Journal of Robotic Surgery (2024) 18:40
https://doi.org/10.1007/s11701-023-01797-3

REVIEW

Technical and ethical considerations in telesurgery

Vipul Patel[1,2] · **Shady Saikali**[1] · **Marcio Covas Moschovas**[1,2] · **Ela Patel**[3] · **Richard Satava**[4] · **Prokar Dasgupta**[5] · **Mischa Dohler**[6] · **Justin W. Collins**[7,8,9] · **David Albala**[10,11] · **Jacques Marescaux**[12]

Received: 12 October 2023 / Accepted: 14 December 2023

Abstract

Telesurgery, a cutting-edge field at the intersection of medicine and technology, holds immense promise for enhancing surgical capabilities, extending medical care, and improving patient outcomes. In this scenario, this article explores the landscape of technical and ethical considerations that highlight the advancement and adoption of telesurgery. Network considerations are crucial for ensuring seamless and low-latency communication between remote surgeons and robotic systems, while technical challenges encompass system reliability, latency reduction, and the integration of emerging technologies like artificial intelligence and 5G networks. Therefore, this article also explores the critical role of network infrastructure, highlighting the necessity for low-latency, high-bandwidth, secure and private connections to ensure patient safety and surgical precision. Moreover, ethical considerations in telesurgery include patient consent, data security, and the potential for remote surgical interventions to distance surgeons from their patients. Legal and regulatory frameworks require refinement to accommodate the unique aspects of telesurgery, including liability, licensure, and reimbursement. Our article presents a comprehensive analysis of the current state of telesurgery technology and its potential while critically examining the challenges that must be navigated for its widespread adoption.

Keywords Telesurgery · Robotic surgery · Remote surgery · Network structure · Latency · Ethical · Technical · 5G

✉ Shady Saikali
shadysaikali@gmail.com

[1] AdventHealth Global Robotics Institute, Celebration, FL, USA

[2] University of Central Florida (UCF), Orlando, FL, USA

[3] Stanford University, Stanford, CA 94305, USA

[4] University of Washington, Seattle, WA, USA

[5] MRC Centre for Transplantation, Department of Urology, King's Health Partners, King's College London, London, UK

[6] Advanced Technology Group, Ericsson Inc., Santa Clara, CA 95054, USA

[7] Division of Uro-Oncology, University College London Hospital, London, UK

[8] Division of Surgery and Interventional Science, Research Department of Targeted Intervention, University College London, London, UK

[9] CMR Surgical, Cambridge, UK

[10] Downstate Health Sciences University, Syracuse, NY, USA

[11] Department of Urology, Crouse Hospital, Syracuse, NY, USA

[12] IRCAD, Research Institute Against Digestive Cancer, Strasbourg, France

Introduction

Telesurgery, also known as remote surgery, refers to a surgical technique that allows skilled surgeons to perform intricate procedures on patients located at a distance. Enabled by advanced robotic systems and high-speed communication technologies, telesurgery involves the use of remote-controlled surgical instruments guided by a surgeon from a control station. This approach is enabled by robotic surgical platforms that combine the precision of robotic technology, efficient and low latency tele-connectivity with the expertise of experienced surgeons, creating a bridge between geographical barriers and medical expertise. Beyond geographical distances, remote surgery can also bridge temporal gaps, allowing surgeons to respond swiftly to emergencies or time-sensitive procedures. The first successful telesurgery, 'Operation Lindbergh', was performed by Jacques Marescaux and his team transatlantically [1], followed by a successful service development at Centre of Minimal Access Surgery by Mehran Anvari, but costs and ethical considerations were prohibitive and telesurgery delivery was paused. However, there has been ongoing development of the technical infrastructure that can now provide a robust and affordable base for successful replication of this unique prospect. Yulun Wang founder of the company Computer Motion and developer of the ZEUS robot, used during operation Lindbergh, listed five main components for successful telesurgery; augmentation, ergonomics, enhancement, image-guidance and data transmission [2].

One of the major limitations to the replication of the initial case study is the availability of an adequate technological infrastructure to support the bidirectional surgical transmission. Due to the intricate nature of surgical procedures, it is vital that the robotic platforms are compatible for remote control and that the communication between the system components be fast, stable, with low latency and minimal jitter to guarantee the reliability of the connectivity and mitigate any added risk to the patient's well-being intraoperatively [3].

Additional concerns before implementing telesurgery in clinical practice would be the credentialing, regulatory and ethical issues of conducting these remote procedures [4, 5]. However, the current literature still lacks robust real-life evidence to support the practical implications of telesurgery, and there is limited published data exploring the opportunities and associated risks in what is the natural evolution of robotic surgery [6]. We aim to highlight the technical, regulatory ethical and credentialing considerations as an integral part of creating a standard model for remote surgical procedures, that will enable this concept to be safely initiated, with a focus on delivering access to surgical expertise, as initially envisioned.

A key concept that will allow wider acceptance by the medical community and patients is understanding why the time is nigh for telesurgical services to be adopted. The practice of telemedicine is now common practice and has been propelled to the forefront from the necessity of remote medical care created by the COVID pandemic. Telemedicine and having the physician located remotely is now an accepted method of care for medical consultation. Remote surgery is not yet commonly practiced or accepted due to past limitations in the technology required for telesurgery. In the past all the robotic ENT, laparoscopic and cardiothoracic surgeries have been reliant on a single platform; the daVinci surgical system from Intuitive surgical. Intuitive and their daVinci surgical robot have not pursued the telesurgical capabilities of their platform since acquiring computer motion and we have, therefore, not seen any advancement in robotic telesurgical ability. The recent introduction of novel advanced surgical robotic platforms from competitor companies has spurred interest in telesurgery. In addition, the evolution of telecom platforms to 5G with reduced latency and increased stability has provided an option for reliable connectivity. The combination of the availability of an array of advanced robotic surgical platforms and low latency stable connectivity has made telesurgery a viable technical reality. Despite this progress many barriers still exist with technology, connectivity, regulation, and ethical conundrums. There is much left still to be resolved, however, the availability of advanced technology has raised the likelihood of its realization.

The reason to perform telesurgery is not to do it just because the technology allows it. The humanitarian, social and medical benefits are potentially enormous. The deficit in skilled surgeons in many rural or impoverished areas of the world is significant with many populous areas lacking skilled surgeons for critical procedures [7]. Telesurgery can provide the opportunities necessary to allow remote surgeons to assist local, less skilled, or experienced surgeons when needed, or to fully perform the procedure remotely. This has significant potential in improving surgical quality and reduce complications, reaping enormous humanitarian benefits. As the robotic system landscape becomes vaster integrating tele-surgical compatibility into the systems themselves will become essential (Fig. 1).

Technical challenges and considerations

Communication systems

As could be expected, the technological prerequisites for successful robotic telesurgery are vast. The main criteria they must fulfill were outlined by Wang et al. as previously described [2]. To create a safe and efficient environment for telesurgery, there must be reliable communication systems, low latency networks and high-quality video feeds. As we are now witnessing a natural emersion of the internet of skills, communication systems become key in providing uninterrupted, safe service to the patient. With 5G being the platform for which to base it on, the internet of skill will allow surgeons to share their skillset and operate remotely in an immersive environment, transforming the landscape from virtual reality to synchronized reality [8, 9].

Reliable communication systems consist of multiple components. From a control perspective, theoretically, successful telesurgery should achieve two main goals; stability (closed loop communication system) and telepresence (give human operator the sense of transparency between themselves and the environment) [10]. They ensure seamless interaction between the critical components of the surgery, decreasing the risk of technical faults in adverse surgical events. High speed, low latency networks are crucial in ensuring high quality video feeds for the surgeon. Generally in ordinary circumstances, the human reaction time to auditory sensation, visual sensation and tactile sensation is 100 ms, 40 ms, and 1ms, respectively [11]. Any communication infrastructure must strive to mimic these values to minimize any

Fig. 1 Physician performing telesurgery on animal mode 1200 km away in china. Surgeon console contains miniature screen of remote site control room and operating room

noticeable delay allowing for effective and safe surgery. The evolution of mobile networks since the first successful telesurgery was performed, especially in recent years, has shown an exponential growth in speed and reliability of networks which has revolutionized human communications, work flow and quality of life in general [12].

Low latency is the key to securing a smooth surgery in terms of minimizing the 'move and wait' strategy [13] as well as avoiding delay in reaction time. Hokayem and Spong have described a formula for completion time (t(*I*)) of an assignment defined as:

$$t(I) = t_{\mathrm{r}} + \sum_{i=1}^{N(I)} \left(t_{mi} + t_{wi}\right) + (t_{\mathrm{r}} + t_{\mathrm{d}})N(I) + t_{\mathrm{g}} + t_{\mathrm{d}}$$

where t(*I*) is the measure of difficulty, N(*I*) is the number of the movements, t_r is the human's reaction time, t_{mi} are the movement times, t_{wi} are the waiting times after each move, t_g is the grasping time and t_d is the delay time introduced into the communication channel [10]. The experiment concluded that the time to completion is linearly related to the delay in the control loop which is affected by latency [13], highlighting the importance of minimizing it in high equity procedures such as advanced surgery.

Another important requirement is achieving transparency. The surgeon operator requires high-quality video feeds, therefore, the communication protocol chosen to transmit the feed is very important. Despite the Transmission Control Protocol/Internet Protocol (TCP/IP) being known for its superior reliability and capacity to efficiently handle substantial data volumes compared to the User Datagram Protocol (UDP), the delays caused by retransmissions make it unacceptable for real-time streaming in telesurgery, hence the use of UDP [14]. Obtaining high-quality and real-time imaging is critical for telesurgery. Challenges can arise in terms of image resolution, depth perception, and the ability to accurately visualize anatomical structures during remote procedures.

Surgical robotic systems

The first robotic system used successfully in telesurgery was the ZEUS system by Computer Motion back in 2001 by Jacques Marescaux and his team when they performed a robotic cholecystectomy on a live patient between New York City (USA) and Strasbourg (France) 6200 km away [1]. The system at the time consisted of three robotic arms on the patient component as well as a 2D video screen on the surgeon component. The advancement in terms of robotic systems since then has been exponential. The ideal robotic system for telesurgery should be ergonomically sound, accommodate excellent 3D video feed for the surgeon to utilize as well as augment the surgeons capabilities [2]. daVinci, the most widely used soft tissue robotic system in the world, has achieved this augmentation by providing the surgeon with extra arms, vision magnification, 7 degrees of wrist freedom as well as dexterity without human tremor or fatigue [4]. This is an example of a master–slave robotic system employed in robotic surgery. Another system with similar architecture is the CorPath GRX® robotic system (Corindus Vascular Robotics, Waltham, MA, USA) used in percutaneous cardiac stenting procedures and has been successfully employed in telesurgical procedures [15]. The master–slave robotic platforms are the most practical and safe in terms of robotic telesurgery, mainly due to its provision of the highest degree of control in terms of surgical maneuvers as well as the fact that it is composed of multiple separate parts that can be placed a distance from each other and connected using a network. A consideration would be the possibility of upgrading the software on the patient cart side to accommodate telesurgery, since most of the control of the robotic arms resides within the surgeon console [16]. It might seem quite simple, however the fact that it has not been achieved yet begs the question as to what the obstacles are.

Network infrastructure

One of the key reasons for the stagnant progression of telesurgery was the lack of a stable network infrastructure that can accommodate large data transfer in real-time while reducing buffering and connection loss. Low-latency and robust networks are paramount for real-time communication. There is still no acceptable single value in terms of maximum round-trip latency (moment between command of an action until visualization of action on surgeon screen) that is considered acceptable for telesurgery, with a range from 100ms up to 300 ms being considered safe to perform surgical procedures [17, 18]. Nankaku et al. conducted a study to determine the acceptable limits of round-trip communication delays in telesurgery. They measured the task completion time and total movement distance in a dynamic environment of 34 different surgeons with varying surgical experience, under different communication delay conditions ranging from 0 to 300 ms [18]. They found a significant increase in latency from 0 to 70 ms, however the difference in task completion time increased slightly afterwards. They concluded that in dynamic environments, a delay of 100ms or below is acceptable for safe surgery in experienced surgeon hands. Decreasing the latency is paramount as discussed earlier to ensure a safe surgery. The robustness of the network, its ability to withstand perturbations and failures, is obviously a key issue in remote connections. The communication system used is key in achieving that goal. Since a large amount of data is being transferred simultaneously, it is imperative to control network congestion. The end points of a connection (sender/receiver) are the main dictators of the amount and structure of data that enters a connection. When the demand for network resources (i.e. bandwidth, a router's switching/buffer capacity) exceeds the network's capacity, congestion occurs [19]. Congestion causes data packet loss and delays which could be catastrophic in telesurgery. To successfully mitigate this challenge, first the network traffic must be classified into different groups according to the nature of the information being transmitted: Realtime traffic (video and audio), Interactive traffic (robotic commands), Bulk traffic (data, large files), etc. TCP/IP was the traditional method of transport for such high-volume data however the real-time nature of telesurgery can cause TCP/IP to get into catastrophic delays very quickly and packet data loss causing even further delays. Newer protocols have been used (QUIC, SCReAM) which allow for reduced latency and an increased proportion of video data transmission successfully reaching back to the surgeon, which is called throughput [20, 21]. In the past satellite communications, optic fiber dedicated lines and Internet communications were commonly used. The benefit of satellite communication was its stability in terms of it being unaffected by range, geographical location or weather, however the latency time was too high (125 ms each way) as well as the amount of data that can be transmitted at once was limited. Fiber optic was also another option with a low delay and high stability however the cost was huge [14, 28].

With countries adopting 5G networks, a wider accessibility as well as optimal network infrastructure is becoming more and more realized. 5G networks provide a very high data transfer rate of up to 10GB/s, compared to its direct predecessor the 4G/LTE network (0.1–1 GB/s) introduced in the year 2010 [22]. 5G network was built with the intent to support multiple services that have different performance requirements including telesurgical requirements [23]. The 'network slicing scheme' unique to 5G networks divides its architecture into multiple networks specialized in one specific function. The benefits of this are allowing the network to sustain ultra-reliable low latency communications (URLLC) which is key in real-time performance applications such as telesurgery. The benefits of 5G include; high speed, increased throughput, reliability, low latency, increased capacity, increasing availability and connectivity, dynamic bandwidth allocation and massive multiple-input multiple-output (MMIMO). These are what makes 5G networks suitable to accommodate large packets of data at once from multiple sources. This is vital in enabling them to transfer high video feeds (4K, 8K), high audio feeds and haptic feedback if necessary [24].

The 5G network quality of service (QoS) attributes are vital in determining confidence in use of the system [25]. They are a set of techniques and mechanisms designed to ensure that different types of network traffic receive the appropriate level of performance and resources, according to their specific requirements. They include enhanced mobile broadband (eMBB), massive machine-type communications (mMTC) and ultra-reliable low latency communications (URLLC). Many parameters are optimized to maintain the QoS provided by 5G networks such as data bitrate, packet loss rate, latency and jitter.

Another key component in telesurgery QoS is redundant communication. By providing at least one backup channel it was shown that interruption of connection during robotic telesurgery would not affect images during surgery [26]. Just like having a backup surgical team in the OR in case of an irreparable technical fault is crucial, so is having a backup communication line.

A consideration however is how telecom providers can build and operate this network. Ultimately, the speed and delay of data flow hinge on the least efficient link within the sequence connecting the local and remote sites. Fiber provided by Internet Service Providers (ISPs) is currently the preferred way to connect the surgery end points. However, fiber has three short-comings with regards to telesurgery: (1) It is not available everywhere (95% 5G vs 80% fiber population coverage in the US, end of 2022); (2) It is a best-effort technology which introduces large delays and jitter at peak hours (e.g., 5 pm); and (3) It has no ability to allocate bandwidth that is exclusive to low-latency requiring services, such as telesurgeries. However, to make 5G function as well as fiber requires further technological upgrades in addition to regulatory and governmental oversight of national telecom operations [27].

Teleoperation interfaces

The telesurgery interfaces employed for governing robotic surgical tools are crafted to furnish surgeons with essential control, accuracy, and response for the efficient execution of surgeries. These interfaces may differ based on the robotic surgical system in use; however, they typically encompass a range of vital elements.

The master/slave control system is the most common robotic interface used in telesurgery as reported in the literature. As we described earlier, its ergonomic design among many other considerations is what makes it ideal for telesurgery [4]. Another key aspect is image visualization and 3D stereoscopic imaging. To ensure safety and precision of the procedure, 3D visualization is key in reducing many issues that could be faced in remote surgery including depth perception, hand eye coordination, fatigue and strain as well as increased capability of training and skill transfer [28]. This interface increases the safety of the procedure as well as reduce time of surgery which directly impact patient outcomes.

Haptic feedback is another interface that needs to be addressed in telesurgery. It is a frequently mentioned deficiency in robotic surgery, especially by training surgeons in the beginning of their learning curve. Skilled surgeons, however, can compensate with sensory substitution such as using visual cues. Haptic feedback can provide two pieces of valuable information: force feedback from the surgical site as well as spatial guidance. Experiments conducted in teleoperated orthopedic surgery showed that usage of both forms of haptic sensation improved human machine interaction in teleoperated robotic surgery [29]. One robotic system (Senhance system from Asensus) is haptics capable however its ability to be used in telesurgery remains to be tested [30]. Haptic fidelity (how accurately a force feedback is perceived by operator), perception and stability are key concepts to be addressed before haptic feedback can be used effectively and safely in telesurgery [30]. As we mentioned before, this is a commentary made mainly among aspiring robotic surgeons starting their learning curve, however by providing accurate haptic feedback, there is a potential to shorten this curve and provide multiple methods of gauging tissue tension effectively.

Video feed and audio communication between patient and surgeon sites is an additional interface unique to telesurgery. Developing a separate line of communication between the surgeon site and patient site is paramount in safe practice of such a procedure. Both teams should be able to communicate seamlessly between each other and relay information bidirectionally (patient clinical condition relayed to the surgeon and surgeon demands relayed to the patient site surgical team instantaneously). As discussed earlier, redundancy, low latency and backup channels are key in maintaining and achieving this environment.

Latency mitigation

As we mentioned earlier, latency is probably the key factor in determining the applicability of telesurgery. For surgical robots to be reliable, they need to be able to continue operating with stable constant network connectivity. Excessive latency and jitter can adversely affect efficient surgery and freeze or delay the image relay. In such situations however, the surgeon perception or command will be delayed or frozen due to the network malfunction [17]. This risk is one of the key barriers to the adoption of telesurgery with previous network infrastructures. Various studies to determine latency effects on surgical performance showed that task completion time, motion, and errors increased gradually as latency increased [31–33]. As one of the key attributes of QoS in 5G networks, URLLC has wide applications (automated controls, tactile internet, remote operations) [12] however other techniques have been investigated to mitigate the effects of latency.

Motion scaling is a proposed mechanism for the negative effects of time delay. When latency is in effect, a surgeon's movement of the robotic instrument to the desired target could not be completed and perceived as an incomplete movement by the surgeon. This might cause the surgeon to move the instrument even further, causing an 'overshooting' phenomena and when the surgeon realizes the results of his actions, even the compensatory mechanism can cause incorrect placement of the arm [34]. A study conducted by Orosco showed that negative motion scaling improved error rates as well as task time when operating under latency conditions [34]. Several papers have showed similar results with negative motion scaling [35–37].

Predictive display algorithms and augmented reality were proposed mechanisms to overcome the effect of latency. They have been investigated in teleoperation and can be transferable to the realm of telesurgery, although they necessitate tackling the distinctive hurdles associated with predicting and monitoring the complete 3D environment, encompassing pliable elements like tissue. Moreover, existing endeavors within the surgical robotics domain underscore the necessity of dynamic tracking. This imperative arises from the surgical operations' millimeter-scale precision [38–40].

Remote monitoring and technical support

Continuous monitoring of robotic systems during surgery is crucial to ensure the safety, accuracy, and successful completion of the procedure. Robotic surgical systems involve complex interactions between hardware, software, and human operators. Continuous monitoring of the procedure is crucial for patient safety and optimal performance, allowing real-time feedback and early detection of anomalies (Fig. 2).

In cases of unforeseen technical issues during robotic surgery, having agreed and standardized robust protocols for remote technical support and troubleshooting is crucial [6]. A dedicated support team of technical experts, specialized in telesurgical communications should be present around the clock for assistance. A real-time communication channel should be available between them and the surgical teams on both ends, using all communication means necessary (phones, messaging systems, video conferencing). This team should also be allowed remote access to the robotic platform's software to diagnose and troubleshoot any malfunctions instantly. Preventive measures should be in place such as regular system checkups and preventive maintenance, minimizing potential technical issues during surgery. Another novel suggestion is the development of a troubleshooting playbook that encompasses common technical problems along with detailed step-by-step solutions to allow universal operation of the technical support team.

Fig. 2 Example of control room and command center regulating connections and monitoring telesurgical sites across china

Along with the playbook, emergency protocols should be put in place for situations that endanger the patient's safety. This would include switching to manual operation or aborting the surgeries. Basic training in technical support and emergency protocols should be allocated to the surgical teams in place as well, to allow them to remediate minor issues, similar to the technical training they receive for robotic surgery in general, as well as navigate emergency situations in case of communication failure between the sites. Documentation of all technical issues and their resolutions, as well as regular reviews should be conducted to allow for future process improvements and refine the experience based on real-world technical considerations.

Achieving robotic platform interoperability in telesurgery is crucial for ensuring the safe and effective exchange of information between various medical devices and technologies. Often, general consumer based devices and cloud services are provided by the same vendor, creating a seamless integration experience. However, issues can arise when proprietary data protocols lock users into a specific cloud service or end user device, limiting their ability to explore alternative devices [41]. Standardization plays a critical role in achieving this interoperability, as it defines common rules and protocols for data exchange and system integration [42]. With standardized interfaces and communication protocols, robotic surgical platforms from various manufacturers can collaborate effectively, enabling surgeons to access the best tools for a specific procedure, regardless of the platform's origin. This not only enhances the flexibility and versatility of telesurgery but also promotes competition, innovation, and patient safety by encouraging the adoption of best practices and ensuring compatibility across the board [43]. Several conferences and attempts have yet to be successful in translating device interoperability into commercial use [44, 45]. As robotic telesurgery continues to evolve, platform interoperability and adherence to established standards will remain central to its growth and widespread adoption in the medical field.

Data and network security and privacy

Data security and privacy is crucial in medical practice, let alone in telesurgical settings. Transmitting patient data and images across different institutions exposes patient data to security threats and breaches as well as unauthorized access to the data. Many security methods in place today need to be employed in telesurgical communication to ensure safety and privacy of patient information [42].

Cyberattacks are a substantial potential threat when performing telesurgery. They can occur in many different forms, as clearly outlined in various studies [46–50]. A lot of research on cybersecurity threats has been conducted on an open platform surgical robot (Raven II) designed specifically for the purpose of collaborative research on advances in robotic surgery [46, 51]. Some cybersecurity threats worth mentioning include denial of service (DDOS) and man-in-the-middle attacks (MITM) which pose a serious threat to all internet of things (IoT) devices [50, 52], as well as robotic surgery consoles. DDOS involves overwhelming a system's resources, causing it not to respond to service requests. This can have catastrophic implications in telesurgery, preventing the robot from responding to the surgeon's commands by, for example, executing the robots emergency stop button [46, 49]. MITM attacks allow the attacker to assume the role of a network intermediary, preventing benign communication between the surgeon and the robot [46]. This form of 'hijacking' or impersonation attack can allow an attacker to potentially manipulate the command, or feedback data that the surgeon sends or receives [53]. Al Asif et al. explore various other cyber security threats along with proposed defense mechanisms to tackle them [47].

Unauthorized access to patient data is another privacy consideration that needs to be addressed using proper data encryption protocols. End-to-end encryption, with encryption at the source and decryption at the intended user, prevents hackers and service providers from accessing this information during real-time feed as well as data saved on the server after the procedure [54]. Transport layer security (TLS) and Datagram Transport Layer Security (DTLS) should be employed to secure connections between the robotic devices and the servers used [48, 54].

Another preventive measure is secure authentication, allowing the appropriate personnel access to the data and surgery. Multifactor authentication, which have been employed in more menial technologies such as mobile phones, is a valid proposed mechanism for authentication. Using biometrics along with username and passwords for access can ensure a higher level of security in terms of authorized access. Role based access control is another form of secure authentication, defining the level of access for each member of the team, for example allowing surgeons access to the surgery controls while technical and supportive staff have limited access. This can be done using multiple levels of authentication and frequent password changes between surgeon and surgeon console as well as with the robotic console on the patient side [55]. Authentication and identification of master and slave consoles is also necessary in pairing the patient and surgeon console correctly. It was suggested by Iqbal et al. to use certificates or tokens unique to each device allowing for correct mutual identification on both ends [48, 54].

It is also worth mentioning that compliance with regulatory standards regarding patient information (Health Insurance Portability and Accountability Act (HIPAA), General Data Protection Regulation (GDPR)) are still valid concerns, and need to be audited during telesurgery [42]. Data recording, storage and transmission must adhere to a stern set of regulations to preserve patient privacy. There is no uniform set of guidelines or best practices established for data privacy in telehealth and further scientific studies and expert meetings are necessary to create universal regulatory statements and codes specifically for data security in telesurgery [56].

A secure network framework has been proposed for the telesurgical environment [54]. The authors suggest splitting up the procedure into three distinct phases (preoperative, intraoperative and postoperative phases) and focusing on mode of security for each one. They list various potential threats to the system along with proposed defensive measures [47, 54]. They interestingly also suggest a third-party regulatory body to oversee all framework components and approve all participating entities whether technical or medical.

Combining communications encryption, secure authentication, and adherence to regulatory standards is paramount in maintaining data security and privacy. Since it is a sensitive and rapidly evolving field, healthcare experts would need to work closely and continuously with cybersecurity experts to assess potential threats and implement preventive and remedial measures accordingly.

Case studies and lessons learned

There have been many real world case-studies over the years, mostly on non-human models. The reason for the scarcity in human subjects is the lack of adequate technology and infrastructure that could support telesurgery safely and efficiently. Table 1 mentions a compilation of prominent case examples of telesurgery throughout the years.

Future technological advancements

As telesurgery continues to develop as a solution to global surgical education and generating equality in healthcare, technical advancements within the field are crucial to accommodate innovative technologies in mainstream healthcare. Many speculations on the advancement in telesurgery have been proposed.

Artificial Intelligence is a rapidly growing field and has become a key component of medical care today. It's use in surgical data science has been explored and studied in various applications [57, 58] AI has the potential of analyzing surgical data in real-time and providing the surgeon with valuable decision support [59]. Real-time image analysis using computer vision is one proposed use of AI in telesurgery. It can provide feedback on complex medical images and identify anomalies intraoperatively that might not be immediately apparent to the surgeon [60]. Surgical planning is another potential application for AI. By assimilating preoperative patient data and knowledge of surgical procedure, it can potentially provide optimal surgical approaches instantaneously in high equity situations such as telesurgery. AI can play a proactive role in telesurgery, predicting potential complications from historical case studies which would allow for preventive measures [61, 62].

One key barrier to adopting AI quickly, despite its obvious performance benefits, is the human lack of trust in these systems and ethical considerations [42]. This trust, or lack of it, is evident in many high-risk industries, surgery being considered a prime example. This is largely due to the lack of transparency, and human understanding of these systems, as well as them being easily influenced by human data input and malicious interactions [63, 64]. This is where the concept of 'Trustworthy AI' is vital in making humans adopt artificial intelligence wholeheartedly. It focuses mainly on two aspects; identifying factors that cause humans to distrust AI systems, and develop methods to improve human trust [63]. While the AI community is attempting to achieve this trust, being able to provide an augmented experience rather than a human alternative is more easily accepted by the surgical community.

Another future prospect to be developed in telesurgery is advanced imaging techniques [65]. Augmented or virtual reality using predictive displays has been investigated as a potential solution to overcoming latency effects of telesurgery however challenges have been met in mitigating 3D geometry tracking [39]. According to Choi et al. other possible emerging technologies in telesurgery such as a floating 3D visual feedback system are already being explored. According to Zhao et al. these real-time holographic images surrounding the surgeon's field of vision allows them to be almost completely immersed in their case or in mentoring a case.

Possibly the most anticipated advance in telesurgical ability would be the ability to apply accurate haptic feedback, which would be incredible for learning surgeons in ensuring the safety and precision of the operation. Schleer et al. found that combining haptic feedback and haptic assistance provided improved human–machine interaction in orthopedic surgery maneuvers [29]. Force feedback and tactile sensors still lack fidelity and robustness in conventional robotic surgery however when combined effectively, it can provide invaluable information to the surgeon on tissue properties and allow for more precise movements in surgical movements [30].

Ethical challenges and considerations

Surgeon–patient relationship

The potential loss of the surgeon–patient relationship is one of the ethical concerns arising in the context of telesurgery

Table 1 Case studies of previous notable telesurgical experiences

Year Performed	Procedure type	Surgeon's names	Clinician location	Patient location	Connection used	Platform used	Distance	Latency	Animal models
1998	Fluoroscopic guided percutaneous renal access	Bauer et al. [69]	Baltimore, Maryland, USA	Rome, Italy	Public telephone line	RCM-PAKY device	7242 km	n/a	No
2001	Robotic assisted laparoscopic cholecystectomy	Marescaux and Rubino [1]	New York, USA	Strasbourg, France	ATM network connected by fiber optic cables	ZEUS	14,000 km	155 ms	No
2003	Lap Nissen fundoplication, Lap right hemicolectomy, Lap sigmoid/anterior resection, Lap hernia repair	Anvari et al. [65]	Hamilton, Canada	North Bay, Canada	IP/VPN network	Zeus TS	400 km	140 ms	No
2005	Stereotactic neurosurgical procedures	Tian et al. [70]	Beijing, China	Yan'an, China	Digital Data Network	CAS-BH5	1300 km	n/a	No
2006	Lap Nissen fundoplication, Lap right hemicolectomy, Lap sigmoid/anterior resection, Lap hernia repair	Anvari et al. [71]	Hamilton, Canada	North Bay, Canada	IP/VPN network	Zeus TS	400 km	150 ms	No
2006	Dismembered Pyeloplasty on 4 swine models	Nguan et al. [72]	London, Canada	Halifax, Canada	Landline based	TS da Vinci	2848 km	370 ms	Yes—porcine
2018	Hepatectomy	Liu, Zhao, Sun Yang, Liu, Huang [73]	Fujian Branch of China Unicom, Fujian, Fuzhou, China	Mengchao Hepatobiliary Hospital, Fujian, China	Huawei, China Unicom	Kangduo	48 km	< 150 ms	Yes—porcine
2019	“One-to-two” simultaneous remote orthopedic robot- Assisted procedure (pedicle screw placement)	Tian, Fan, Zeng [74] Liu, He, Zhang	Beijing Jishuitan Hospital, Beijing China	1. Shandong Yantaishan Hospital 2. Zhejiang Jiaxing Second Hospital China	China Telecom, Huawei	TiRobot system	1. 530 km, 2. 1470 km	28 ms	No

Table 1 (continued)

Year Performed	Procedure type	Surgeon's names	Clinician location	Patient location	Connection used	Platform used	Distance	Latency	Animal models
2019	"One-to-three" simultaneous remote orthopedic robot Assisted procedure (pedicle screw placement)	Tian, Fan, Zeng Liu, He, Zhang [74]	Beijing Jishuitan, China Hospital, Beijing, China	1. Tianjin First Central Hospital 2. Hebei Zhangjiajou Second Hospital 3. Xiniang Karamay Central Hospital China	China Telecom, Huawei	TiRobot system	1. 100 km, 2. 200 km, 3. 3150 km	28 ms	No
2019	Transoral laser microsurgery–1. Ventriculotomy, 2. type 1 cordectomy, 3. type 4 cordectomy	Acemoglu et al. [75]	Vodafone Village, Milan, Italy	San Raffaele Hospital, Milan, Italy	Vodafone Italia (5G)	1. CALM, 2. Panda robot, 3. VITOM 3D	15 km	~ 102 ms	No
2019	Laparoscopic Gastrectomy	Di. Nardo Eberspacher Palazzini [76]	Auditorium del Massimo, Rome, Italy	Saint Mary's Hospital, Temi, Italy	TIM 5G	NP	129 km	NP	No
2018	Robotic-assisted percutaneous coronary intervention With balloon angioplasty and stent deployment	Patel et al. [14]	Akshardham, Gandhinagar, India	Ahmedabad, India	LAN/MAN/WAN connectivity	CorPath GRX	32 km	53 ms	No
2020	1. Left nephrectomy, 2. partial hepatectomy, 3. cholecystectomy, 4. cystectomy	Zheng et al. [77]	Qingdao, Shangdong, China	Anshun, Guizhou, China	5G (public) monitored by China Unicom	1. MicroHand, 2. Hisense CAS	3000 km 300–700 km	264 ms < 60 ms	Yes—porcine Yes
2021	Kidney and ureteric dissection	Chu et al. [78]	Shanghai, China	Quingdao, Shangdong China	5G China Mobile Communication group	Microhand			
2021	Radical Nephrectomy (29 patients)	Li et al. [79]	Qingdao, Shangdong, China	Multiple locations	5G				

[4]. While telesurgery offers numerous advantages, including the ability to provide specialized care remotely, certain aspects might impact the traditional surgeon–patient relationship. In sequence, are a few points that illustrate this potential issue:

1. *Limited physical presence* in traditional surgery, the physical presence of the surgeon during preoperative consultations, the surgical procedure itself, and postoperative follow-up promote a strong sense of trust and connection between surgeon and patient. Telesurgery, on the other hand, introduces a physical distance between the two, potentially leading to a reduced sense of familiarity and connection, and this lack of direct in-person interactions might hinder the development of a deep personal relationship.
2. *Emotional connection* the emotional support and empathy that surgeons provide to patients can play a significant role in the healing process. The remote nature of telesurgery may limit the surgeon's ability to effectively convey empathy and emotional support. This can lead to a sense of detachment on both ends, potentially eroding the emotional bond between the surgeon and the patient.
3. *Patient confidence* patients often draw confidence from meeting their surgeons in person, discussing concerns, and receiving personalized explanations about their procedures. Telesurgery may undermine this confidence, as patients might perceive the surgeon as distant and less accessible due to the virtual nature of the interaction. This can lead to doubts about the surgeon's commitment to their well-being, especially in surgical complications *("Who is my doctor if something happens?").* Telesurgery, by nature, focuses on the procedural aspects of surgery and might lead to more transactional interactions. The absence of face-to-face interactions and physical touch can hinder the formation of a holistic understanding of the patient's needs and emotions. As a result, the surgeon–patient relationship may become more transactional and less personalized.
4. *Communication challenges* effective communication is the cornerstone of any successful surgeon–patient relationship. In telesurgery, communication might be restricted by technical issues, time delays, or language barriers. Misunderstandings or misinterpretations can lead to patient dissatisfaction and compromise the trust that underpins the surgeon–patient relationship.
5. *Lack of treatment continuity* in traditional surgery, the surgeon often remains involved in the patient's care throughout the surgical journey, from diagnosis to recovery. Telesurgery might involve a team of surgeons working from different locations, potentially resulting in a lack of continuity in patient care. This fragmentation can weaken the sense of familiarity and consistency patients experience with their surgeons.

While telesurgery offers remarkable possibilities, these ethical considerations highlight the importance of maintaining a solid surgeon–patient relationship [66]. Addressing these concerns through transparent communication, empathetic interactions, and efforts to ensure patients feel valued and understood is crucial for preserving ethical surgical care. Telemedicine consultations and interaction between remote surgeons and patients are essential during distant patient care.

Potential dehumanization and objectification

Patient objectification is an important ethical concern that arises in the context of telesurgery, reflecting the potential shift from viewing patients as individuals with unique needs and experiences to perceiving them as mere objects within a surgical process [4]. This phenomenon is further emphasized sometimes by the virtual nature of telesurgery, which might inadvertently depersonalize patients and prioritize the surgical procedure over the patient's well-being.

Surgeons and medical teams may become preoccupied with perfecting the technical execution of the surgery, becoming inattentive to patient concerns should they arise. Being in a different geographical region than the patient can further instigate this notion.

Without the direct physical presence of the patient, surgeons might perceive them as data points or anatomical entities rather than individuals with fears, concerns, and emotions. This distancing effect can restrict the development of a compassionate and empathetic connection between surgeon and patient.

Surgeons remotely operating rely on visual cues and data transmitted through robotic interfaces, potentially reducing their emotional acuity towards the patient. This can undermine the crucial doctor-patient relationship, where mutual understanding, empathy, and trust play pivotal roles.

The risk of depersonalization in telesurgery emphasizes the ethical obligation to prioritize patient-centered care. By recognizing each patient's unique journey, addressing their emotional needs, and fostering open communication, telesurgery can extend beyond its technical aspects and honor the fundamental dignity and humanity of those it assists.

Patient vulnerability

Patient vulnerability is also a significant ethical consideration in telesurgery, highlighting the potential challenges and risks patients may face when undergoing surgical procedures through remote robotic systems [67].

The expertise and surgical skills required from remote surgeons often highlight the limitations of the local team in performing a specific procedure entirely unassisted. This raises concerns about the capacity of the local surgeon and team to handle potential complications or continue the surgery if any technical failure should occur. This situation can expose patients to potential vulnerabilities.

While we recognize that certain geographical regions face challenges related to limited healthcare access and expert availability, we firmly believe that the potential vulnerabilities introduced by telesurgery must be openly discussed with both patients and medical personnel before any remote procedure is undertaken. Patients should have a clear understanding of the advantages, limitations of both local and remote teams, and potential complications. This awareness empowers them to actively participate in decisions aligning with their needs and expectations.

Moreover, it's crucial to present patients with feasible options and contingency plans. For example if for any technical reason the surgery cannot be continue remotely, a local surgeon can step in whether via robot or traditional open approach to continue the surgery. The patient should acknowledge beforehand their understanding of the probability of that happening and its resultant outcomes, which could possibly be below expectations. This allows patients to comprehend the medical team's optimal decisions in cases of complications during surgery, aligned with the patient's preferences. By acknowledging and addressing these vulnerabilities, telesurgery can genuinely uphold the principles of ethical medical practice and prioritize patient well-being.

Conflict of interest

Conflict of interest is a multifaceted ethical issue that can arise in different aspects of healthcare, including the realm of robotic and telesurgery [6]. Surgeons engaged in telesurgery may confront conflicts of interest that have the potential to impact patient care, decision-making, and the overall integrity of the medical field. In such scenarios, financial or professional interests might compromise their primary obligation to deliver optimal patient care. These conflicts can manifest due to diverse factors, including financial ties with technology manufacturers, research funding, consulting arrangements, or affiliations with specific medical institutions. Moreover, surgeons could potentially offer procedures outside their expertise or scope [68].

Surgeons and medical institutions must implement rigorous policies that promote transparency and unbiased decision-making, along with regulatory bodies within the institution monitoring any conflicts of interest the patient should be aware of. Medical and scientific societies should offer clear guidelines for disclosing financial relationships, and hospitals and healthcare systems should establish robust peer-review processes to identify potential conflicts of interest.

Informed consent in telesurgery

In healthcare, informed consent stands as an ethical cornerstone, gaining specific importance in telesurgery [69]. Beyond a mere signature, informed consent entails thoroughly informing patients about procedures, including risks, benefits, and alternatives. In telesurgery, this process takes a distinct form due to the remote and technology-driven nature of the procedures.

Informed consent in telesurgery ensures patients understand the procedure being undertaken as well as the remote nature of it, along with the reasons why a local surgeon is not performing the surgery along with all the implications and possible complications that could be encountered [5]. This could lead to patients questioning the physically present surgeon's abilities to intervene in case of emergencies. Addressing these concerns and outlining contingency plans is essential while applying preoperative informed consent.

Informed consent also involves defining the responsibility for any potential complication (local surgeon or remote surgeon along with the institutions involved and technical institutions involved in transmitting the surgery). The role of each surgeon in that specific procedure should be described and discussed in detail. A proposed solution could include virtual consultations before the surgery, allowing patients to ask questions, voice concerns, and develop a relationship with both surgical teams (local and remote).

Transparency fosters trust and empowers patients to decide independently. By tailoring the informed consent process to address remote surgical challenges, healthcare providers can bolster patient autonomy, cultivate trust, and enable informed decisions regarding their care.

Legal and jurisdictional issues

Remote surgery often spans geographical boundaries, leading to complex legal and jurisdictional challenges [69]. Determining responsibility in case of adverse outcomes, exploring licensure requirements across different regions, and establishing frameworks for international collaborations raise ethical dilemmas that need robust legal and regulatory frameworks.

In the United States, state-specific physician licensing poses a challenge for seamless telesurgery adoption across states [70]. Various states require distinct licenses for remote patient care, hindering cross-border practice. Despite expedited licensure efforts, a unified multistate framework is lacking. Similar licensing challenges are present globally, with no specific international laws for telesurgery spanning countries.

In the United States, the challenge of state-specific physician licensing impedes the seamless adoption of telemedicine across state lines [70]. For instance, various states mandate distinct licenses for physicians engaging in remote patient treatment, while some restrict telemedical encounters to post-physical visit follow-ups [70]. Although expedited licensure has been introduced to facilitate remote physician engagement, a unified legal framework for multistate licensing and cross-border practices remains absent. These legislation and license issues also happen in other nations, and we still lack specific international laws connecting different countries for the telesurgery practice. Having guidelines set by consensus meetings, led by international medical societies is mandatory to overcome legal issues and facilitate telesurgery expansion.

In telesurgery, medical malpractice laws typically pertain to the patient's location, which complicates determining legal responsibility for adverse events. The presence of robotic systems further raises liability questions, involving the surgeon, manufacturer, and technology. Informed consent laws might not fully cover telesurgery's unique challenges, requiring additional disclosures about technology, technical risks, and surgeon's absence. Integrating these aspects into existing consent frameworks is complex.

Another challenge revolves around the issue of reimbursement, as the regulations and policies in place tend to differ based on jurisdiction and frequently play a crucial role in determining the financial viability of implementing novel medical technologies. Many healthcare systems have distinct reimbursement models for telehealth services and in-person care. telesurgery, operating at the juncture of these categories, can encounter obstacles in terms of reimbursement, particularly when procedures span different countries.

Furthermore, telesurgery introduces the transmission and storage of sensitive patient data and medical imagery. Data privacy regulations, as we mentioned earlier, such as the Health Insurance Portability and Accountability Act (HIPAA) in the U.S., impose stringent demands on the management of patient information. Ensuring adherence to these regulations while transmitting data across remote networks poses challenges, particularly in the face of potential cyberattacks.

Addressing these legislative challenges requires a collective endeavor involving policymakers, healthcare institutions, legal experts, and the medical community. Collaborative efforts to amend existing laws, formulate fresh regulations, and advocate for legal frameworks that account for the intricate nature of telesurgery can pave the way for responsible and ethically sound practices in today's medical landscape.

Conclusion

While telesurgery holds immense potential to transcend geographical barriers and enhance patient care, it also introduces complex challenges. The evolution of surgical robotics, network infrastructure (mainly 5G networks), and teleoperation interfaces has brought us closer to realizing the full potential of telesurgery. However, challenges related to latency, network stability, and data security must continue to be addressed. Lessons learned from real-world case studies have provided insights into technical challenges and best practices. Future technological advancements, such as AI-driven decision support and haptic feedback, can potentially enhance the capabilities and safety of telesurgery.

Another equally important consideration pertains to the ethical and legal challenges in implementing telesurgery. As technological advancements rapidly progress, so should the ethical and moral guidelines for safe and equitable practice [71]. Ensuring patient autonomy, transparent communication, and the preservation of trust within the surgeon–patient relationship are ethical imperatives. As we navigate the challenges of patient vulnerability, potential conflicts of interest, and data privacy issues, it is essential to maintain a strong ethical framework. This framework ensures that technological advancements are in harmony with the core principle of patient-centered care. The ethical landscape surrounding telesurgery requires a careful balance between innovative progress and a steadfast commitment to patient well-being. It is vital to create a regulatory organization and gather panels of experts from diverse fields to craft the most effective practice guidelines for telesurgery. As advancements in this field grows exponentially, the collaboration between experts in healthcare, technology, law and ethics remains indispensable in molding the future landscape of innovative telesurgical advancements.

Author contributions VP prepared figures, wrote and oversaw coordination SS wrote technical part in main manuscript MC wrote the ethical part in the main manuscript EP prepared the table PD, RS oversaw the ethical considerations MD, JC oversaw the technical considerations JM helped coordinate the preparation with VP

Funding The authors have not disclosed any funding

Data availability Not applicable.

Declarations

Conflict of interests The authors declare no competing interests.

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