robotic system, Corindus Vascular Robotics	LAN/MAN/WAN connectivity	53 ms	Human	5
Tian, W., et al. [19]	2020	Pedicle screw placement for thoracolumbar fractures, lumbar spondylolisthesis, and lumbar stenosis	TiRobot system	5G network	28 ms	Human	12
Acemoglu, A., et al. [20]	2020	Transoral laser microsurgeries on the vocal cords	Franka Emika Panda	5G network	102±9 ms	Cadaver	1
Li, J., at al. [21]	2021	Robot-assisted laparoscopic radical nephrectomy	The Micro Hand S system	5G network	176 ms	Human	29

3.1. Evolution of Long-Distance Telesurgery

The concept of long-distance telesurgery using robotic technology, with its roots dating back to the 1970s, has evolved significantly over the years, marking notable milestones in the intersection of medical science and cutting-edge technology. The journey began with a visionary project by the National Aeronautics and Space Administration (NASA) in the 1970s, where the idea was to employ remotely controlled robots for conducting surgical procedures on astronauts [22]. This early initiative laid the groundwork for the subsequent development of telesurgery.

The true potential of remote telesurgery began to materialize in the 1980s and 1990s, with remarkable progress in telecommunications and robotic surgery. The convergence of these technological advancements paved the way for telerobotic surgery to become a tangible reality, setting the stage for transformative innovations in the field.

A pivotal moment in the history of long-distance telesurgery occurred in 2001 with a groundbreaking attempt—a robot-assisted laparoscopic cholecystectomy on a porcine model. Spanning an impressive round-trip signal distance of more than 14,000 km, this procedure showcased the possibilities of remote surgery. The ZEUS system from Computer Motion, featuring 'surgeon-side' and 'patient-side' subsystems, was instrumental in this early success [14]. Despite the challenges of signal transmission through ATM transport, including delays for video encoding and decoding, the procedure, with an average duration of 45 min, marked a significant advancement. The delay through ATM (asynchronous transfer mode) transport was measured between 78 and 80 milliseconds. Incorporating an additional 70 ms for video encoding and decoding, along with a slight delay for rate adjustment and the conversion of Ethernet to ATM packets, the surgeon's actions in New York became visible on his video screen in approximately 155 ms. The average duration for performing the cholecystectomy procedure was 45 min.

In the same year, Professor Jacques Marescaux achieved a milestone in long-distance telesurgery with the 'Lindbergh Operation'—a telerobotic cholecystectomy in Strasbourg, France. This complex procedure, completed in 54 min without complications, involved a 68-year-old patient undergoing a remote laparoscopic cholecystectomy. The ZEUS system played a crucial role, with a 'surgeon-side' in New York and a 'patient-side' in Strasbourg. The New York–Strasbourg connection utilized ATM technology with an impressive 99.99% network availability rate. They recorded a consistent time delay of 155 milliseconds throughout the procedure. Surgeons evaluated image quality, giving an average score of 9.5. Overall procedure safety was assessed based on high-quality video images, effective visualization, precise control of surgical movements, and coordinated cautery for vessel coagulation. All three surgeons expressed perfect confidence in the operation's safety, with no patient risks linked to tele-transmission or robotic system use. The patient recovered smoothly, was discharged after 48 h, and underwent postoperative monitoring through daily phone calls. In-office assessments at two and four weeks revealed well-healed wounds without infection [15].

Despite these achievements, concerns arose about the applicability of remote telesurgery in underserved rural areas where a dedicated ATM might not be readily accessible. Questions also emerged regarding the assembly of robotic arms by individuals without expertise in robotics, especially when located at the remote patient's bedside.

Addressing these concerns, in 2003, Anvari et al. [16] established a pioneering telerobotic service between St. Joseph's Hospital in Hamilton and North Bay General Hospital, situated 400 km north of Hamilton. The surgeons successfully performed various laparoscopic procedures using a commercially accessible IP/VPN network with a bandwidth of 15 Mbps. Before initiating the service, both the local laparoscopic surgeon and the nursing team in North Bay underwent training in the utilization of robotic arms and instrumentation. Additionally, an experienced technician was present during each case to guarantee the seamless setup of the robotic arms. The ZEUS TS microjoint systems served as the robotic platform, and the overall latency experienced by the telerobotic surgeon ranged from 135 to 140 ms. No significant intraoperative complications occurred in any of the 21 surgeries. Concerning the postoperative complications, out of the 13 patients who underwent laparoscopic Nissen fundoplication, two reported experiencing some dysphagia during the postoperative visit at 2 weeks, while a third patient presented with atypical chest pain at that time. This initiative demonstrated the feasibility of remote surgery over considerable distances.

Building on this success, Anvari documented 22 more cases performed over the identical network connecting McMaster University and North Bay General Hospital. The program, utilizing the Zeus TS robotic platform and a Bell Canada IP/VPN network, showcased successful telepresence surgery for all 22 cases, including laparoscopic fundoplications, colectomies, and hernia repairs. Reported time delays ranged from 135 ms to 150 ms. All 22 patients experienced no significant intraoperative complications, and their postoperative recovery was without any notable events [17].

In 2019, Patel and colleagues expanded the horizons of telerobotic surgery into the field of cardiology. The team performed five instances of tele-robotic-assisted percutaneous coronary artery interventions, covering a distance of 32 km. Utilizing the CorPath GRX robotic system from Corindus Robotics, these procedures were completed successfully without any complications, featuring an observed mean time delay of 53 ms [18]. All five patients were free from major adverse cardiac events 24 h after the procedure. Twelve-lead electrocardiograms were conducted immediately post-procedure and on the following mornings, revealing no indications of significant ischemia. All subjects maintained hemodynamic stability and remained asymptomatic throughout their hospital stay and at the time of discharge.

The current landscape of telesurgery is characterized by robust developments in information and communication technology (ICT), highlighted by the improvement of the fifth-generation (5G) internet. This era also witnesses advancements in artificial intelligence, haptic feedback technology, augmented reality, and nanotechnology, collectively contributing to the resurgence of remote surgery. Numerous tests, simulations, and real cases on patients have been successfully conducted, underscoring the expanding scope and application of telesurgery.

A monumental achievement unfolded in China in 2019, showcasing the potential of telerobotic spinal surgery utilizing 5G technology. This groundbreaking approach facilitated 12 surgeries across six cities, involving the precise implantation of 62 pedicle screws. What set this apart was the "one-to-many" remote surgery concept, where a lead surgeon operated from a control room, simultaneously caring for isolated patients. The study demonstrated the feasibility of minimal latency, high bandwidth, and error-free communication through the 5G telerobotic system. Efficient operations were ensured, with an average latency of 28 milliseconds, no network-related issues, and a mean surgery duration of 142.5 min. There were no intraoperative adverse events observed. Nevertheless, a patient diagnosed with lumbar spondylolisthesis developed a cerebrospinal fluid (CSF) leak on the day following the operation. This incident was determined to be unrelated to the robotic manipulation of the screw implant but associated with the nerve decompression procedure. This pioneering study marked a significant stride in telerobotic spinal surgery, emphasizing its safety and reliability via 5G technology [19].

In the same year, Acemoglu et al. [20] conducted transoral laser microsurgeries on the vocal cords of a cadaver utilizing an innovative surgical robot (Franka Emika Panda) connected to a 5G Network. They observed an average round-trip latency of 102 ms at a distance of 15 km.

In 2021, a surgeon in Qingdao, China, further validated the potential of telesurgery by remotely performing laparoscopic radical nephrectomy on 29 patients in eight primary hospitals [21]. This remarkable achievement boasted a 100% success rate, with a median operation time of 67 min and minimal postoperative complications. Patients maintained stable vital signs throughout the entire procedure, and assessments such as the 24 h Visual Analog Scale score and Comprehensive Complication Index indicated that the majority experienced low levels of postoperative pain and did not encounter major postoperative comorbidities. A sole elderly male patient received an intraoperative prophylactic transfusion of two units of red blood cells due to preoperative anemia. Additionally, two elderly female patients encountered delayed postoperative wound healing and mild intestinal obstruction; however, their prognosis remained unaffected. As of now, all patients have been monitored for more than 6 months, and they are experiencing positive prognostic outcomes. The study also delved into urologists' attitudes toward telesurgery in China, revealing a 66% expression of enthusiasm, though cost and legal concerns were noted. This study provided tangible evidence of the potential of remote surgery in expanding healthcare access.

Figure 2 describes the schema for the realization of a long-distance telesurgery service in all the selected studies.

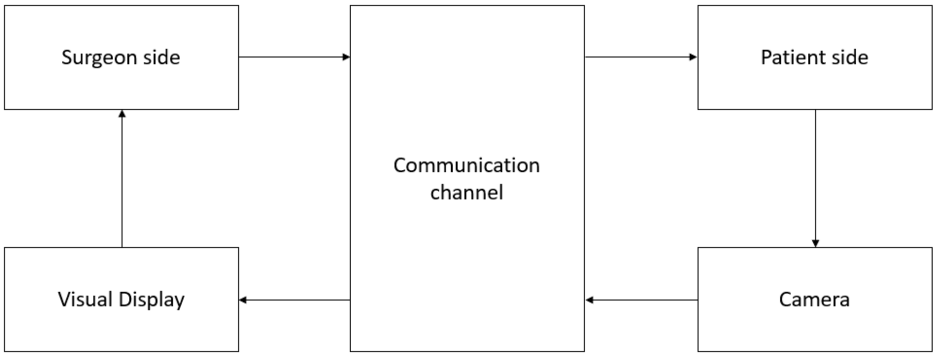

Figure 2. Schema for the realization of a long-distance telesurgery service.

Table 2 reports a comparative analysis of the selected papers, showing the commonalities and distinctions among these studies. In particular, the elements for the comparison are the following:

- Type of surgical procedure.
- Number of procedures.
- Number of surgeons performing the intervention.
- Success rate defined as was defined as the rate of successful remote procedure performed without conversion to other surgical procedures and no major intraoperative complications.
- Operation time.
- Latency time.
- Intraoperative bleeding occurrence.
- Hospital recovery time.
- Postoperative pain.
- Postoperative complication.
- Surgical precision.
- Remote operator personal evaluation of image quality, the impact of time lag and/or overall safety.
- Presence of an engineer or expert technician to ensure the connection and setup of the robot.
- Presence of a backup surgical team close to the patient capable of intervening in case of emergency.

Table 2. Comparison table of the above research papers.

	Marceaux, J., et al. [14]	**Marceaux, J., et al. [15]**	**Anvari, M., et al. [16]**	**Anvari, M. [17]**
Type of surgical procedure	Laparoscopic cholecystectomy	Laparoscopic cholecystectomy	13 laparoscopic Nissen fundoplications, 2 laparoscopic right hemicolectomies, 4 laparoscopic anterior/sigmoid resections, and 2 laparoscopic hernia repairs	13 laparoscopic Nissen fundoplications, 3 laparoscopic right hemicolectomies, 4 laparoscopic sigmoid/anterior resections, and 2 laparoscopic hernia repairs
Number of procedures	6	1	21	22
Number of surgeons performing the intervention	3	1	2	2
Success rate	100%	100%	100%	100%
Operation time	45 min (mean)	54 min	Laparoscopic Nissen fundoplications: 72 min, laparoscopic right hemicolectomies: 56 min, laparoscopic anterior/sigmoid resections: 111 min, laparoscopic hernia repairs: 27 min (mean)	Laparoscopic Nissen fundoplications: 75 min, laparoscopic right hemicolectomies: 75 min, laparoscopic anterior/sigmoid resections: 97.5 min, laparoscopic hernia repairs: 27.5 min (median)
Latency time	155 ms	155 ms	135–140 ms	150 ms
Intraoperative bleeding occurrence	Not available information	Not present	Not present	Not present
Hospital recovery time (days)	Not available information	2	Laparoscopic Nissen fundoplications: 1.6, laparoscopic right hemicolectomies: 4, laparoscopic anterior/sigmoid resections: 3.7, laparoscopic hernia repairs: 0 (median)	Laparoscopic Nissen fundoplications: 2, laparoscopic right hemicolectomies: 4, laparoscopic anterior/sigmoid resections: 3.5, laparoscopic hernia repairs: 0 (median)
Postoperative pain	Not available information	Not available information	Not available information	Not available information
Postoperative complication	Not available information	Not present	Out of the 13 patients who underwent laparoscopic Nissen fundoplication, two reported experiencing some dysphagia during the postoperative visit at 2 weeks, while a third patient presented with atypical chest pain at that time.	In laparoscopic Nissen fundoplication: Dysphagia requiring dilation (1 case)

Table 2. *Cont.*

	Marceaux, J., et al. [14]	**Marceaux, J., et al. [15]**	**Anvari, M., et al. [16]**	**Anvari, M. [17]**
Surgical precision	Not available information	Not available information	Not available information	Not available information
Remote operator personal evaluation of the image quality, impact of time lag and/or overall safety	Evaluation was on a 0–10 scale (where 0 is the worst possible and 10 is the best possible). Scores were 9.1 for the quality of the image, 8.5 for the impact of time lag (0, unacceptable impact; impact of time lag (0, unacceptable impact; 10, imperceptible impact), 9.2 for coordination of electrocautery, and 8.7 for overall safety	The overall safety of the procedure was intended as the combination of high-quality video images for appropriate visualization of structural and anatomic details, the ability to control surgical movements, and perfect coordination in the use of cautery for coagulation of vessels. All three surgeons rated 10 on the score of "perception of the safety of the operation"	Not available information	Not available information
Presence of an engineer or expert technician to ensure the connection and se-tup of the robot	Not available information	Not available information	Yes	Yes
Presence of a backup surgical team close to the patient capable of intervening in case of emergency	Not available information	Yes	Yes	Yes
	Patel, T. M., et al. [18]	**Tian, W., et al.** [19]	**Acemoglu, A., et al.** [20]	**Li, J., at al.** [21]
Type of surgical procedure	Robotic-assisted percutaneous coronary intervention	Thoracolumbar pedicle screw placement	Transoral laser microsurgeries on the vocal cords	Radical Nefrectomy
Number of procedures	5	12	1	29
Number of surgeons performing the intervention	1	1	1	1
Success rate	100%	100%	Not applicable	100%
Operation time	23.6 min (mean)	142.5 min (mean)	Not available information	67 min (median)
Latency time	50 ms	28 ms	102 ms	176 ms

Table 2. *Cont.*

	Patel, T. M., et al. [18]	**Tian, W., et al.** [19]	**Acemoglu, A., et al.** [20]	**Li, J., at al.** [21]
Intraoperative bleeding occurrence	Not present	Not present	Not applicable	A singular elderly male patient received a prophylactic intraoperative transfusion of two units of red blood cells due to preoperative anemia.
Hospital recovery time (days)	1 (mean)	Not available information	Not applicable	8 (median)
Postoperative pain (method)	Not available information	Not available information	Not applicable	Low (Visual Analog Scale)
Postoperative complication	Not present	A patient diagnosed with lumbar spondylolisthesis preoperatively was discovered to have a cerebrospinal fluid (CSF) leak the day after the operation. This occurrence was deemed unrelated to the robotic manipulation of the screw implant but was associated with the nerve decompression procedure.	Not Applicable	Two elderly female patients encountered delayed healing of postoperative wounds and experienced mild intestinal obstruction; however, their prognosis remained unaffected.
Surgical precision	Not available information	The accuracy of pedicle screw placement was evaluated using Gertzbein–Robbins criteria. A total of sixty-two pedicle screws were surgically implanted. Among them, fifty-nine screws (95.2%) were classified as grade A according to the Gertzbein–Robbins criteria, while the remaining three screws received a grade B rating. The overall acceptable rate, considering grades A and B, was 100%. The deviation between the planned and actual positions of the pedicle screws averaged 0.76 ± 0.49 mm.	Not available information	Not available information

Table 2. *Cont.*

	Patel, T. M., et al. [18]	**Tian, W., et al.** [19]	**Acemoglu, A., et al.** [20]	**Li, J., at al.** [21]
Remote operator personal evaluation of the image quality, impact of time lag and/or overall safety	Safety data were collected, as were questionnaire scores from the remote operator evaluating the robot-network composite, image clarity, and overall confidence in the procedure. The operator's rating of the response time, device control, and ability to communicate with the local in-lab team were all rated as satisfied or extremely satisfied	Not available information	Not available information	Not available information
Presence of an engineer or expert technician to ensure the connection and se-tup of the robot	Not available information	Yes	Not available information	Yes
Presence of a backup surgical team close to the patient capable of intervening in case of emergency	Yes	Yes	Yes	Yes

Table 3 reports the main characteristics of the robotic arm of the surgical robots used in the selected studies.

Table 3. Main characteristics of the robotic arms.

Robotic Platform	Type of Patient Cart	Number of Robotic Arm	Degree of Freedom
Zeus TS robotic platform, Computer Motion	3 independent patient-side units, each hosting a robotic arm	3	4
CorPath GRX robotic system, Corindus Vascular Robotics	1 independent patient side unit, with 1 robotic arm	1	-
TiRobot system	1 independent patient side unit, with 1 robotic arm	1	6
Franka Emika Panda	1 independent patient side unit, with 1 robotic arm	1	7
The Micro Hand S system	Single patient cart	3	7

The evolution of telesurgery from its conceptualization in the 1970s to the present day stands as a testament to the relentless pursuit of merging medical expertise with cutting-edge technology. The journey has witnessed pioneering projects, groundbreaking procedures, and transformative innovations. From the early experiments with remotely controlled robots to the establishment of telesurgery as a tangible reality, the field has addressed challenges, expanded its scope, and demonstrated its potential to revolutionize global healthcare. As technology continues to advance, telesurgery stands at the forefront of healthcare delivery, promising transformative changes in surgical practices worldwide. The citation for this comprehensive overview includes references to the key studies and milestones that have shaped the narrative of telesurgery.

3.2. Benefits

The evolution of telesurgery, stemming from the broader concept of telemedicine, represents a significant milestone made possible through the strides in surgical minimally invasive robotics and sophisticated telecommunication technology. The advantages of telesurgery, intricately intertwined with the benefits of minimally invasive surgery and robotic surgery, are expounded upon in detail.

Advantages associated with the minimally invasive approach:

- Reduction in the level of invasiveness: telesurgery, adopting a minimally invasive approach, contributes to a noteworthy reduction in the overall invasiveness of surgical procedures.
- Reduction of blood loss: the minimally invasive nature of telesurgery leads to a substantial decrease in intraoperative blood loss, promoting patient safety.
- Less postoperative pain and discomfort: patients undergoing telesurgery experience diminished postoperative pain and discomfort compared to conventional surgical methods, enhancing the overall patient experience.
- Reduction in the risk of infection: the minimized incision size in telesurgery significantly lowers the risk of postoperative infections, a critical consideration in surgical interventions.
- Shorter hospitalization: telesurgery facilitates a quicker recovery process, contributing to shorter hospitalization periods for patients and thereby reducing healthcare costs.
- Faster recovery: patients benefit from an expedited recovery period, allowing them to resume normal activities sooner, leading to improved quality of life [23,24].

Advantages associated with robotic surgery:

- Removal of surgeon's tremor: telesurgery, utilizing robotic systems, eliminates the inherent hand tremors of the surgeons, ensuring precise and controlled surgical maneuvers.

- Ergonomic posture for the physician: robotic systems in telesurgery enable surgeons to maintain ergonomic postures during procedures, minimizing fatigue and enhancing procedural accuracy.
- Improvement systems for the vision of anatomical structures: telesurgery incorporates advanced imaging systems that enhance the visualization of anatomical structures, aiding in meticulous surgical navigation.
- Ease of access to less accessible anatomical points: robotic instruments utilized in telesurgery offer increased dexterity, facilitating access to anatomical points that may be challenging with traditional surgical approaches.
- 3DHD visualization of the operating field: telesurgery provides three-dimensional high-definition visualization of the operative field, offering an unprecedented level of detail for enhanced surgical precision [25,26].
- Mitigation of the risk of human error: the incorporation of robotic assistance in telesurgery mitigates the risk of human error, thereby contributing to improved overall surgical outcomes.

In summary, the multifaceted advantages of telesurgery emanate from its integration with both minimally invasive and robotic surgical approaches. These advantages collectively contribute to enhanced patient outcomes, streamlined recovery processes, and a paradigm shift in the landscape of contemporary surgical interventions.

In addition to these compelling advantages, telesurgery offers a myriad of specific benefits that revolutionize the landscape of surgical care:

- Enhanced healthcare access: telesurgery serves as a beacon of hope for geographically remote or underserved populations by providing access to high-quality surgical care. Furthermore, this innovative approach extends its reach to special environments, such as battlefields or spacecraft, ensuring that individuals in unique and challenging circumstances receive prompt and efficient medical attention [5,6,14,15,21,27].
- Minimized travel burden: telesurgery significantly alleviates the burden on patients, allowing them to reduce extensive travel requirements associated with receiving specialized medical procedures. This reduction in travel is not merely a matter of convenience; it addresses broader issues such as financial constraints, health risks, travel restrictions, and time delays [8,28].
- Addressing surgeon shortages: telesurgery emerges as a potential panacea for the global shortage of surgeons. Leveraging remote technologies enables surgical expertise to transcend geographical boundaries, ensuring that patients in need can access surgical care regardless of the availability of local surgical professionals [5,29].
- Real-time collaborations: telesurgery facilitates seamless real-time collaborations between surgical professionals stationed at different healthcare facilities. This interconnectedness not only promotes knowledge sharing but also enhances the collective expertise of the surgical community, ultimately benefiting patients through a collaborative and interdisciplinary approach to healthcare [6,8,28].
- Remote surgical training: telesurgery extends its transformative impact to the realm of surgical education. On-site surgeons can engage in immersive learning experiences by connecting with remote experts. This educational exchange spans various levels of interaction, ranging from telementoring through video guidance to the integration of advanced remote robotic assistance. This not only augments the skills of existing surgeons but also contributes to the development of a robust and globally connected surgical community [29].

In essence, telesurgery not only addresses immediate healthcare challenges but also fosters a paradigm shift in how surgical care is delivered and accessed, promising a future where geographical constraints no longer limit the availability of high-quality medical expertise.

3.3. Limitation

Despite the promising potential of telesurgery, it encounters a series of challenges that must be addressed to fully realize its benefits:

- Latency issues: one of the primary hurdles faced by telesurgery is latency, which is defined as the delay in transmitting and receiving audio-visual feeds. The success of telesurgical procedures relies heavily on high-speed, low-latency networks to ensure real-time control for surgeons. Studies indicate that latency times exceeding 700–800 ms result in significant and unacceptable reductions in surgical performance, emphasizing the critical need for latency to remain under 300 ms. Ideally, latency times should be less than 100 milliseconds to avoid major inaccuracies in instrument handling during surgeries [28,30–33].
- Global network development: establishing a robust worldwide network that seamlessly connects every corner of the globe is a monumental challenge for launching telesurgical services. The creation of such a network is hindered by the substantial cost of high-speed telecommunications, particularly in developing countries [34].
- Financial costs: the implementation of telesurgery involves high expenses related to the acquisition and maintenance of robotic systems, presenting significant obstacles, especially in economically challenged regions. Additionally, the presence of a complete surgical team in the operating room to intervene in case of communication loss with the remote surgeon adds to the overall costs. Consequently, even if the communication means and the surgical robots are available at both hospitals, the cost of the operation remains higher compared to robotic surgery performed within the same facility [5,8,17].
- Regulatory and legal complexities: the development of comprehensive legal and regulatory frameworks for telesurgery, encompassing licensing and liability issues, is an ongoing and intricate process. Striking the right balance between innovation and patient safety is essential to foster the widespread acceptance and implementation of telesurgical practices [21,35].
- Cybersecurity and privacy concerns: the protection of sensitive patient data and safeguarding surgical procedures from cyber threats are paramount concerns in the realm of telesurgery. Establishing robust cybersecurity measures is crucial to maintaining patient confidentiality and the integrity of surgical processes [36].

Navigating these challenges requires collaborative efforts from the medical community, policymakers, and technology experts to ensure that telesurgery can overcome these hurdles and emerge as a transformative force in modern healthcare.

3.4. Future Perspective and Emerging Trends

The future of telesurgery holds great promise. The evolution of technology may further enhance the capabilities of remote robotic surgery and thus enable its spread around the world.

The following are the main technological trends that could revolutionize this sector:

- Haptic feedback: it is a long-standing challenge in robotic surgery, affecting laparoscopic procedures. This technology could transform wireless robotic surgical systems, enabling operators to feel tissue consistency and suture tension and boosting confidence.
  To enhance precision and dexterity, upgrading the human-machine interface (HMI) and sensor-based instruments is crucial [37]. The research aims to develop a seamless haptic-enabled telesurgical system for accurate feedback.
  In 2015, the Telelap Alf-x prototype, featuring haptic feedback and eye-tracking technology, reduced cholecystectomy time [38].
- Augmented reality in telesurgery: augmented reality (AR) is a crucial tool in telesurgery, enabling remote visualization, robot control, and proximity alerts, ultimately enhancing surgical accuracy [39]. Studies have focused on improving the remote operators' visualization and situational awareness in telesurgery using AR. This technology provides intuitive and immersive feedback on anatomical structures, instruments within

the human abdominal cavity, and depth information. Furthermore, AR in telesurgery robotic systems offers advantages like improved hand-eye coordination, reduced cognitive load, enhanced remote collaboration, and decreased radiation exposure [39]. Additionally, AR enhances telesurgery by facilitating remote visualization, robot control, and collaborative efforts, ultimately enhancing patient care [40]. Research studies, including those conducted by Lin et al. [41], Gasques et al. [42], and Huang et al. [43], illustrate the effectiveness of AR in improving remote visualization and providing real-time feedback during surgical procedures.
The integration of AR into telesurgery robotic systems not only improves hand-eye coordination and reduces cognitive load [44,45] but also expands the possibilities for remote collaboration. AR addresses challenges related to latency by predicting robot motion [20,39,44]. These advancements underscore the profound impact of AR in enhancing efficiency and overcoming obstacles in the realm of telesurgery [40].

- High speed and quality telecommunication: the effectiveness of data sharing and the level of latency are contingent on the network's bandwidth, which determines the data flow capacity. To achieve this, a telecommunication network with ample bandwidth, minimal delay, and minimal data loss is essential.
  5G wireless networks facilitated significantly improved data transmission stability, achieving speeds up to 100 times faster than their predecessors (10 GB/s) [24]. Thus, the application of 5G Internet can fulfill the telecommunication requirement.

4. Discussion

Telesurgery, situated at the crossroads of medical expertise and cutting-edge technology, represents a fascinating journey from its initial experiments to its current pivotal role in healthcare. This evolution sets the stage for an exciting future where the ambitious aim of universal healthcare accessibility could soon be realized through the seamless integration of telemedicine and telesurgery into the fabric of healthcare. While telemedicine holds the potential to mitigate healthcare disparities, the establishment of telesurgery facilities demands a robust network infrastructure and cost-effective surgical robots.

Beyond the noble cause of addressing the shortage of expert surgeons in remote areas, telesurgery is a beacon of empowerment for patients. It allows them to exercise agency in selecting their preferred surgeon, potentially saving invaluable time and financial resources for both patients and their families. Furthermore, remote telesurgery emerges as a lifeline for treating injured soldiers in combat zones and astronauts in the vast expanse of space. Its significance is heightened by providing a platform for trainee surgeons to gain hands-on experience under the watchful supervision of seasoned experts, all while placing paramount importance on patient safety.

This review illustrated the main studies on long-distance telesurgery, showing its feasibility, advantages, and disadvantages. One of the future developments of this review is to also consider robotic short-distance telesurgery by comparing it with open and laparoscopic surgery in order to have a complete picture of its benefits.

The review at hand delves into eight studies exploring the feasibility of leveraging robotic platforms for long-distance telesurgery, with the Zeus platform emerging as the most widely adopted. Interestingly, despite the prevalence of the da Vinci platform in robotic surgery, its absence in telesurgical studies raises intriguing questions about its potential in this specific domain. The studies span diverse medical fields, including general surgery, cardiac surgery, urology, and spinal surgery.

The communication methods employed in these studies showcase a current trend favoring the utilization of 5G technology. Despite the touted 100-fold increase in speed compared to its predecessors, a study revealing substantial latency with 5G warrants further investigation into its true potential [21]. As we tread the path of innovation, the verification of 5G's actual efficacy in telesurgery becomes a crucial avenue for future exploration.

The clinical areas in which the selected studies were conducted are diverse, ranging from cardiothoracic surgery to urology. As a result, the procedures reported in the chosen papers are not homogeneous, and this does not allow for a precise comparison of clinical outcomes, such as duration of surgery or length of post-operative hospital stay. However, it can be said that none of the trials reported intraoperative or postoperative complications associated with long-distance telesurgery.

Only one study [19] reported some measures of surgeon accuracy. In most studies [15–21], a backup team is present near the patient to intervene in case of an emergency, while only a few studies [17,18,21] report the presence of an engineer or an experienced technician to intervene in the configuration of the robot or the connection in case of a malfunction.

In the realm of limitations, the high cost associated with implementing telesurgery services stands out prominently. Surprisingly, the lack of detailed cost breakdowns in the reviewed papers underscores the need for future studies to conduct comprehensive economic evaluations. These evaluations would provide essential insights into the cost-effectiveness of telesurgical treatments, contributing significantly to the discourse on the practical implementation of this groundbreaking technology.

Other important telesurgery issues are legal considerations, notably in jurisdiction and licensing, where compliance with diverse medical regulations is crucial. Clear and informed patient consent becomes pivotal due to the remote nature of telesurgery. Robust data privacy measures are imperative for safeguarding sensitive patient information. Medical liability complexities necessitate clear roles and responsibilities delineation, addressing adverse outcomes or malpractice. Insurance coverage adaptation is vital, ensuring malpractice policies cover the unique risks of telesurgery. Regulatory frameworks are continually evolving, requiring collaborative efforts to balance innovation with patient welfare. In essence, a proactive legal approach is essential for the ethical and safe integration of telesurgery into broader healthcare practices.

Looking ahead, as robotic technology progresses and seamlessly integrates haptic and visual feedback with 5G networks, telesurgery stands on the brink of revolutionizing global healthcare and surgical treatment. This convergence harnesses the strengths of robotic surgery, encompassing enhanced visualization, augmented reality, improved ergonomics, and heightened dexterity. Notably, telesurgery extends its reach to provide surgical care in remote and challenging-to-access locations, such as spacecraft and ships.

However, despite its immense potential, telesurgery confronts several challenges. The quest for achieving zero-latency time and the continuous improvement of haptic feedback technology are pivotal for ensuring precision in surgical procedures. Simultaneously, the ongoing tasks of addressing cost, legal, and ethical considerations are paramount to guaranteeing the widespread adoption and ethical practice of telesurgery in the medical field. The journey of telesurgery unfolds, promising transformative changes in healthcare delivery and surgical practices worldwide, with each challenge representing an opportunity for innovation and progress.

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