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REVIEW ARTICLE

Telemedicine and telerobotics: from science fiction to reality

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Abstract

Advances in communication technologies have paved the way for telemedicine to transform the delivery of medical care throughout the world. Coinciding developments in minimally invasive surgery and in particular teleoperated robotic surgical systems will allow the surgeon to deliver expert care in remote locations. This study presents a systematic review of telemedicine, focusing on telerobotic surgical systems. A brief historical review of telemedicine and telerobotics is provided, including a description of the various subtypes of telemedicine. Currently available systems and recent experimental utilization, including long-distance remote telesurgery, are discussed. Experimental telerobotic surgical systems and future developments in the field are reviewed and the potential applications are considered. Future challenges to the implementation and opinions on the future direction of telerobotics are provided in this review.

Keywords Telemedicine · Robotics · Surgery · Telerobotics

History of telemedicine

Information and communication technologies (ICT) have made tremendous advancements over the last 100 years, resulting in an ever-shrinking world. Medical advancements have mirrored this growth, stimulating a boom in the field of telemedicine. Broadly, telemedicine is considered "the practice of medicine and/or teaching of the medical art, without direct physical physician–patient or physician–student interaction, via an interactive audio–video communication system employing tele-electronic devices" [1]. Telemedicine encompasses clinical teaching/mentoring, patient monitoring, and consultative, diagnostic, and therapeutic services. The impetus for telemedicine stems from the need to provide health-care services to areas with geographical barriers and/or limited resources [2].

The ancient Greeks and Native Americans have been attributed with the first uses of telemedicine, in its most primitive form, to convey medical information via smoke and light signals. The twentieth century saw expanded use of telemedicine starting with the first transmission of an electrocardiogram via telegraph in 1906 [3]. The contemporary form of telemedicine originated in the 1960s in both the government and private sectors. In 1962, Dr. Michael DeBakey utilized the intercontinental communication satellite, Early Bird, to videoconference an aortic valve replacement procedure occurring in Houston, Texas, to medical staff in Geneva, Switzerland [4–6]. Simultaneously, the University of Miami School of Medicine was experimenting with the transmission of EKGs from the scene to physicians through radio channels [7]. A partnership between the Kaiser Foundation International and Lockheed Missiles and Space Company in the 1970s led to remote monitoring of patient information at the Papago Indian Reservation in Arizona with the goal of providing better health-care services [8].

These pioneering examples, among others, were the catalyst for the growth and widespread acceptance of telemedicine. The field of radiology was an early adopter, starting in the 1980s, with the transmission of radiological images via coaxial cables for consultation [9]. Surgery followed shortly thereafter, coinciding with the development and advancement of minimally invasive surgical techniques. Many of the improvements in quality health care in all fields of medicine can at least be in part attributed to the expansion of telemedical and communication technologies, including the World Wide Web.

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Methods

A literature search was conducted using the terms: "robotic surgery" and "telemedicine" on PubMed, Medline in Process, and Journals@OVID resulting in 121 articles. An independent manual Internet, open access, and industry review yielded 20 additional articles. The abstracts were reviewed for those written in the English language, leaving 138 articles. After filtering for articles pertaining to surgical robotics history, teleproctoring and telesurgery, and experimental technology, 58 abstracts were identified. Duplicates were eliminated, and the remaining 35 articles were read in their entirety by two reviewers (Fig. 1).

The robotic platform

Minimally invasive surgery is considered one of the greatest advancements in surgical care of the last century. Laparoscopy has provided numerous benefits to the patient including decreased pain, shorter recovery times, and improved cosmesis. The benefits of laparoscopy come at the cost of surgeon ergonomics, lack of dexterity, and loss of depth perception. These shortcomings combined with advances in ICT provided the catalyst for development of robotic surgical systems.

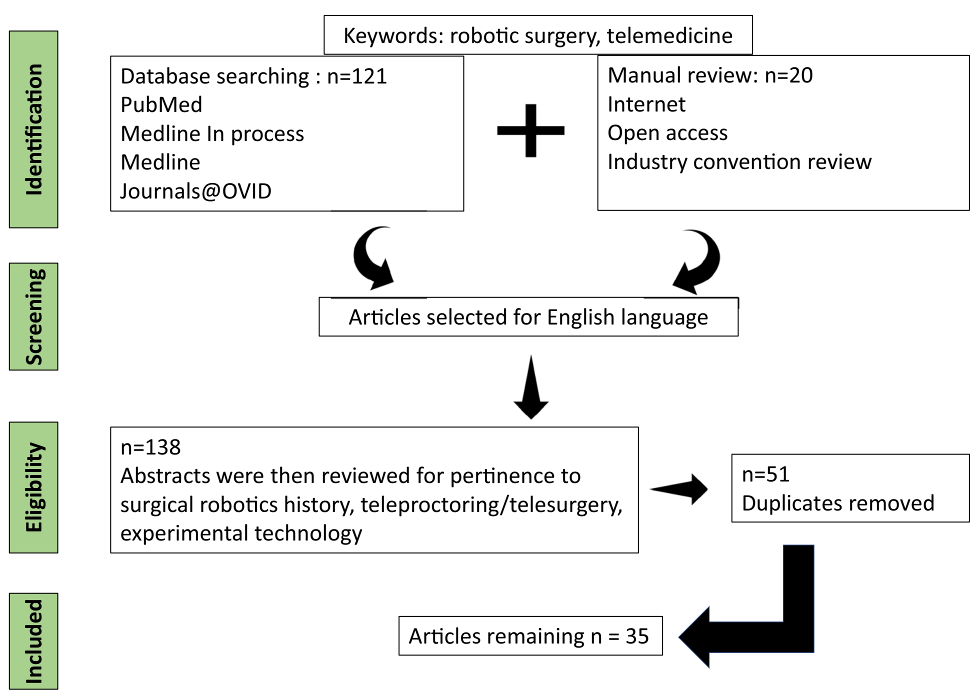
Robotic surgical systems have been designed to overcome the inherent weaknesses of laparoscopy while incorporating advancements in telemedicine and expanding the benefits of minimally invasive surgery [10]. Improvements in dexterity have been accomplished by the elimination of physiologic tremor and constraining, "wristless" straight stick laparoscopic instruments. Three-dimensional visualization provides the surgeon with the depth perception lost in two-dimensional laparoscopy. An often overlooked, but nonetheless important benefit of robotic surgical systems is the improvement in surgeon ergonomics.

The application of robotic systems in surgery began in 1985 when the Puma 560 robot was used by Kwoh et al. to perform neurosurgical biopsies [11]. The same system was later used to perform a transurethral resection of a prostate and led to the development of the PROBOT [12]. Simultaneously, the first FDA-approved robotic surgical system was developed by Integrated Surgical Supplies, Ltd., named ROBODOC. This system was designed to aid in femur manipulation during hip replacement surgery [13].

Concurrently, the National Air and Space Administration (NASA) began development and testing of robotic surgery technology. NASA in conjunction with the Stanford Research Institute (SRI) created a telemanipulator for hand surgery that incorporated the element of dexterity and became a cornerstone for robotic surgical development in the 1990s. The US Army became interested in developing this technology as a potential modality to decrease wartime mortality by giving a surgeon at a Mobile Advanced Surgical Hospital (MASH) the ability to operate on an exsanguinating soldier remotely, through telepresence [13].

Continued developments led to commercial interest in surgical robotics technology. A voice-activated robot designed to manipulate an endoscope, Automated Endoscopic System for Optimal Positioning (AESOP), was

Fig. 1 Literature search flowchart



developed by Computer Motion, Inc. using US Army investment capital. The Green Telepresence Surgery System was developed by SRI in 1992 and consisted of a three-dimensional workstation, an audio component, and force-feedback grasping. This system was later be licensed by the predecessor to Intuitive Surgical [10]. After redesign, the Green Telepresence Surgery System was morphed through multiple iterations, eventually becoming the now more well-known, da Vinci™ telesurgery system. The da Vinci system was FDA approved for general laparoscopic surgery in July 2000. Following suit, Computer Motion Inc. developed a similar in design robotic surgical system named ZEUS®, utilizing the AESOP endoscopic arm. FDA approval was achieved in 2001, but Computer Motion was acquired by Intuitive Surgical and the Zeus product line discontinued in 2003 [14].

Intuitive Surgical has continued development of the da Vinci system over the last 20 years. The second-generation da Vinci S was released in 2006, followed by the da Vinci Si in 2009. The Si provided improved full-HD, improved ergonomics, and the ability to have a dual console [14]. The latest generation, the da Vinci Xi, was released in 2014 and improved on many of the shortcomings of the Si system. The da Vinci system remained the only FDA-approved complete teleoperated robot until 2017, when TransEnterix, Inc. obtained FDA clearance for the Senhance Surgical Robotic System.

Telemedicine and telerobotic clinical applications

Robotic surgery techniques have been applied to nearly all surgical specialties. Urology and gynecology experienced the largest adoption during the early years of robotic surgery. Recently, significant growth has been noted in other surgical specialties, including general surgery. Continued acceptance of robotic surgical systems and the advancement in telecommunication technologies have led to increasing development and utilization of telemedicine, extending from telepresence to telesurgery.

Telepresence is the basis for telemedicine and telerobotics. Telepresence is the presentation of a remote environment in a natural fashion, thus generating a feeling of presence at the remote site [15]. The information is relayed via telecommunication networks to the physician [16]. In effect, the remote site could be in a neighboring city or, theoretically, on a submarine or in space [17]. Telepresence is responsible for laying the groundwork for the extension of telemedicine into the robotic platform.

Expanding on telepresence is the concept of telementoring, the remote guidance of a procedure where the physically present surgeon often has limited experience with the treatment technique [18]. Simplistically, telementoring is the extension of professional mentoring to remote locations [14]. Mentoring remains one of the most effective tools for learning; however, the utility is limited due to costs, time, and geographical constraints [19]. Telementoring can minimize or negate these limitations and bring the "expert" to the remote site. This concept has broad applications including residency training, resource-poor locations, and remote environments.

Telestration improves on telementoring by allowing the mentor to remotely illustrate and annotate on a monitor that is visible in the operating room and overlaid on the real-time picture of the operative field. This technology can assist telementoring when combined with verbal cues and is currently a technique used in proctoring residents during robotic surgical procedures. Multiple experimental and commercially available telestration systems have been developed including Intuitive Surgical's Connect™ and a system developed in a joint effort between Intuitive and InTouch Health to be used with the da Vinci system [20]. A mounting body of literature consisting primarily of pilot studies and case series has demonstrated the feasibility and safety of telementoring. Definitive evidence of the effectiveness of telementoring is lacking, but current evidence does suggest high trainee satisfaction, low complication rates, and surgical improvement [19].

Teleproctoring or tele-assist gives remote mentors the ability to control a portion of the operation, either via the laparoscope or surgical instrumentation. This additional input allows mentors to participate in portions of the procedure to further enhance the guidance provided to the novice surgeon. The Socrates™ Telementoring System developed by Computer Motion, Inc. was the first robotic teleproctoring device approved by the FDA and allowed remote control of a robotic arm or AESOP by the mentor. Two-way audio and video as well as telestration were included in the system [20]. In surgical education, teleproctoring was shown to be equally as effective compared to side-by-side instruction in robot-assisted radical prostatectomies [21]. Coupled with telestration, attending surgeons can precisely demonstrate maneuvers and techniques to their surgical resident trainees.

In contrast to teleproctoring, telesurgery is the completion of the bulk of a surgical procedure remotely. The first true telesurgical operation occurred in 2001 utilizing the ZEUS system. Named "Operation Lindbergh", a robotic cholecystectomy was performed on a 68-year-old female resident of Strasbourg, France, by a New York-based surgeon. Surgeons assisting in France obtained pneumoperitoneum and set up the robotic system. The intra-abdominal portions of the procedure were carried out by the New York-based surgeon [22, 23]. The world's first telerobotic surgical service was established in the early 2000s between the Center for Minimal Access Surgery (CMAS) at McMaster University Centre in Hamilton, Ontario, and a community hospital in North Bay, approximately 400 km away [24]. The ZEUS system was utilized to complete 22 telerobotic cases before the ZEUS system was discontinued in 2003. Most of the additional works regarding telesurgery are based on simulation and animal models which have proven feasibility. A publication by Hung in 2018 reviewed a number of telesurgical applications in animal simulation models in urology and neurosurgery [20]. Using telementoring and telesurgery in urology, Sterbis et al. conducted a study in which residents used the da Vinci robot to successfully perform four porcine nephrectomies as their attending surgeons were seated at consoles 1300 and 2400 miles away. Round-trip signal latencies of 450–900 ms were noted [25]. A phantom pituitary excision from an artificial skull was carried out both locally (robot and surgeon in the same room, 1 m away) with a direct connection and remotely by a surgeon manipulating a robot located 800 km away using an Internet connection. Both successfully carried out the tumor resection in 20 min. As previously acknowledged, a common underlying problem seen among these models was the latency lag, though less than 100 ms was recorded in the pituitary removal experiment using an Internet connection [26].

Future of telerobotics

Robotic surgery has made significant strides toward an established technology while advancing minimally invasive surgery and telemedicine. The surgical robotics market is expected to grow from $3.2B in 2014 to $20B in 2021 [27]. As of September 30, 2017, there were 4271 da Vinci units installed worldwide with 2770 located in the USA, 719 in Europe, 561 in Asia, and 221 in the rest of the world [28]. October 2017 saw the addition of the first new, complete telerobotic surgical system to gain FDA approval since 2001, the Senhance Surgical Robotic System (TransEnterix). This system hopes to make robotic surgery a more cost-effective tool for medical systems while adding haptic feedback and eye-sensing camera controls for the surgeon.

Systems designed to address all angles of surgical intervention are on the horizon. The Magellan Robotic System and the CorPath 200 are platforms developed to address minimally invasive endovascular and coronary procedures. Single-site surgery and natural orifice transluminal endoscopic surgery (NOTES) continue to be areas of developmental interest. Intuitive Surgical is developing a single port add on to the da Vinci Xi system named the da Vinci SP Surgical System. Titan Medical is looking to enter the arena of single-site surgery via their SPORT Surgical System. ARAKNES is attempting to integrate single port laparoscopy and NOTES with their SPRING (Single Port Lapa-Roscopy bImaNual roboT) system. Though still in animal trials, using a robotic approach enhances the efficiency of NOTES procedures by using a magnetic docking frame to dock three modular robots and a camera that can provide multiple angles of visualization, free from collision [29]. Multiple other investigational devices are in developmental and testing phases currently, including a joint venture between Johnson & Johnson's Ethicon and Google's Verily Life Sciences, Verb Surgical.

The future applications of robotic surgical systems including telesurgery are immense. On land, telerobotics will likely play an increasingly vital role in providing expert surgical care to geographically isolated, resource scarce, and military environments. This includes mentorship of novice surgeons via telementorship and teleproctoring. This will allow for delivery of expert care to patients who otherwise would not have the means to obtain such care while promoting dissemination of knowledge and skills to remote or novice surgeons.

Military applications include delivering immediate expert surgical care to the battlefield without endangering the surgeon. The US Army has developed miniature robotic surgical systems complete with haptic controllers and telestration capacities that are controlled via wireless networks. This system is capable of internal and external procedures, even providing anesthesia or placing a port. The deployment of these compact robots overcomes a major hurdle to the widespread use of telerobotics, namely size constraints. This miniature robotic surgery system may facilitate telesurgery, thus allowing faster operative intervention to remote and often dangerous locations where Forward Surgical Teams (FSTs) are present [30]. In conjunction with these advancements in telesurgery, the US Department of Defense in collaboration with SRI has plans to develop the Trauma Pod system by 2025 that is focused on providing trauma care and operative capabilities from a safe distance between military surgeons and wounded soldiers in the battlefield [31].

Surgical care at sea presents many similar challenges as geographically remote environments that could be addressed by telesurgery. The RAVEN, an 80-lb portable surgical robot was developed at the University of Washington and funded by the Department of Defense. This system was tested using NASA's Extreme Environment Mission Operations (NEEMO), a NASA training site at the National Undersea Research Center (NURC) off the coast of Key Largo, Florida. Three separate NEEMO projects investigated telecommunication links, remote surgeon capabilities, and robotic system set up in space-confined locations, and simulated surgery [32].

The NEEMO missions were designed to simulate telemedicine and telesurgery in space. NASA further tested the capabilities of these technologies in space by conducting a weightless robotic skills task using the M7 robot (SRI International) in 2007 [14]. The success of this testing reinforced the feasibility of telerobotics in space. Currently, the only option for astronauts on long orbit missions in need of surgical intervention is to return to earth. This is time consuming, costly, and can put the astronaut at increased risk. Availability of surgical care via telerobotics may prove beneficial in this setting, allowing the astronaut to receive expert surgical care in a more time-sensitive manner and without the need for a costly return to Earth.

Challenges to implementation

A number of challenges lie ahead of the widespread implementation of telemedicine and telerobotics. Regulatory approval and physician licensure remain significant barriers. Varying regulations regarding device approval exist including FDA regulations in the US and CE marking in Europe. These regulations are not identical, and each requires a significant amount of development time and cost. In addition, physician licensure is not universally regulated at a national (in the USA) or international level. A more concrete licensure system will need to be established before telemedicine and telerobotics can become ubiquitous.

Long-distance telerobotics require fast and reliable data connections capable of transmitting a large quantity of data. Studies have indicated that longer latency delays reduce operator performance and are associated with more errors. Latency times greater than 1–2 s make telesurgery unrealistic [14]. Stable networks are often not available in remote geographical locations, the same areas that could benefit most telerobotics. One potential solution is the low earth orbit (LEO) satellite communication system, which includes 78 microsatellites in six orbits that is being developed by Microsat Systems Canada, Inc. with a projected global coverage of 100% [6].

In addition, long-duration space flights exceed the capabilities of latency requirements for telesurgery. Beyond approximately 380,000 km (average Earth–Moon distance), telesurgery becomes semi-real time. Future solutions include semi-autonomous and autonomous robotic surgical systems that will only require verification from a surgeon to proceed with a given task or procedure [14]. A current autonomous surgical robot named Smart Tissue Autonomous Robot (STAR) has been shown to make more accurate incisions than a surgeon cohort with less surrounding tissue damage [33].

The connection of humans via telemedicine advances does not come without consequence.

The first cyberattack on hospitals, or MEDJACK, in 2015 raised significant concerns regarding the confidentiality and safety of future telerobotic operations. Cyberattacks can effectively result in technical difficulties, modified haptic feedback, prolonged operative times, and complete loss of control of the surgical robot leading to patient harm. Bonaci et al. were able to breach a number of elements in the RAVEN II robotic surgical system during their studies attempting various cyberattacks. To aid in creating more secure systems, the authors note that end point encryption and authentication may make an attack more difficult to accomplish. Despite utilizing more memory (average increase usage reported of 3000 KB), they did not see a significant increase in CPU usage for 128-bit, 192-bit, and 256-bit key lengths [34].

Cost remains a significant barrier to the adoption of telerobotics and telesurgery. Operation Lindbergh was performed using ATM telecommunications fibers; while present in multiple countries, these fibers are not equipped at most hospitals. ATM lines, as used in the Lindbergh operation, cost anywhere from approximately $100,000 and $200,000. Robotic surgical systems are a substantial capitol expense. The estimated cost for the da Vinci system is approximately $2 million in addition to maintenance and instrument costs. A final component to the cost equation is the lack of a clear re-imbursement system for the telementor or telesurgeon.

Ethical, legal, and liability concerns will need to be addressed before telerobotics can be widely adopted. Will governing bodies need to be established to certify telesurgical networks? In the event of a complication, how will breach of duty be assigned to a telementor or telesurgeon? How will these issues be addressed regarding international patient/surgeon relationships? Additionally, the consenting process presents further challenges for telementoring and telesurgery. Does the patient need to be informed of the potential for technical failure and cyberattacks? Would the patient need to consent to all providers involved in his or her care? [20].

Widespread use of telesurgery will depend heavily on the availability of adequately trained surgeons. Telesurgery will require specialized skills not widely taught in surgical training. Surgical simulation and telementoring will likely become even more integral in the advancement of telerobotics. An educational and certifying curriculum will need to be established in addition to legal regulations to prevent unauthorized service providers in this field [16].

Conclusions

Synthesizing the available literature, one can speculate on the next generation of telerobotics. The telerobotic platform of the future may consist of many human-automation-centric design features. These design solutions are not simply more automation, but the correct levels of automation for the desired goal. Thus, systems should be blended, providing adaptive automation which contains both human–machine interface that coincides enough to provide appropriate amounts of feedback. Having a blended design philosophy focuses on extending the human perception, limiting the amount of cognitive load, and can reduce error. It is here, where a symbiotic relationship must be targeted to yield the operational goal, while providing ease and efficiency to the human operator even during chaotic or novel clinical scenarios. The future of telemedicine and telerobotics is promising and applications are seemingly endless despite the current challenges. What once was only dreamed of in science fiction may soon become reality for the next generation of surgeons.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Research involving human participants and/or animals All procedures performed in studies involving human participants were in accordance with ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent For this type of study formal consent is not required.

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