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Remote telesurgery in humans: a systematic review

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Abstract

Background—Since the conception of robotic surgery, remote telesurgery has been a dream upon which incredible technological advances haven been built. Despite the considerable enthusiasm for, there have been few published studies of remote telesurgery on humans.

Methods—We performed a systematic review of the English literature (PubMed, EMbase, Inspec & Compendex and Web of Science) to report studies of remote telesurgery in humans. Keywords included telesurgery, remote surgery, long-distance surgery, and telerobotics. Subjects had to be human (live patients or cadavers). The operating surgeon had to be remote from the patient, separated by more than one kilometer. The article had to explicitly report the use of a long-distance telerobotic technique. Articles that focused on telepresence or tele-mentoring were excluded.

Results—The study included eight articles published from 2001 to 2020. One manuscript (1 subject) described remote surgery on a cadaver model, and the other seven were on live humans (72 subjects). Procedure types included percutaneous, endovascular, laparoscopic, and transoral. Communication methods varied, with the first report using a telephone line and the most recent studies using a 5G network. Six of the studies reported signal latency as a single value and it ranged from 28 ms to 280 ms.

Conclusions—Few studies have described remote telesurgery in humans, and there is considerable variability in robotic and communication methods. Future efforts should work to improve reporting of signal latency and follow careful research methodology.

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Keywords

Robotic surgery; Motion scaling; Signal latency; Telesurgery; Telerobotics

Since the inception of robotic surgery, pioneers and researchers have dreamed of performing surgery across great distances. In the latter half of the twentieth century, NASA and the United States military began investing in the development of novel technologies to remove surgeons from dangerous environments [1]. Initial strides in teleoperated systems gave way to the PUMA 200 robot for CT-guided brain biopsies in 1985 [2]. A major breakthrough came with the ZEUS robotic system which was approved for general surgery in 1998 [2]. Development continued and in 2000 the da Vinci Surgical System was launched (Intuitive Surgical, Sunnyvale, CA) [2].

Advances in technology have paved the way for the inclusion of telemedicine in surgery. These inroads first started with telepresence, where the remote operating site is presented in a natural fashion resulting in the feeling of presence [3]. Research continues to show the effectiveness of telementoring, where an experienced surgeon can "mentor" a trainee during a procedure using telecommunication technology [4]. Finally compared to telepresence and telementoring, remote telesurgery is where a primary surgeon operates on a distantly located patient. Although the fundamental hardware elements necessary for remote telesurgery exist, the field of clinical remote surgery remains in its infancy. This systematic review focuses on published applications of remote telesurgery in humans.

Methods

We performed a systematic review of the available English literature to evaluate clinical experiences in remote telesurgery in humans. PubMed, EMbase, Inspec & Compendex and Web of Science were queried on August 2nd, 2021 for articles using the keywords: telesurgery, remote surgery, long-distance surgery, and telerobotics. The following inclusion criteria was used to select articles: (1) subjects in the cases must be human (live patients or cadavers) (2) the operating surgeon and patient must be at different locations separated by more than one kilometer, (3) this off-site clinician must be the primary surgeon in the case, (4) the article must explicitly report the use of long-distance telerobotic technique. The following exclusion criteria were used: (1) articles that exclusively contained animal experiments, (2) articles that were focused on telepresence or tele-mentoring. No systematic reviews or meta-analyses were included in this study. Article titles and abstracts were screened to determine their relevance based on the inclusion criteria. Each article's references were cross-checked to locate relevant studies, and for articles deemed eligible, and full-text manuscripts were reviewed. Two authors independently reviewed each article at each stage, and disagreements were settled by mutual discussion.

Results

The initial database search yielded 2339 articles after the removal of duplicates (Fig. 1). Two independent reviewers identified 24 articles which potentially met the inclusion criteria and were then screened via full text. Sixteen articles were excluded due to lack of original content, focus on experimental procedures, or proximity of the primary surgeon to the patient site. Eight articles qualified for inclusion in the systematic review spanning from 2001 to 2020.

The earliest article was in 2001 when Bauer et al. described a renal access procedure in which the operating surgeon was located in Baltimore, Maryland while the patient was more than 7000 km away in Rome, Italy [5]. Using a PAKY (percutaneous access of the kidney) robot connected to a plain old telephone system (POTS) line, they were able to successfully gain percutaneous access in under 20 min. The signal latency was not measured or reported.

In 2002, Marescaux et al. report the first trans-Atlantic robotic assisted laparoscopic cholecystectomy, in a case known as the “Lindberg Operation.”[6] The operating surgeon and the surgical robotic system (ZEUS, Computer Motion, California) were connected through a high-speed terrestrial optical fiber network (FranceTelecom/Equant). This is the longest published telesurgical procedure at approximately 14,000 km and they reported a total time delay of 155 ms (ms). The procedure was completed in 54 min without any complications.

In 2005, Anvari et al. explored the role of remote telerobotic surgery in 21 cases performed between McMaster University in Hamilton, Ontario and the North Bay General Hospital in Northern Ontario, Canada [7]. The surgeons performed these laparoscopic operations between February and December 2003 using the ZEUS TS microjoint system (Computer Motion, California) connected to an existing Internet Protocol Virtual Private Network (IP-VPN). Round trip delay ranged from 135 ms to 140 ms and there were no major intraoperative complications.

Anvari later reported 22 additional cases conducted on the same network between McMaster University and the North Bay General Hospital. Reported time delay ranged from 135 ms to 150 ms, but it was noted that an increased latency above 200 ms necessitates the surgeon slowing down to avoid overshooting [8].

Tian et al. describe the use of telerobotics in stereotactic neurosurgery. The group used the CAS-BH5 frameless robotic system in 10 different cases performed between Beijing and Yan’an in late 2005 [9]. The distance between the primary surgeon and patient was more than 1500 km, and there was no mention of signal latency over the “Digital Data Network” used for telecommunication.

In 2019, Patel et al. described the use of long-distance telerobotic surgery in cardiology. The group reported the five tele-robotic-assisted percutaneous coronary artery interventions conducted over a distance of 32 km [10]. Using a CorPath GRX robotic system (Corindus Robotics, Waltham, MA, USA), the procedures were performed without complications with an observed time delay of 53 ms.

The final two articles included in this review involve connection via 5G networks. Tian et al. conducted twelve spinal surgeries using the TiRobot system connected to a 5G network (China Telecom and Huawei Technologies Co. Ltd.) and reported no network delays or adverse intraoperative events [11]. Acemoglu et al. performed a laser microsurgical procedure on a cadaver using a novel surgical robot connected to a 5G Radio Access Network. At 15 km distance, they reported a maximum round-trip latency of 280 ms [12].

Discussion

Remote telerobotic surgery, though first pioneered more than two decades ago, remains in its infancy. Safety, cost, and latency concerns have limited the growth and pursuit of remote telesurgery. Previous reviews have assessed the state of robotic surgery, its adoption across surgical specialties, and its potential use in remote surgical settings, but none have focused on the purely clinical applications [3, 13]. Including three manuscripts published since these contemporary reviews, we found only 8 peer-reviewed papers that report a total of 73 telerobotic surgery cases.

A variety of robotic platforms that have been used for human telesurgery. The most published experience comes from the Zeus platform. Despite how ubiquitous the DaVinci platform is in clinical use today, it has not been employed for human remote telesurgery.

A variety of signal communication methods have been employed, and the recent trend is to use a 5G network. Efforts describing the technical methods behind the landmark Lindberg Operation were valuable [14], but there remains great opportunity to describe, optimize, and standardize modern communication methods. Interestingly, the greatest signal latency (280 ms) in our review was reported when a 5G network was used across a 15 km distance.

The 5G network is a complex set of data transactions over local devices as well as national telecommunication service providers. Ultimately, the throughput and latency will be dependent on the weakest part of the chain of transactions between the local and the remote site. Because 5G is a short-range data transmission protocol, the infrastructure to realize a fully 5G network across a large geographical area is enormous, and thus realizing a network of any significant distance that runs purely on 5G will be unrealistic in the short term as service providers would invariably force traffic routes through older infrastructure. Furthermore, service providers are entirely in control of allocating bandwidth, and while priority levels are assigned typically to split the available bandwidth of all traffic (i.e., military networks are given high priority whereas residential are given low priority), these priorities are negotiated by the government and each telecom provider, and a similar undertaking to priorities telemedicine would involve significant, national pressure on telecom corporations. In the meantime, one would imagine that we simply would not have as consistently stable transmission resulting in larger latencies and variability in those latencies.

It is well-established that latency causes significant deterioration in task performance, but there is no consensus as to what the safe or acceptable amount of signal latency is for remote telerobotic surgeries. There are more errors, and tasks take longer when surgeons are working under time delayed conditions [15–20]. Latencies below 200 ms may be ideal [21], but impairment has been reported at 135 ms[22] and even with time delays as small as 50 ms [23, 24]. Though successful robotic telesurgery has been reported with 450–900 ms of latency [17], surgery under latency greater than about 700 ms may not be feasible. [21, 25] Beyond work in basic surgical task models [20], there is a need to analyze performance with more clinically relevant robotic surgery tasks under time delay. Unfortunately, latency is not well characterized in the pre-clinical and clinical telesurgery literature. Future studies should recognize that signal latency is not static and changes over the course of a procedure. Most telesurgery publications only measure mean/average signal latency. The variance, or degree of time delay fluctuations, is never mentioned nor is its impact on a surgery ever mentioned.

In 2003, Butner and Ghodoussi emphasized that “because human life is at stake, issues relating to safety, detection of errors, and fail-safe operation are principal importance” in robotic telesurgery [14]. Safety is directly linked to issues with signal latency, and we believe that safety is the principle barrier to growth of remote telesurgery. Haptic feedback [26], augmented reality predictive display [27], and compensatory motion scaling [20] have been shown to improve surgical performance in experimental models, but there is a paucity of work aimed at combating signal latency. To date there are no studies of clinical remote telerobotic surgery that test potential safety interventions.

There are several other key barriers to remote telesurgery that merit careful consideration but are outside of the scope of this manuscript. These include things like challenges with localization and mapping and signal transmission optimization. The approval process for robotic telesurgery technologies also stands to be defined, as this is a novel realm. Future work in remote telesurgery is needed to better-understand latency parameters and to design and test technologies aimed at ensuring safety. Beyond that mandatory benchmark for safety, there is a great deal of work to be done within surgeon and team training, managing cost and value, risk mitigation, and medicolegal realms.

Transparent and honest methods should be followed when approaching remote telesurgery studies. There are some guidelines as put forth by the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) which advised that telerobotic surgery be performed under strict IRB supervision with careful design and methodology [28]. We hope that our summary of current clinical telesurgery experience and discussion of key limitations and technical considerations will add to the momentum of this exciting realm of research. Millions of future patients stand to benefit from expanded robotic surgery capabilities.

Conclusion

Remote telerobotic surgery is a long-awaited but still nascent capability. A few reports have emerged showcasing this new technology, with encouraging results. However, none of the works to date have presented efforts to combat signal latency, and robust safety remains a critical and still-unproven benchmark. A tactful approach to future studies in remote robotic surgery is necessary to harness its potential while adequately addressing the existing questions regarding safety and feasibility. Quality studies accounting for these limitations can advance robotic surgical care and have far reaching implications spanning multiple surgical specialties (Table 1).

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Declarations

Conflict of interest Patrick Barba has nothing to disclose. Dr. Joshua Stramiello has nothing to disclose. Dr. Emily K. Funk reports grants from NIH/NIDCD, during the conduct of the study; Dr. Florian Richter has a patent motion scaling for time delayed robotic surgery pending. Dr. Michael C. Yip has a patent motion scaling for time delayed robotic surgery pending. Dr. Ryan K. Orosco reports grants from UC San Diego—Academic Senate, grants from UC San Diego—Altman Clinical & Translational Research Institute (ACTRI), during the conduct of the study; in addition, Dr. Ryan K. Orosco has a patent motion scaling for time delayed robotic surgery pending.

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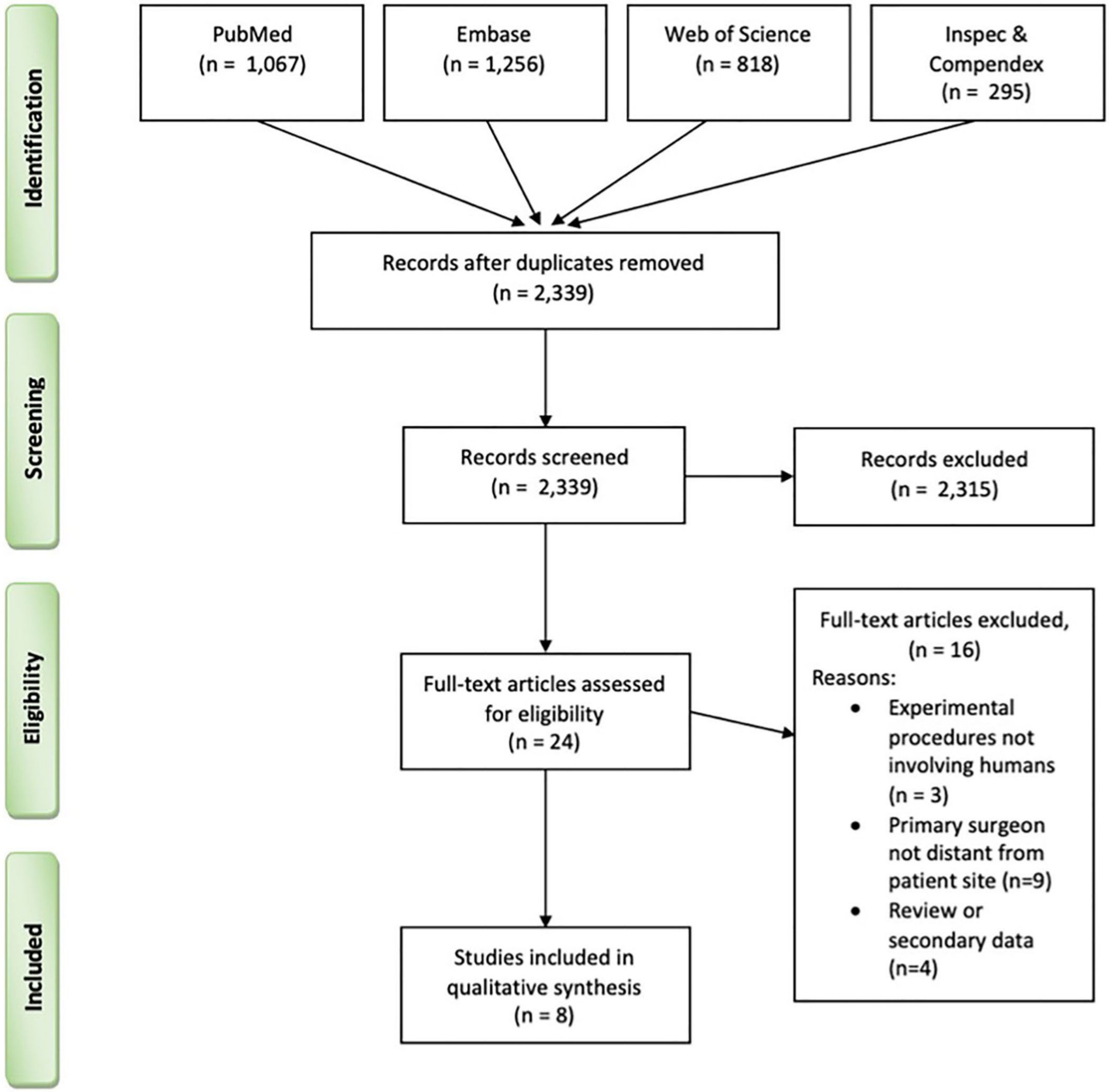

Fig. 1.
Systematic review flow diagram

Table 1

Studies included in final review and key findings

Study	Procedures	Number of subjects	Test subject	Distance from surgeon to subject (km)	Latency Reported (ms)	Communication method	Surgical platform
Bauer, J., et al. (2001)	Fluoroscopic guided percutaneous renal access	1	Human	7242	n/a	POTS (Plain Old Telephone System) line	PAKY needle driver and RCM robot
Marescaux, J. and F. Rubino (2002)	Robotic-assisted laparoscopic cholecystectomy	1	Human	14,000	155	ATM network connected via fiber optic cables	ZEUS system (Computer Motion, Galeta, CA, USA)
Anvari, M., et al. (2005)	Lap Nissen fundoplication, Lap right hemicolectomy, Lap sigmoid/anterior resection, Lap hernia repair	21	Human	400	140	IP/VPN network	Zeus TS robotic platform (Computer Motion Inc., Goleta, CA, USA)
Anvari, M. (2007)	Lap Nissen fundoplication, Lap right hemicolectomy, Lap sigmoid/anterior resection, Lap hernia repair	22	Human	400	150	IP/VPN network	Zeus TS robotic platform (Computer Motion Inc., Goleta, CA, USA)
Tian, Z., et al. (2007)	Variety of stereotactic neurosurgical procedures	10	Human	1,300	n/a	Digital Data Network	CAS-BH5 robot system
Patel, T. M., et al. (2019)	Robotic-assisted percutaneous coronary intervention with balloon angioplasty and stent deployment	5	Human	32	53	LAN/MAN/WAN connectivity	CorPath GRX robotic system (Corindus Vascular Robotics, Waltham, Ma, USA)
Acemoglu, A., et al. (2020)	Transoral laser microsurgery	1	Cadaver	15	280	5G network	CALM (computer-assisted laser microsurgery) system
Tian, W., et al. (2020)	Pedicle screw placement for thoracolumbar fractures, lumbar spondylolisthesis, and lumbar stenosis	12	Human	Variable	28	5G network	TiRobot system