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Telepresence in Healthcare: Engineering Remote Consultations

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ABSTRACT

The COVID-19 pandemic significantly accelerated the adoption of telemedicine, highlighting both its transformative potential and the limitations of existing technologies. This paper examines the engineering of telepresence systems in healthcare, an advanced form of teleconsultation designed to emulate in-person consultations through immersive, interactive, and high-resolution communication platforms. It provides a historical context for telemedicine, detailing its evolution from simple telephone consultations to sophisticated systems incorporating augmented and virtual reality. The technological foundations of telepresence are analyzed, including hardware and software components, network infrastructures, and integration protocols. Clinical applications such as telecardiology and telepsychiatry are reviewed, alongside emerging use cases involving mobile robots and 3D visualization tools. Despite their potential, these systems face considerable challenges, including cost, usability, ethical concerns, and disparities in digital literacy and access. Case studies demonstrate how engineered telepresence solutions can address rural and underserved populations. The paper concludes by identifying future trends and recommending strategies to develop equitable, efficient, and ethically sound telepresence systems that bridge the gap between patients and providers across distances.

Keywords: Telepresence, Remote consultations, Telehealth engineering, Telemedicine technologies, Telepresence robots, Virtual healthcare, Healthcare accessibility.

INTRODUCTION

The healthcare ecosystem is evolving rapidly, especially due to the COVID-19 pandemic, which has increased the demand for remote healthcare services. Initial teleconsultations relied on basic video call applications, while healthcare professionals adapted protocols to meet the needs of a larger patient cohort. Despite the swift integration of telemedicine, significant challenges remain. Emerging technologies continue to enhance healthcare delivery, especially in audiovisual communication formats like teleconsultation and teletherapy, each catering to distinct needs and operational characteristics. However, current tools often fall short of being useful due to the diverse needs of users and a lack personalized solutions. Many existing applications fail to accommodate patients with disabilities or overlook significant differences between rural and urban settings. Additionally, they may not adequately address the varying levels of digital literacy among users or the urgent needs of vulnerable patients, such as children requiring immediate care [1, 2].

Historical Overview of Telemedicine

Telemedicine is rapidly growing within healthcare, serving patients who might otherwise be isolated. Initially, utilizing the telephone it allowed physicians to consult without traveling to remote areas. With advancements like cameras and televisions, doctors can communicate directly with patients in various locations. The integration of telecommunications and sophisticated medical technology has evolved significantly, spurred by increased competition in the telecom industry over the past decade, offering diverse options for telemedicine applications. This modern telemedicine enhances older methods where physicians examined patients through telecommunication means. It involves justified, remote

consultations where healthcare providers gather comprehensive health information without an in-person visit. The term "telemedicine" is often associated with specialized practices, while "telehealth" includes broader public notifications aimed at educating about diseases. Other relevant terms include teletherapy, the remote delivery of radiation, and telediagnosis, which means diagnosing a disease remotely. Specialties have also expanded into teledermatology, teleradiology, telepsychiatry, telecardiology, and others [3, 4].

Technological Foundations of Telepresence

The concept of telepresence in healthcare includes its technological foundations, focusing on the technology and the necessary infrastructure for connections between remote locations. Telepresence systems are defined, alongside an introduction to state-of-the-art systems. Hardware for telepresence, particularly multi-camera setups, is discussed, addressing issues of integration, synchronization, and calibration. The software for telepresence systems is categorized into four parts: video codecs for image transfer, synchronization programs to equalize video delay, driver software for camera and microphone integration, and applications for transmitting video streams. Existing video conferencing systems enable virtual meetings with video and audio communication as if participants were present together. These systems have proven effective for personal and business applications. State-of-the-art telepresence engineering includes video conferencing, augmented reality, and virtual reality systems, employing multiple cameras and microphones for capturing audio and video data. This data is transmitted and displayed on monitors, but results in flat 2D images, lacking depth and interaction cues, which diminishes the sense of presence in communications [5, 6].

Key Components of Telepresence Systems

Telepresence relationships can be categorized as (1) remote observation, (2) remote 2D input for advice, and (3) remote stereo output for 3D presentations. Various technologies support these applications, with commonly used 2D collaborative environments in videoconferencing facilitating remote healthcare discussions. Advancements include technologies for three-dimensional collaborative activities and volumetric displays. Key attributes of telepresence systems involve surgical procedure abstraction, remote stereo input cameras, surgical monitoring, 2D video input access via computers, and software for process management. High-resolution input comes from surgical cameras like Panasonic's models. The proposed telepresence system distributes surgical information over hybrid online 2D and 3D networks based on direct and indirect observations. While modern examples are rare, innovative systems integrating these concepts have emerged. A telepresence surgical teaching system utilizing image and video output for 2D arrangement builds on traditional workstations with a pen and tablet. Moreover, integrating telepresence with surgical visualization tools enhances input with augmented reality views and tracking markers as additional outputs [7, 8].

Clinical Applications of Telepresence

Telepresence applications for remote patient examinations have been in development for years, with increased interest in mobile telepresence robots for medical uses. Many companies have introduced autonomous or teleoperated telepresence robots. However, these commercial units may not meet the specific needs of healthcare professionals. Often, they are designed autonomously, which isn't ideal for healthcare contexts. The design of telepresence robots must align with clinical workflows and comply with healthcare standards. One such robot was developed for telecardiology consultations, enhancing access to specialists and extending services to additional areas through telemedicine satellite sites in Southern New York State. The COVID pandemic has accelerated the telehealth landscape, prompting legislative changes to expand access and reimbursement for telehealth services. Providers must navigate new workflows and compliance requirements, as a wave of tele/remote health ARC™ technologies presents significant opportunities for digital transformation in home-based, collaborative healthcare [9, 10].

Benefits of Telepresence in Healthcare

In healthcare, telepresence technology enhances traditional consultations, replacing face-to-face interactions with audio-visual communication for remote exams and diagnoses. The widespread use of cameras and video conferencing extends telepresence beyond hospital settings to community infrastructures, all while under public surveillance. These consultations must adhere to regulations akin to those for in-person meetings. Telepresence maintains traditional workflows, including (1) remote-sensing to transmit images with minimal quality loss; (2) networking for secure, real-time information transfer; (3) remote cognitive processing for extensive evaluation of received data; and (4) remote response to create comprehensive feedback. The telepresence architecture includes (1) distributed nodes

at both patient and expert locations; (2) an interface system for easy initiation of consultations; and (3) engines for various processing tasks. Implementation generally involves off-the-shelf solutions, constrained by regulatory and site-specific considerations [11, 12].

Challenges and Limitations

Telehealth, particularly teleconsultation, has evolved over many years, driven by previous healthcare successes. This rising demand for telehealth introduces advantages, but also significant challenges, particularly regarding emerging telepresence technologies. These technologies, such as telepresence robots, pose new engineering and social issues. The complex nature of telepresence systems comprising hardware, networking, and software presents usability and quality concerns. The operation, usability, and cost of telemedicine systems are essential to ensure practical equity and integration. Compared to traditional teleconsultation, telepresence systems are more sophisticated and challenging to control. The influence of complex remote healthcare environments on user experience and teleconsultation effectiveness remains largely uncharted. Most telepresence robots currently used are general-purpose; tailored solutions for specific consultation scenarios are needed. Moreover, human factors and social issues, including caregivers missing crucial patient cues due to limited telepresence, can impede remote consultation effectiveness. Engaging patients, caregivers, and healthcare professionals in collaborative design processes may enhance system requirements. Additionally, conducting extensive quantitative studies will yield insights into these systems, fostering better design. Research should also focus on patient acceptance of telepresence systems and their operators for improved telehealth outcomes [13, 14].

Case Studies: Successful Implementations

The use of telepresence for remote healthcare consultations is an emerging technology with potential benefits for rural health. While initial costs may be high, both patients and healthcare providers can gain significantly. Success relies on selecting appropriate technology and clients. Telepresence technology is rapidly advancing, offering more affordable and customizable systems. For instance, a telemedicine application was created to connect incarcerated patients in upstate New York with healthcare providers at the University of Rochester Medical Center, 27 miles away. This involved a sophisticated setup, including a 10-piece telepresence video conferencing system, a full duplex audio connection, and a custom 70-inch wall-mounted screen to enhance the consultation experience. Patients gained access to various specialists globally and participated in remote education. The system included various cameras, a document camera, a switchboard for video input management, and a touch screen for user control. Recorded interviews allow broadcasters to present scenes with voiceovers, explaining topics and highlighting key aspects. Close-ups and mid-shots provide emotional context, enhancing the narrative. A voice-over sequence transitions from still images to deeper understandings of the subject matter, enriching the viewers' experience [15, 16].

Future Trends in Telepresence Technology

Telepresent environments connect users remotely, enabling immersion and interaction with remote sites. Previous systems allowed users to view or affect these sites. A review of technical requirements and future deployment of 3D videocapture suggests telepresence applications that promote social engagement across locations. Future systems may utilize fixed cameras or inexpensive wide-field lenses combined with volumetric capture displays. In telemedicine, non-invasive sampling and imaging technologies, enhanced by machine learning and AI, provide significant health data. This data is aggregated, enabling communication between centers that implement disease management, perform monitoring, and conduct research on risk factors and treatments, thus transforming medical practice. These advancements significantly impact health system productivity and raise ethical concerns. Regulation must evolve alongside technological progress, presenting challenges across disciplines. Traditionally, assessments precede activity planning, but communities should conduct assessments concurrently to enhance institutional capacity within limited timeframes. Participatory assessments, acknowledging conflicting sources while seeking symmetry, can empower reflective discussions rather than relying on consensus-driven agreement [17, 18].

Ethical Considerations in Telehealth

The emergence of COVID-19 led to a rapid adoption of remote consultations across health sectors, sparking debates on equity and ethics. North American and European governments hastily funded systems for these consultations, raising concerns about digital inequities regarding access and provision. Similar issues emerged in the UK, while the American Medical Association addressed commercialization. Despite an urgent focus on digital inequalities during the pandemic, these concerns had minimal impact on health system responses. Accounts from marginalized communities revealed that remote consultations

often reinforced existing inequalities, demonstrating the risks of rushing into telehealth without considering ethical implications. While policymakers discussed data issues broadly, clinicians concentrated on individual harms. Issues raised by practitioners align with four established principles of medical ethics: beneficence, non-maleficence, autonomy, and justice. Telehealth is revolutionizing healthcare delivery worldwide, utilizing telecommunications to eliminate distance barriers. By addressing challenges like travel conditions, costs, and lost work, telehealth aims to enhance access to care, particularly for underserved communities [19, 20].

Training Healthcare Professionals for Telepresence

Medical consultations can be remote or in-person, but in-person visits may not always be possible. Therefore, remote consultations should be explored thoroughly. Telepresence-based consultations require high-quality video equipment, such as industrial-grade 4K cameras, and robust lighting solutions that can be customized or built-in. A large video wall at eye level facilitates understanding of caregiver movements, mimicking in-person interactions. Integrating these components fosters warmth and empathy, resembling physical visits. However, the lack of advanced engineering in telepresence systems has curbed the growth of remote consultations. Both hardware and software of video communication systems must continue to evolve, particularly in the realm of telemedicine. The pandemic has heightened the demand for online consultations, intensifying the need for effective telepresence solutions. Studies have investigated training healthcare providers for remote consultations, but engineering standards for telepresence remain ambiguous. While video consultations are generally accepted by both patients and doctors, there is a pressing need to develop scalable, safe, and reliable telemedicine models. Many challenges, such as compatibility between various teleconsultation systems, require resolution. The successful implementation of telemedicine hinges on proper equipment procurement, infrastructure, training, and policy development in healthcare settings [21, 22].

Patient Perspectives on Telehealth

The COVID-19 pandemic has led many primary care and behavioral health systems to drastically cut in-person visits. While telemedicine has recognized benefits, it's essential to evaluate patient perceptions in this challenging time. Patient familiarity and acceptance of telemedicine vary widely; some opted for text consultations, while others resisted using such technology altogether. This analysis focuses on telemedicine systems and patient experiences during the shift. In New York City, Federally Qualified Health Centers (FQHCs) served nearly two million patients and aimed to enhance integrated primary care (PC) and behavioral health (BH) service delivery. During the pandemic, patients were pushed to use telemedicine for care. A study examined 18 patients from NYC FQHCs (12 PC and 6 BH), who were over 20, English-speaking, and engaged in weekly telemedicine consultations. Exclusions were made for those with severe mental illness or cognitive impairments. Conducted between December 2020 and February 2021, interviews were held via phone or video and lasted 30–90 minutes, with recordings transcribed for accuracy. Thematic analysis was applied to coded data. Discussions centered on patient experiences and feelings related to shifting to telehealth, detailing the transition before the New York state on-pause order, the types of healthcare received, and differences between in-person and telemedicine consultations [23, 24].

Economic Impacts of Telepresence in Healthcare

Telemedicine is a vital advancement in socio-economic health development, revolutionizing healthcare management in daily life. It enables access to diagnosis, advice, and treatment across all socio-economic segments globally, making medical services borderless. Ongoing telemedical research aims to enhance service integration, with advanced telecommunication technology as its foundation. Tele/Video Conferencing underpins telemedicine, which encompasses telepathology, teleradiology, and telepsychiatry, providing a range of healthcare services. Internet-based protocols enable online consultations, remote imaging, tele-ICU, and more. Apps facilitate chronic health management, prescription compliance, and patient monitoring, assisting individuals with conditions like heart issues and diabetes. Advanced IT services improve healthcare management for providers. Case-shared ICT remote consultancy offers swift solutions for both general and specialists, while automated hospital systems and healthcare analytics enhance service delivery. Additionally, digital learning has transformed medical education and training, addressing patient demands due to long wait times for physical appointments. Typically, telehealth involves scheduling consultations with healthcare professionals [25, 26].

Policy Implications and Recommendations

Telemedicine has evolved since the late 1800s, starting with the telephone, and has now advanced to smartphones, enabling real-time diagnosis and treatment through imaging and diagnostic technologies. The COVID-19 pandemic disrupted healthcare globally, making in-person visits impossible due to lockdowns and social distancing measures. This situation transformed traditional hospital care delivery, leading to a new approach where outpatient services are accessed via personal devices. The rise of smart technologies and tele-technology created a crucial moment for adopting direct-to-consumer Healthcare 3.0 or the hospital-at-home (H@H) model. Triage in teleconsultation is vital and involves assessing consult priority, urgent, semi-urgent, or routine, and determining whether issues should be directed to specialists or multi-specialists. It's essential to categorize inbound information from community sources like health systems, hospitals, public health departments, and scientific media. Effective communication includes broadcasting health bulletins and sharing updates on vaccination, bed occupancy, and medicine availability, emphasizing positive health messaging. The relevance of inbound data must be evaluated to determine its direct or indirect correlation to the consultation. Implementing AI/ML technology can enhance the management of longitudinal healthcare data, promoting a more efficient telemedicine experience [27, 28].

Global Perspectives on Telehealth Adoption

In 1999, Cruz Medical Center, the main hospital in Moose Factory, Ontario, initiated a telehealth program that eventually grew to link with 40 remote sites in the Northern and Southern Ontario regions. Using teleconferencing technology, English-speaking presenters share oral stories with patients in communities at great distances from the hospital. Materials in Oji-Cree are made accessible to Ojibway and Michif speakers in other communities. With training, communities are encouraged to create their own stories on video that can be catalogued and telecast by MWFN and the hospital. In addition to community telemedicine efforts, telehealth has developed into a formal collaboration that brings patients and doctors at democratized video-conferencing hospitals into live consultations. Initially funded separately by the federal and provincial governments, these initiatives paved the way for what evolved into the Coordinating Telemedicine Network, an interoperable collaboration of hospitals and their satellite communities across the province of Ontario that was officially opened by the then Ontario Minister of Health in 2002. What began as a telemedicine inquiry led to a discovery that the delivery of better medical services was as much an inquiry into the ethics of health care inequities as it was an exercise in technology that extended the reach of high-tech medicine. By now, in 2005, there has already been much discussion of technology and rhetoric, equity and access. The efficiency of telehealth is at the same time a political strategy for provincial medical institutions in need of new economies. Telehealth is also still an academic inquiry into the ways that telemedicine technologies work to construct both understanding and understanding. However, what began as an inquiry into the growth and development of a valuable health service is also a frank admission of the choice and rigour required to develop and expand it. Where the medical service is expanded by the introduction of telehealth cameras, the exploration of its roles and developments is exactly that of research detailing pedagogies that democratized them [29, 30].

CONCLUSION

Telepresence represents a critical evolution in the telehealth continuum, offering immersive, real-time interactions that bring healthcare providers and patients closer, regardless of location. As healthcare systems seek to balance efficiency, accessibility, and patient engagement, the engineering of telepresence systems must address several key challenges. These include accommodating patients with diverse needs, ensuring regulatory compliance, and overcoming limitations related to cost, interoperability, and digital literacy. Case studies reveal the value of tailored, context-specific solutions, especially in rural and institutional settings. Looking forward, integrating artificial intelligence, volumetric capture, and participatory design processes will shape the next generation of telepresence technologies. For telepresence to reach its full potential in clinical practice, a multidisciplinary approach involving engineers, clinicians, patients, and policymakers is essential. By embedding ethical considerations and inclusivity into the design process, telepresence can serve as a cornerstone of equitable, high-quality remote healthcare delivery in the years to come.

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