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Article

Survey on haptic technologies for virtual reality applications during COVID-19

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Abstract: This paper presents a comprehensive survey on the advancements and applications of haptic technologies, which are methods that facilitate the sense of touch and movement, in virtual reality (VR) during the COVID-19 pandemic. It aims to identify and classify the various domains in which haptic technologies have been utilized or can be adapted to combat the unique challenges posed by the pandemic or public health emergencies in general. Existing reviews and surveys that concentrate on the applications of haptic technologies during the Covid-19 pandemic are often limited to specific domains; this survey strives to identify and consolidate all application domains discussed in the literature, including healthcare, medical training, education, social communication, and fashion and retail. Original research and review articles were collected from the Web of Science Core Collection as the main source, using a combination of keywords (like 'haptic', 'haptics', 'touch interface', 'tactile', 'virtual reality', 'augmented reality', 'Covid-19', and 'pandemic') and Boolean operators to refine the search and yield relevant results. The paper reviews various haptic devices and systems and discusses the technological advancements that have been made to offer more realistic and immersive VR experiences. It also addresses challenges in haptic technology in VR, including fidelity, ethical, and privacy considerations, and cost and accessibility issues.

Keywords: haptic technology; tactile; virtual reality; augmented reality; Covid-19; pandemics; public health

1. Introduction

1.1. Background and context

The outbreak of the COVID-19 pandemic has dramatically reshaped global communication patterns. The imposition of social distancing measures, lockdowns, and other restrictions to curb the spread of the virus necessitated the development and integration of technologies to maintain personal and professional communication. In a world where physical contact became a health risk, there was a surge of attention given to implementing digital solutions to facilitate remote communication for work, education, and social interaction. Among these technological innovations, haptic technologies emerged as a key player in bridging the gap between physical and digital worlds during these difficult times [1].

The definition of haptics is the sense of touch and movement and the mechanical interactions involving them [2]. Haptic technologies refer to the innovations and methods that facilitate the sense of touch and movement. Haptic systems, on the other hand, are more specific in their scope and function. These systems employ haptic technologies to interact with human users through haptic perception and interaction [3]. This interaction not only involves the transmission of forces, vibrations, or motions to the user but also the stimulation of temperature and pain.

Haptic technologies are integral in various fields, such as virtual reality (VR) [4], augmented reality (AR) [5], and teleoperation systems [6], where the sense of touch significantly enhances the user experience of the systems. They are crucial for creating immersive experiences in virtual environments, aiding in skill development in simulation-based training, and enhancing accessibility in technology interfaces.

The study of the application of haptic technologies in pandemic response is rather new, as it emerged primarily in response to the unique challenges posed by the COVID-19 pandemic, which necessitated innovative solutions for remote interaction and communication. Previous pandemics occurred at times when haptic and VR technologies were still in their infancy; hence, the adoption of such technologies in pandemic management during the COVID-19 pandemic is unprecedented. On the other hand, the application of VR and AR in emergency management is an established field of research [7]. Haptic technologies for VR and AR applications enable telepresence and remote touch interactions without the inherent risks associated with physical proximity. This is particularly crucial when physical presence is either not possible or restricted due to regulatory measures. The role of haptic technologies for VR applications in pandemic response draws parallel to their utility in disaster management. Both scenarios leverage these technologies for training, remote operation, and social communication.

1.2. Objectives, motivation and contributions

The objective of this paper is to provide a comprehensive survey on the most recent advancements and applications of haptic technologies within VR/AR in the context of the COVID-19 pandemic. Specifically, this review aims to identify and classify the various domains in which haptic technologies have been utilized or can be adapted to combat the unique challenges posed by the pandemic or public health emergencies in general. By identifying and discussing emerging trends of haptic technologies within VR/AR, exemplified through practical applications and real-world case studies, and by assessing their impact and future prospects in a post-pandemic world, this paper consolidates existing literature and makes significant contributions to the field.

While some existing works offer insightful reviews on haptic technologies in VR/AR [4–6,8–11], a significant gap remains in discussing their application domains and adoption in the context of pandemic response and management. Several review articles have concentrated on the applications of haptic technologies during the Covid-19 pandemic, however their scope is often limited to specific domains such as medical training [1], dental education [8], home rehabilitation [12], or teleoperation [13]. There is a noticeable absence of a comprehensive review that encompasses and consolidates all application domains, including healthcare, medical training, education, social communication, and fashion and retail.

This survey aims to address this gap by providing a more inclusive and holistic overview of the development and application of haptic technologies across a diverse range of domains. As such, it seeks to offer a broader perspective on the significance of haptic technologies in response to the unique challenges posed by the pandemic.

This wholesome approach will not only highlight the multifaceted uses of haptic technologies but will also shed light on their potential to transform various aspects of human interaction and response strategies in global emergency situations like the COVID-19 pandemic. **Table 1** summarizes recent reviews and surveys on haptic technologies in VR/AR, highlighting the specific application areas they cover. This is contrasted by our current survey, which investigates a broader range of application domains. The goal is to provide a foundational reference that encapsulates the current state of haptic technology within VR/AR applications in the context of the pandemic.

Table 1. A summary of recent reviews and surveys on haptic technologies in VR/AR, highlighting the application domains they cover.

Work	Year	Focus	Social interaction	Education and learning	Healthcare and medical	Fashion and retail
Tong et al. [4]	2023	Hand-based haptic simulation in VR	√			
Bermejo and Hui [5]	2021	Wearable haptic devices and applications in VR/MAR	√		√	
Abdi et al. [6]	2020	Haptic devices in teleoperated medical applications			√	
Imran et al. [8]	2021	Haptic and VR simulation in dental education		√	√	
Sampath et al. [9]	2022	Haptic-enabled VR in physical examination education		√	√	
See et al. [10]	2022	Sensing and actuation technologies in haptics			√	
Adilkhanov et al. [11]	2022	Wearability of haptic devices	√	√		
Su et al. [13]	2021	Haptic-enabled VR/AR for teleoperation			√	
Sanfilippo et al. [14]	2021	Haptic-enabled VR/AR in multisensory learning		√		
Ours	2024	Application domains of haptic technologies within VR/AR	√	√	√	√

2. Methodology

To gather high-quality research from well-recognized scholarly journals, a methodical research methodology was adopted. This involved using the Web of Science Core Collection as the main source to search for relevant original research and review articles. The articles selected for inclusion in this study were sourced from the Science Citation Index Expanded (SCIE), the Social Sciences Citation Index (SSCI), and the Emerging Sources Citation Index (ESCI) databases.

The research material was filtered using a combination of keywords and Boolean operators to refine the search and yield relevant results. The search keywords were carefully chosen according to three main aspects: technology involved, application domain and application context. The focus of the review was centered on haptic technologies for virtual reality applications during the COVID-19 pandemic. Technology keywords like 'haptic', 'haptics', 'touch interface' and 'tactile' were included. Application domain keywords included 'virtual reality', 'augmented reality' and 'mixed reality', whereas context keywords included 'Covid-19' and 'pandemic. A combination of Boolean operators was used to form the search term consisting of keywords from the three aspects. Example search terms are (haptic OR haptics OR "touch interface") AND (covid-19 OR pandemic) AND (haptic OR haptics OR tactile) AND ("virtual reality" OR "augmented reality").

To maintain the study's relevance to the context of the COVID-19 pandemic, only publications from March 2020 to 2023 were included. This criterion ensures a focus on recent research developments that emerged in response to or during the pandemic. It is important to note that while some of the included publications may not explicitly mention 'Covid-19' or 'pandemic', they have been selected for their relevance to the application domains discussed in this paper. This approach was taken to cover a comprehensive range of recent developments in the field, especially those that offer significant contributions to haptic technologies within VR/AR applications during the period of the pandemic.

This search strategy initially yielded a substantial number of publications. A manual screening process that involved a review of the titles and abstracts was conducted to select relevant research. This step helped in eliminating irrelevant papers and narrowing the list to those specifically addressing the intersection of haptic technology and VR applications during the Covid-19 pandemic.

The final phase involved snowballing, a method where additional relevant articles were identified and included by reviewing the references of the selected papers and employing additional search keywords related to the topic. This process enriched the review with diverse perspectives and recent developments in the field.

The selected literature spanned various disciplines, reflecting the interdisciplinary nature of the topic. Most of the contributions came from fields such as computer science, human-computer interaction, healthcare, and psychology.

3. Applications of haptic technologies during COVID-19

The applications of haptic technologies in VR/AR saw a surge during the pandemic, offering users the experience of physical presence and interaction without the risks associated with physical proximity. These technologies extended beyond entertainment and gaming into other realms such as education, medical training and social interaction.

The application areas of selected publications have been identified and consolidated into the following domains: social interaction, education and learning, healthcare and medical training, and fashion and retail. In each of these domains, the integration of haptic technologies has been instrumental in enhancing the efficacy and realism of virtual experiences.

Social interaction involves studies on social touch, stress management, and psychophysiological aspects during the pandemic. It explores the role of haptic technology in understanding and improving social and emotional well-being.

Healthcare and medical training includes applications in remote surgeries, telemedicine, robotic diagnostics, medical training with VR and AI, dental education, and nursing. It focuses on enhancing medical practices and education through haptic feedback.

Education and learning comprise online teaching, psychomotor skills development, blended learning, and virtual reality education. It utilizes tactile feedback to improve the learning experience in various educational settings.

Fashion and retail explore the application of haptics in the fashion industry for presenting fabrics in digital environments. It involves communicating the tactile qualities of materials virtually.

3.1. In social interaction

During the COVID-19 pandemic, haptic technologies have played an increasingly critical role in facilitating personal communication amidst widespread social distancing and isolation measures. As physical forms of human interaction became limited due to public health concerns, individuals and communities turned to technological solutions to maintain social connections, relieve loneliness, and support mental health [15].

During the lockdown, affective haptic technologies have gained increased attention as tools to mitigate touch deprivation experienced by people living alone [16]. These technologies are capable of simulating virtual touch sensations, complementing the conventional forms of online interactions, thereby providing a sense of closeness and connection in times of isolation. The use of these technologies has been particularly appealing to those in long-distance relationships or those unable to physically interact with their loved ones due to work or travel restrictions. Through the integration of haptic feedback in VR/AR platforms, users can experience a semblance of touch, from a simple handshake [17] to a comforting hug [18] or an intimate kiss [19].

In the workplace, the pandemic led to a shift towards remote work from home for most occupations. However, essential workers, particularly medical professionals, were more profoundly affected by the challenges and risks associated with the disease. Doctors and nurses, facing extreme stress and isolation from their families, found solace in peer-to-peer support within their work environment [20]. Haptic support, such as comforting touches and hugs from colleagues, provided essential emotional and psychological relief. For these frontline workers, haptic technologies are particularly helpful in mitigating the effects of physical and emotional distancing imposed by the pandemic, providing a sense of human touch, and maintaining psychological and physical well-being in high-stress work environments [21].

Haptic technologies have been integrated into social virtual reality (VR) platforms [22], which have seen a surge in popularity during the pandemic as people sought virtual experiences that could replicate real-world socialization [23]. Within these VR environments, haptic feedback has provided users with realistic sensations that enhance the virtual experience, making online interactions more engaging and emotionally fulfilling. By simulating various forms of physical contact through haptic gloves [24] or haptic suits [25], social VR environments have served as a venue for people to socialize in a more lifelike manner, attending events, playing games, or simply having conversations in a way that facilitates a sense of togetherness and reduces the feelings of isolation.

In mobile and desktop applications, haptic feedback has also been utilized to enhance the experience of communication apps [5]. Smartphones and tablets equipped with advanced haptic engines can deliver nuanced vibrations and tactile effects that can be customized to convey specific emotions or notifications, adding a layer of depth to messaging and social media interactions [26].

Haptic technologies have shown the potential to enhance personal communication by recreating the emotional richness of physical interactions in various digital formats. As the pandemic persists in influencing social norms and practices, the role of haptic technologies in personal communication is likely to expand further, driving innovation in how we connect, empathize, and support each other in times of need.

3.2. In education

Education is another sector that witnessed significant disruptions during the COVID-19 pandemic. Since the early days of the pandemic, education institutions around the world have quickly transitioned to remote learning. With traditional classroom learning curtailed, educators sought innovative approaches to replicate the quality of in-person learning experiences [27,28].

VR and AR technologies were adopted as schools turned to online learning [29]. These technologies provided immersive learning experiences, enabling students to engage with educational content in a more interactive and realistic manner [30]. VR was used to create virtual classrooms and simulations, offering students a sense of presence and participation that traditional online platforms lacked. AR, on the other hand, augmented real-world environments with digital information, enhancing understanding and engagement.

Haptic interaction is often integrated into VR/AR learning applications in fields where tactile experiences are essential. VR classrooms can provide immersive learning experiences in organic chemistry instruction, using haptic gloves to provide tangible experiences of molecular interactions [31]. In dental education, haptic feedback in VR systems offers students realistic simulations of dental procedures [8]. Similarly, Sinou et al. [29]. highlighted the use of VR and AR with haptic interaction in anatomy education during the COVID-19 pandemic, enabling students to interact with anatomical models in a more engaging and effective way. These studies demonstrate the importance of haptic feedback in providing a comprehensive and immersive educational experience in specialized fields.

Moreover, the application of haptic technologies in education extended to teaching students with disabilities. Studies have shown that auditory and haptic feedback can effectively train basic mathematical skills in children with visual impairments [32]. In another study, a virtual haptic perception approach that combines virtual reality and haptic technologies has been used to teach fundamental 3D shapes to blind children, focusing on their ability to explore and recognize virtual objects and the knowledge gained from virtual perception learning [33]. The results affirmed the effectiveness of this method as an assistive technology in education for the visually impaired.

Additionally, the development of intelligent systems based on metaverse learning for students with disabilities has highlighted the potential of haptic feedback in creating more accessible and inclusive learning environments. Sghaier et al. [34] delve into the integration of spatial audio and haptics within a metaverse environment, enhancing multisensory experiences, especially in education. They developed a simple intelligent system for meta-learning in a 3D virtual environment, connected to a learning management system. This system proved to be particularly beneficial for students with different disabilities, demonstrating its effectiveness through improved performance in mathematics courses.

3.3. In healthcare and medical training

Haptic technologies in medical training, a well-established research area before the pandemic [35,36], played a crucial role in medical education and skill development. Prior to the pandemic, these technologies were extensively used in hands-on training for medical practitioners. During the pandemic, their application expanded significantly in remote medical training and healthcare, addressing the challenges of physical distancing and limited in-person instructions [1].

The use of haptic devices in VR/AR environments extended to several areas of medical training, including surgery simulation [37–40], medical diagnosis [41,42], physical examination [36], and, more prominently, dental education [8,43–45]. Medical training through virtual and augmented reality environments, empowered by haptic feedback systems, provided a safe and effective method to maintain the proficiency of trainees and experienced medical professionals. These systems simulate the feel of tissues, resistance during suturing, and other surgical nuances through haptic force feedback, which is crucial for developing and retaining procedural skills amidst restrictions on traditional hands-on training [38,44]. For example, HapTEL and DenTeach platforms created detailed and responsive environments for dental training, incorporating tactile interaction that closely simulates drilling and other dental procedures [46].

Haptic feedback is beneficial in training and preparing medical staff for high-pressure situations. In simulation-based training for surgeons, haptics provides realistic feedback in VR simulations, which helps trainees to understand and cope with stress experienced in real-life surgical settings [37]. This enhanced realism in training, including tactile sensations, increases engagement and motivation, enabling trainees to develop essential coping strategies for their roles as surgeons. Additionally, educators can use insights from trainees' stress responses to adapt simulation training, making it more effective and aligned with the trainees' skill levels and psychological needs [37].

During the COVID-19 pandemic, the integration of haptic and VR technologies expanded significantly into telehealth services to address the challenges in remote healthcare. These technologies were used for home therapy and rehabilitation, providing tactile feedback that enhanced the effectiveness of therapy for individuals with various disabilities [12]. The integration of tactile devices into rehabilitation practices not only supported the recovery of sensorimotor impairments but also promoted functional gains through practice in enriched environments. Through technologies like the Tactile Internet, healthcare providers could deliver remote palpation and diagnostics [36,47], thus bridging the physical gap between patients and practitioners. In rehabilitation, haptic-enabled VR systems facilitated the continuation of therapy sessions from home, allowing patients to engage in immersive environments that respond to their tactile input, promoting recovery and maintaining the regimen despite the absence of in-clinic visits [12].

In broader applications, haptic-enabled virtual reality was instrumental in enhancing remote team collaboration within healthcare settings. Teams could perform collaborative tasks, such as operating virtual medical machinery or participating in emergency response drills, with tactile feedback that increased the realism and effectiveness of the training [1].

3.4. In fashion and retail

During the COVID-19 pandemic, the fashion and textile industries faced unique challenges due to restrictions on physical retail, which traditionally drove the majority of the purchasing and sales. To counter these challenges, haptic technologies emerged as a critical tool in enabling virtual try-ons and fabric assessments, thus bridging the gap between physical and digital consumer experiences [48,49].

The tactile nature of fabrics is a paramount factor influencing consumers' purchasing decisions [50]. Tactile simulation of fabrics, through the use of VR and advanced haptic interfaces, allowed consumers to experience the texture, drape, and quality of fabrics without direct physical contact [51]. Innovations in ultrafine nanofibers, such as those made from polyvinylidene fluoride (PVDF), enabled the production of detailed and realistic haptic feedback [52].

The fashion industry's shift to digitization posed similar challenges for fashion designers, particularly in understanding the fabric properties remotely. Traditional methods like photographs, videos, and textual descriptions from suppliers were insufficient. Designers and consumers sought virtual environments that could replicate the haptic sensations of fabric [53]. By developing specific guidelines for presenting fabric information digitally and conceptualizing a framework for tactile communication in digital environments aided by haptic devices and 3D clothing simulation software, fashion designers could perceive the tactile properties of fabrics online.

4. Case studies

4.1. Implementation denteach in remote dental training

The implementation of the DenTeach platform in remote dental training is an example of how haptic-enabled VR applications were employed in dental education during the pandemic [54]. This system comprises an instructor workstation (DTPerformer) and a student workstation (DT-Student), both equipped with advanced wireless networking, cloud-based data storage, and retrieval capabilities. The key feature of DenTeach is its ability to synchronously link the instructor and the student through real-time video, audio, feel, and posture (VAFP) inputs. This integration provides tactile feedback and a comprehensive teaching and learning experience remotely.

The results of DenTeach's implementation were noteworthy. Students could experience a nearly hands-on learning environment, enhancing their comprehension and practical skills in dental operations. The DenTeach system successfully facilitated the teaching, shadowing, and practice modes, allowing students to not only learn from the instructor but also to engage in self-learning and skill refinement. The quantifiable improvement in students' dental skills was evident through the key performance indices (KPIs) that the system calculated, providing a comprehensive assessment of their progress.

User experience with DenTeach has been overwhelmingly positive. Both instructors and students benefited from the real-time interaction and feedback. The portable and easy-to-set-up nature of the system also added to its practicality, making it a feasible solution for remote dental education. This innovative approach has opened new avenues in dental training, suggesting a promising future for remote and virtual learning in specialized fields.

4.2. Using haptic devices for virtual laboratory on e-learning platforms

In another case study, haptic devices were used to complement e-learning systems during the early stages of the pandemic in Pakistan, where students transitioned to remote learning [55]. A relatively low-cost haptic device, Novint Falcon, was employed in e-learning platforms to enhance the learning experience in virtual laboratories. The implementation involves setting up a virtual environment where the instructor and students can interact with physical principles such as friction, viscosity, and inertia through the haptic interface. This setup allows the students to feel the forces and experience a more immersive learning environment.

The results of this approach indicate a significant improvement in the learning experience. The hands-on interaction provided by the haptic devices helps in better understanding and retention of the concepts being taught. The user experience as reported in the study was overwhelmingly positive, with students expressing enhanced engagement and a deeper understanding of the subject matter. This innovative use of haptic technology in e-learning platforms presents a promising direction for the future of online education, especially in fields that require hands-on experimentation and interaction.

5. Challenges and limitations

5.1. Fidelity issues

One of the key limitations of current haptic devices in virtual reality applications is their inability to provide high-fidelity haptic feedback [46]. This shortcoming affects the overall user experience in haptic VR systems, which ideally should include robust immersion, interaction, and simulation of real tactile sensations. Challenges include accurately simulating and sensing interactive objects in the virtual space, as well as ensuring the device offers free motion without resistance and sufficient interaction with virtual objects. To address these issues, novel sensing, actuation, and control techniques are being made in designing haptic devices with features like low inertia, adjustable impedance, high-resolution sensing, and adequate workspace for realistic task simulation [56–58].

5.2. Ethical and privacy considerations

The implementation and use of haptic technologies for communication during the COVID-19 pandemic, while innovative and beneficial in numerous aspects, presents several ethical and privacy considerations. Firstly, the usage of haptic devices inherently involves the collection of sensitive user data such as touch, movement patterns, and potentially identifiable information [59]. This raises concerns regarding the privacy of individuals and necessitates robust data protection mechanisms to prevent unauthorized access, misuse, or breach of personal data.

Another concern is associated with the touch element intrinsic to haptic technologies. During a public health crisis where physical distancing is promoted to prevent viral transmission, ethical use policies must consider individuals' comfort levels and cultural perceptions regarding touch, even in a virtual setting [60]. Hence, user autonomy and consent become paramount; users should have the ability to control the intensity and nature of haptic feedback and be able to opt-out of such interactions as needed.

The ethical and privacy challenges associated with haptic technologies demand collaborative efforts from researchers, ethicists, technologists, and policymakers. They must work together to establish guidelines that protect individual privacy, promote equitable access, ensure user well-being, and uphold ethical standards in the design and application of these emergent technologies.

5.3. Cost and accessibility issues

Issues concerning the accessibility, cost, and steep learning curve associated with haptic technologies are additional barriers that need to be overcome before widespread adoption of such technologies in various application domains [61]. The current high costs associated with advanced haptic devices can be a significant barrier, limiting their accessibility to well-funded institutions or individuals. Additionally, the complexity and sophistication of these technologies often entail a steep learning curve, requiring specialized training and expertise for effective utilization. These factors combined can hinder the widespread adoption of haptic technologies, especially in educational and training contexts where resources and technical expertise might be limited. To facilitate broader access, efforts must be directed towards reducing costs, simplifying the technology for user-friendly operation, and providing comprehensive training and support [61,62]. This approach would help in overcoming the barriers to accessibility and ensuring that the benefits of haptic technology can be leveraged by a wider audience.

6. Conclusions

The exploration of haptic technologies in VR applications during the COVID-19 pandemic has highlighted both their potential and challenges. While these technologies have significantly enhanced user experiences across various fields by offering more immersive and realistic interactions with virtual environments, the pandemic has also exacerbated certain challenges. For instance, the urgent need for remote solutions during COVID-19 brought fidelity issues, ethical and privacy concerns, and cost and accessibility barriers into sharper focus, particularly as these technologies were rapidly deployed in critical areas like healthcare and education. The pandemic highlighted the importance of developing robust, scalable haptic systems that can meet the demands of widespread remote use during global health crises. Moving forward, addressing these challenges will be crucial not only for improving current applications but also for preparing for future public health emergencies. The continued development and refinement of haptic technologies will be key to realizing their full potential in creating engaging and effective virtual environments. The future of haptic technologies in VR holds great promise for diverse applications, extending well beyond the pandemic era, but with lessons learned from the COVID-19 crisis guiding their evolution.

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