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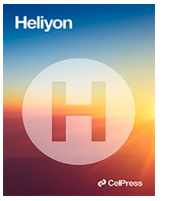

Review article

A comprehensive study on unraveling the advances of immersive technologies (VR/AR/MR/XR) in the healthcare sector during the COVID-19: Challenges and solutions

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ABSTRACT

The current COVID-19 pandemic has affected almost every aspect of life but its impact on the healthcare landscape is conspicuously adverse. However, digital technologies played a significant contribution in coping with the challenges spawned by this pandemic. In this list of applied digital technologies, the role of immersive technologies in battling COVID-19 is notice-worthy. Immersive technologies consisting of virtual reality (VR), augmented reality (AR), mixed reality (MR), extended reality (XR), metaverse, gamification, etc. have shown enormous market growth within the healthcare system, particularly with the emergence of pandemics. These technologies supplemented interactivity, immersive experience, 3D modeling, touching sensory elements, simulation, and feedback mechanisms to tackle the COVID-19 disease in healthcare systems. Keeping in view the applicability and significance of immersive technological advancement, the major aim of this study is to identify and highlight the role of immersive technologies concerning handling COVID-19 in the healthcare setup. The contribution of immersive technologies in the healthcare domain for the different purposes such as medical education, medical training, proctoring, online surgeries, stress management, social distancing, physical fitness, drug manufacturing and designing, and cognitive rehabilitation is highlighted. A comprehensive and in-depth analysis of the collected studies has been performed to understand the current research work and future research directions. A state-of-the-artwork is presented to identify and discuss the various issues involving the adoption of immersive technologies in the healthcare area. Furthermore, the solutions to these emerging challenges and issues have been provided based on an extensive literature study. The results of this study show that immersive technologies have the considerable potential to provide massive support to stakeholders in the healthcare system during current COVID-19 situation and future pandemics.

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1. Introduction

COVID-19 pandemic will likely to continue for the significant long period of time [1]. The highly contagious nature of COVID-19 makes it hard to control the spreading of this menace. The spreading of this virus ravaged almost every walk of life but its impact is more visible in healthcare systems where it crippled the hospitals due to overflowing patients, scarcity of oxygen and understaffing. The existing healthcare systems faced several challenges due to limited resources and infrastructure especially in developing countries. Health departments all over the globe adopted different digital technological solutions to cope with the COVID-19 outbreak [2]. The artificial intelligence is the game changer in the list of technological solutions amidst the COVID-19 pandemic [3–5]. The major purpose of technological solutions is to provide staff protection, quality care, telesurgery, medical education and clinical training. In these technological solutions, the role of immersive technologies in the context of coping with COVID-19 is also important to be highlighted. As, these technologies provided interactive and innovative experiences to the users by bringing real-world situations in virtual fashions in the medical care systems. The immersive technologies consisting of Virtual Reality (VR), Augmented Reality (AR), Extended Reality (XR), Mixed Reality (MR), etc. not only contributed to the healthcare sector but also covered the other spheres of life such as education, engineering, surveillance, agriculture, industries, training, tourism and online trading [6,7]. However, in this research work, the main focus is to highlight the significant role of all the types of immersive technologies in the medical care system with respect to curbing COVID-19.

In the list of immersive technologies, the VR role is the most important one. VR technology provide the illusion of the real-world environment to the users where they feel the impression of working in the real-world environment [8]. VR technology has been used in healthcare to deal with COVID-19 for enormous purposes such as medicine, training, physical therapy, reducing pain and stress management, mental health, surgery, dentistry, counseling, and physical and cognitive rehabilitation. It has shown significant outcomes in the healthcare system by providing many features such as interactivity, customization and task engagement [9]. It influenced the healthcare system through remote diagnosis, people awareness, treatment, training healthcare professionals and surveillance in the current pandemic. VR assisted in reducing face-to-face communication between the healthcare profession and COVID-19 patients by using live video streaming [10]. It revolutionized the healthcare system by providing medical education and professional training through distance separation [11]. During the peak hours of pandemic, VR provided a virtual clinical environment known as Oxford Medical Simulation. It provided a medical platform for students learning about diagnosis, treatment and report histories from the digitally simulated patients [12]. VR immersive experience has also brought significant advancements in telemedicine and tele rehabilitation for the patients suffering from cognitive disorders [13]. The role of VR in dealing with COVID-19 will be discussed with detail in the later section of this paper.

Augmented reality (AR) has also been applied to provide different features and services for healthcare area. AR is a blend of real-world objects and computer-generated images which enhances the real world scenario by adding the computer-generated contents/information. AR is the most modern visualizing tool and has the features of digital interaction with the real world [14,15]. AR is a key contributor in dealing with the COVID-19 pandemic. As, it is helpful in restrictions or lockdown where its video game-based applications have been used to improve mental and physical health [16]. The role of AR in social distancing is also noticeable in the pandemic as it enables people to get connected through social distancing and less mobility by following World Health Organization (WHO) guidelines in the tourism sector [17]. The AR integrated into a mobile application has also been applied for handwashing to stop the spread of coronavirus. The application AR technology is to monitor the handwashing movements and gestures in front of the camera by using a mobile application [18]. The AR was also adopted in interactive and live surgical training to the students through the medical proctoring by surgeons at a remote distance [19]. The AR tools have been employed for dealing with COVID-19 patients and remote surgery. Tele-surgical tools assisted both doctors and patients against the viral infection by allowing fewer people physically present in the operation theatre. The application of AR is more ideal in scenario of surgical patients who were tested positive for COVID-19. It also reduced the use of PPEs consequently. The applications of AR were also witnessed for remote stress management and mental health care [20].

Similarly, Mixed Reality (MR) known as the extension of augmented reality which allows users to interact with both real world items simultaneously through an immersive experience [21]. MR technology has the potential to combine both virtual and real world objects in single display [22]. MR combines both AR and VR technologies to provide better engagement and immersive experience. The MR concerning COVID-19 has also been proven imperative in the healthcare system. It has been observed as the latest application of immersive technology in the healthcare system during the pandemic for many purposes such as clinical care, medical education and remote care in the hospital environment. In the United Kingdom, the HoloLens2 devices with the support of MR technology have been deployed in medical wards to provide staff safety and telemedicine services to the COVID-19 patients [23]. MR technology also adopted in the medical wards for surveying patients and infection control [24].

Immersive technologies also contributed in indirectly by leveraging Gamification and Metaverse. Gamification provided significant contribution to the healthcare sector with the support of the different immersive technologies. As, VR and gamification are the complementary to each other. Therefore, VR-based games have the potential to provide more immersive experience to the users. VR-based games have the ability to change the patient's behavior and outcomes in the healthcare sector. These games are more effective in providing good rehabilitation, improving mental health, and creating therapy sessions. Similarly, Metaverse also played a crucial role in the healthcare area which cannot be sidelined due to its wider range of applications. Metaverse is the combination of VR and AR technologies (MR) and other innovative technologies that are providing a virtual space by integrating real and virtual worlds [25]. Metaverse can be adopted to bring the healthcare services such as clinic management, training and remote medical consultancy services [26].

The major reason of conducting this review study is that the existing reviews or surveys available in this area are covering the

application of only one or two types of immersive technologies for single healthcare purpose only. However, this review covers all the type of immersive technology in a broader sense. This review highlights all the forms of immersive technologies employed for various healthcare tasks such as medical training, proctoring and medical education, mental health, stress management, social distancing, physical fitness, cognitive rehabilitation, drug manufacturing, health diagnosis, health treatment, health awareness, health feedback, telemedicine and virtual surgery. This study explores the applications of all types of immersive technologies for different healthcare aspects. This review also reports various challenges and provides solutions in the healthcare sector based on extensive literature study.

A. CONTRIBUTION

- This is the first review of its kind to showcase the applications of immersive technologies and their related products such as apps, platforms, frameworks and tools in the fight against COVID-19 in the medical care system. This review discusses in detail and comprehensive fashion all the applications employed against the COVID-19 in the healthcare department. While, the previous studies have highlighted the only one type of immersive technology in this area. Previously presented works did not cover the overall visualization and real-world simulation technologies such AR, VR, Metaverse, Gamification and MR in detailed, holistic and comprehensive fashion.
- The role of immersive technologies to mitigate the coronavirus impacts for the various healthcare purposes such as remote surgeries, medical education and proctoring, stress and anxiety management, physical health and fitness, pain management, cognitive rehabilitation and telemedicine has been pinpointed.
- We performed the broad meta-data analysis of collected studies to understand the current research work related to the deployment of immersive technologies in healthcare sector during the pandemic.
- We investigated and identified various issues that are hindering the deployment of immersive technologies in healthcare sector during the COVID-19 and post-COVID-19. We also provided solutions towards these challenges to enhance the application of immersive technologies in healthcare domain to battle the pandemic.

This review is composed of seven (7) remaining sections such as in Section (II) is about discussing the related works. In Section (III), the research method of this research is presented. The meta-data analysis and synthesis of immersive technologies in tackling the COVID-19 in a healthcare environment is given in section (IV). The significant role of immersive technologies for medical education, training and proctoring, mental health, stress management, social distancing, rehabilitation, online surgeries, and telemedicine during the COVID-19 outbreak in the healthcare industry is briefly explained and analyzed in Section (V). Section (VI) is related to highlighting the issues involved in deploying immersive technologies and providing solutions in adoption of immersive technologies. Section (VII) is related to the discussion and finally section (VIII) concludes this study by presenting concluding remarks.

2. Related work

The aim of this literature review is to report all those studies which were focusing on the applications\contributions of immersive technologies in healthcare setup. According to our literature review, we did not find enough studies that were reporting the role of immersive technologies in this domain in holistic way. However, we are reporting all those studies that are contributing towards healthcare sector by using any type of the immersive technology.

The study presented by Mathew et al. [27] is exploring the applications of XR technology for improving the competencies and skills of medical professionals during the medical education and healthcare training. The proposed review highlights the benefits, applications and different challenges during the adoption of XR technology for healthcare training and education. By comparing their review to the proposed review work, it has come to our knowledge that is only covering the applications of XR technology in healthcare education and operation theatre. This review also explores very few challenges in context of the application of XR technology in delivering the medical training and education. Another study conducted by Mathew et al. [28] is also exploring the three major priniciples and factors that are to be addressed before taking the full adavantages of immersive technologies in healthcare education and training.

Similarly, the study conducted by Pears et al. [29] is also utilizing XR technologies for medical training and education during the COVID-19 pandemic. This study is aimed to discuss the role of XR technologies for delivering training about technical, non-technical skills in theaters, wards and virtual clinics. By comparing this review with the proposed review, it has been noticed that this work is exploring the applications of XR for the purpose of education and training aspects in the healthcare during the pandemic. It does not identify arising challenges as well and covers very few immersive technologies for training purpose only. Another similar work presented by Pears et al. [30] is related to get a deep insight about the future of immersive technology along with the support of Artificial Intelligence (AI) in the healthcare education. This study presents a guideline about developing a collaboration framework for tele surgery by leveraging immersive technology for collaboration. The proposed study is only targeted to highlight the application of immersive technology (VR/AR) in the healthcare education. This study is not reporting any challenge during the development of the proposed work.

Newbutt et al. [31] study is based on overviewing the applications of immersive technologies in three different key areas such as education, employment and anxiety for autistic patients during the COVID-19 pandemic. This study is utilizing only VR technology for dealing with problems addressed by people suffering from autism. It covers the limited aspects of immersive technologies and only few healthcare areas are covered in comparison to our work.

Higginbotham [32] highlighted his viewpoint by applying VR and AR immersive technologies to deal with neurosurgery sector duing the pandemic. Author demonstrated the potential applications of VR/AR in global surgery with intentions of enhancing the

surgical process. This study has limited area focusing related to healthcare i. e surgery aspect is targeted. Similarly, challenges during the study were not properly addressed by the author.

Ryan et al. [33] presented systematic literature review that outlines the role of MR and VR technologies for medical education and nursing at university level. It compares the significant contributions of immersive technologies with the traditional modalities of education. This study does not highlight the challenges and other immersive technologies such as AR and XR were not addressed.

Tang et al. [34] presented SLR-based study which discusses the current research trend, application area, recipients, evaluation approaches, contents of immersive technologies in the medical education sector. The proposed SLR covers only the specific area of healthcare and it does not identify any emerging challenges and issues in this area.

Sadek et al. [35] also reviewed the impacts of VR and AR on quality of medical education and practice. Authors reviewed the existing literature by highlighting the applications of immersive technology during the COVID-19 era. The major focus of this study is to provide innovative learning such as 2D and online student learning by using the immersive technologies. They compared the advanced methods of learning with the traditional style of learning and found in their study that the innovate style of teaching-learning is very encouraging for the students during the restricted hours of the pandemic. In comparison to our study, this review is focusing only the education aspects of healthcare by using VR and AR. The role of MR and XR is not focus of this study. Similarly, there are many studies available [36–38] in the existing literature that are utilizing the immersive technologies for the medical training and education purpose only.

Linares-Chamorro et al. [39] suggested a study which analyses the effects of VR technology for emotional well-being and anxiety of healthcare professionals. It has limitation such as the VR technology is applied while the remaining immersive technologies like AR, MR and XR were not highlighted in this study.

Spittle et al. [40] in their review work explored the literature for finding the remote studies conducted during the COVID-19. This study describes only the social distancing or remote studies conducted during the pandemic. Comparing with our review, it highlights the immersive technology contributions in social distancing without highlighting the challenges or limitations.

The completed detail of existing related works in comparison to the proposes review is given in Table 1.

3. Research methodlogy

The proposed literature review covers the aspects of cross-disciplinary, meta-analysis and scoping reviews. It performs meta-analysis review by collecting the different studies from the online sources. It performs data synthesis and analysis of different articles based on different perspectives. This review also identifies the research gaps and offers a panoramic view of the existing literature in this domain. This review also includes some aspects of cross-disciplinary as it provides a good overview of the application of immersive technology in the healthcare sector. This literature review follows a well-known literature review methodology known as Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [43]. The major purpose of using PRISMA is to bring quality and transparency in the literature process. This literature review completes in four major steps. The complete details about the research methodology steps are given below as.

a) Identifying studies

This is the initial step of the research methodology. This step is followed in well organized and systematic fashion. In this step, first of all we created keywords according to our research topic. Then we concatenated these keywords to form a suitable search string. This search string was then applied in all the selected online databases. Our search string looks like as given:

" Immersive" AND Virtual reality AND Augmented Reality AND Mixed reality AND metaverse AND Gamification AND healthcare care applications OR medical sector AND Covid-19 OR Corona virus OR SARS-CoV-2". The main database sources of well-reputed journals such IEEE, Elsevier, Springer, MDPI, Taylor and Francis, De Gruyter, Karger and Wiley were thoroughly searched for collecting various studies related to this topic. These are the most ideal online sources for the collection of data. Other relevant sources such as Google scholar, Pubmed and Scopus databases were also searched for finding any relevant studies related to the main topic. These sources were thoroughly searched and all the related papers to main topic were collected. We collected the most relevant studies after thoroughly performing both automatic and manual searching procedures in the online database sources. The collected papers were written in spreadsheet file.

b) Paper screening

This is the second step of our literature review where redundant papers were removed. All the collected papers were screened based on titles, abstracts and full reading. In this step, we also applied the inclusion and exclusion criteria. According to the inclusion criteria, all papers written in English language were selected. The focus was to select primary studies. All studies were extracted from authentic sources. Similarly, according to our exclusion criteria, papers written in other languages, gray papers, irrelevant and papers that were less than three pages were discarded.

c) Eligibility

It is the vital step as it decides the list of paper to be included in our research analysis and discussion. All the screened papers were investigated and assessed. Papers focusing on the immersive technology in the healthcare sectors during the COVID-19 pandemic were

Table 1
Comparison of proposed literature review with the existing works.

Study	Focus	Immersive technologies				Healthcare area	Limitations/Comparison to our study
		AR	VR	XR	MR		
Mathew et al. [27]	Reviewing XR technology in medical education and training	×	×	✓	×	Medical education and training	- Training and education aspects only highlighted - No challenges found
Pears et al. [29]	Reviewing XR technology in medical education and training	×	×	✓	×	Healthcare education & training	- Training and education aspects only - No challenges found
Newbutt et al. [31]	Highlighting the applications of VR for people suffering from autism	×	✓	×	×	Anxiety & healthcare education	- Very limited applications of immersive technologies - No issues were addressed - Limited healthcare aspects covered
Higginbotham [32]	Discussing the virtual experience of VR & AR in neurosurgery	✓	✓	×	×	Neurosurgery	- Discussing only neurosurgery healthcare aspect - No problems have been highlighted in this area - Only AR and VR are pinpointed
Mathew et al. [28]	Identifies principles affecting the healthcare education	×	×	✓	×	Medical training & education	- Very limited applications of immersive technologies - Training and education aspects only highlighted
Pears et al. [30]	Discusses immersive technologies role in surgery education using Artificial intelligence	✓	×	×	×	Tele surgery and education	- Only medical education aspect - Only AR immersive technology is highlighted
Ryan et al. [33]	This SLR discusses the role of immersive technologies with the traditional technologies for nursing and healthcare education	✓	×	×	✓	Healthcare education	- XR and VR were not addressed - Challenges were not identified
Tang et al. [34]	SLR discusses the current research trend, application area, recipients, evaluation approaches, contents of immersive technologies in medical education	✓	✓	✓	✓	Medical education and practice	- Covers only the specific area of healthcare - More work is required to identify the emerging challenges and issues
Sadek et al. [35]	SLR reviewed the impacts of VR and AR on quality of medical education	✓	✓	×	×	Medical education	- Some other like XR and MR were left unaddressed - Only one aspect of healthcare is reported - Issues during the applications of VR and AR not highlighted
Linares-Chamorro et al. [39]	Study analyses the effects of VR technology for emotional well-being and anxiety of healthcare professional	×	✓	×	×	Anxiety and emotional well-being	- The analysis is based on only VR technology - Targeted only for the anxiety and depression
Pallavicini et al. [36]	VR role in medicine and medical training and education is put forward	×	✓	×	×	Medicine & medical training and education	- Discusses the role of VR at abstract level - Finding of study requires more extensive literature work - Barriers are highlighted without proposing solutions
Wilcha et al. [37]	SLR investigates the advantages and disadvantages of VR technologies in medical teaching	×	✓	×	×	Medical education	- Other immersive technologies not fully covered - Only medical education is focus of study
Spittle et al. [40]	This review explores literature for finding the remote studies conducted during the COVID-19	×	×	✓	×	Social distancing	- Describes only the social distancing or remote studies - No challenges or limitations addressed by authors
Jacobs et al. [38]	The aim of study is to analyze the existing studies to understand trend, quality of medical education, learning experience using immersive technologies	✓	✓	×	✓	Medical education	- Only medical education aspect is addressed - Issues during the implementation of immersive technologies were not found
Morimoto et al. [41]	It reviews the applications of immersive technologies in spine medicine	✓	✓	✓	✓	Medicine manufacturing and designing	- Covering the drugs and medicine aspects only
Kerdvibulvech [42]	Reviews the role of XR technologies during the pandemic in education and healthcare	×	×	✓	×	- Telemedicine, - mental health and social distancing	- Uses XR technology for healthcare - Challenges and issues not found

(*continued on next page*)

Table 1 (*continued*)

Study	Focus	Immersive technologies				Healthcare area	Limitations/Comparison to our study
		AR	VR	XR	MR		
Proposed review	✓ Highlighting contributions of immersive technologies in different healthcare areas i. e. medical education and proctoring, online surgeries, stress management, social distancing and rehabilitation ✓ Identifies challenges and provides solutions	✓	✓	✓	✓	- Medical training & education - Online surgeries - Virtual surgeries & operating procedures - Stress management & mental health, - Cognitive rehabilitations - Social distancing & fitness - Drugs manufacturing & designing	- Proposed review discusses the immersive technologies contributions in broader sense - Covers almost every healthcare aspect based on advances/ applications of immersive technologies - Identifies the prevailing challenges and provides solutions based on extensive literature study

selected. Those studies highlighting the application of any form of immersive technology such as XR, VR, AR, MR, Gamification and Metaverse for healthcare purpose were selected. All paper from 2010 to 2023 are selected for analysis. This paper also leverages snowballing techniques for selecting the desirable studies. This is very good statistical approach for selecting the most relevant studies. It uses both forward and backward approach for the selection of final studies for this literature review. Those papers that were focused on the application of immersive technology but were not focused on the COVID-19 pandemic aspects were also eliminated. Papers that were not published under the peer review process were also eliminated.

d) Included studies

In this step, we conducted the quality assessment of the selected studies. All the collected were checked against a particular numerical scale ranging from 1 to 5. The quality assessment procedure was conducted by independent reviewers. The quality assessment questions were formulated, and weights were given to the papers according to the answers of the quality assessment questions. Every paper was checked and papers that obtained less than 2.5 score values were removed. Finally, the number of paper selected in this review reached to 220. The complete flow diagram of PRISMA guidelines in context of the research methodology adopted in this research is given in Fig. 1.

4. Analysis and application immersive technologies during pandemic in healthcare

In this section of the literature review, the main objective is to perform meta-data analysis of different studies collected from the literature. Hopefully, this analysis will be helpful for the researchers and medical practitioners to fully understand the existing applications of immersive technologies for healthcare tasks amidst the COVID-19. We collected every research paper that was focusing on using the immersive technologies in the healthcare sector for different proposes like medical education, proctoring, training, mental health and stress management, cognitive rehabilitation, social distancing, physical fitness, drugs designing and manufacturing, virtual clinics and surgery, health feedback, health awareness, health diagnosis/treatment, telehealth and chronic pain management. During the pandemic, the major applications of immersive technologies has been witnessed with respect to medical training, proctoring and medical education. The complete detail of immersive technologies for healthcare-based applications during the pandemic is shown in Fig. 2.

From the content of Fig. 2, it is obviously clear that AR and VR technologies have been extensively applied by the majority studies during the pandemic. According to our literature study, the significant number of studies are using VR and AR are distributed as VR (n = 17) and AR (n = 9), have been applied for the medical education, proctoring and training. VR and AR technologies have played a dominant role in providing medical training, education and proctoring during the pandemic.

This pandemic had a major impact on the mental health of the people around the world. Therefore, it was imperative to deal with the cognitive rehabilitation, mental health and stress management by the healthcare professionals and practitioners. In this regard, we searched the literature and collected all the studies that were utilizing immersive technologies for the stress management, mental health and cognitive rehabilitation. The different studies were conducted to highlight the applications of immersive technologies for mental health as details are given in Fig. 3.

According to our literature study the number studies conducted to deal with the mental health can be divided such as VR (n = 14), AR (n = 4), XR (n = 3), Gamification (n = 3), metaverse (n = 3) and MR (n = 1). Many studies have applied the VR technology to deal with for mental health problems followed by AR technology during the COVID-19 outbreak.

Similarly, VR and AR and XR immersive technologies played a pivotal role in dealing with the stress related issues during the pandemic. The complete picture of immersive technologies adoption for the stress management is given in Fig. 4. It can be seen from Fig. 4 that AR and VR have played a vital role in dealing with the stress management.

During the peak hours of the pandemic, it was important to keep a distance from each other to avoid the contact of highly

contagious virus. Different research studies have been conducted by leveraging the immersive technological experience. We collected all the studies that were utilizing the immersive technologies for the social distancing. The detail of studies focusing on social distancing by using immersive technologies is given in Fig. 5. It is clear that AR (n = 5) and VR (n = 4) have been most frequently adopted for social distancing or isolation to deal with COVID-19 pandemic.

During the pandemic, the lockdown restrictions compelled people to stay in their home places. However, the immersive technologies provided some immersive experience to perform the aerobic activities to combat the virus. Different studies have been proposed to use the immersive technologies for the physical fitness. The complete detail about the applications of different immersive technologies for the physical fitness is given in Fig. 6.

From the graphical data of Fig. 6, it has been observed that VR, AR and Gamification are the leading immersive technologies that are adopted for the physical fitness.

Similarly, it was also important to provide cognitive rehabilitations services to the people, who suffered from anxiety or mental disorders. The immersive technologies played important role in this regard. We collected some of the studies, where such technologies have been used to provide cognitive support towards the mentally impaired people. The complete detail about the number of studies highlighting the application of immersive technologies for the cognitive rehabilitation is given in Fig. 7. We can see from this figure that VR and AR have been on the top of other immersive technologies for cognitive rehabilitation during the COVID-19 pandemic.

In this research, we extensively studied and highlighted the applications of immersive technologies for healthcare features like health feedback, medical awareness, drugs manufacturing, virtual surgery, telehealth/telemedicine and health diagnosis and treatment. The overall pictorial representation of immersive technologies for the different healthcare purposes is given in Fig. 8.

From Fig. 8, it is clear that VR has major applications in dealing with the health feedback, medical awareness, drugs manufacturing, virtual surgery, telemedicine and health diagnosis. Similarly, the AR technology has also been used for health feedback, medical awareness, drugs manufacturing, virtual surgery, telemedicine and health diagnosis. The complete detail about the different studies focusing on the application of different immersive technologies for the different healthcare tasks is given in Table 2.

5. Applications of immersive technologies in healthcare during COVID-19 pandemic

Immersive technologies have been applied for many purposes in medical care system such as medical training for students and doctors, treatment, medical marketing and awareness about the diseases or medical conditions. These technologies have shown enormous applications during the pandemic in healthcare department from application as well as marketing perspectives. According to a report [134], the current VR market value in 2023 is $25.11 billion and it is predicted that by the end of 2030 the global market value of VR will reach up to $165.91 billion. In the list of immersive technologies, VR technology has been witnessed as more potential candidate for different purposes in healthcare sector. It has been applied for telemedicine, controlling the spread of the virus, planning, treatment, and alerting people about the disease [135]. It was applied in neurology and cardiology to improve and monitor the patients' outcomes [136]. According to the survey, 82 % of healthcare professionals found VR a convenient way of learning and accessing information, and 62 % of patients welcomed the VR healthcare services as a substitute for the conventional healthcare system [137]. VR technology can be leveraged to propose VR-based healthcare model or architecture [137].

This working procedure of general architecture of VR based healthcare system is given in Fig. 9. Generally, VR-based healthcare architecture comprises three major components such as client virtual reality application, database server and web admin panel. In this model, the client VR app extracts data from the database server and displays it on output components such as HMD or desktop devices. The VR app consisted of data loading and simulation modules to provide visualized representation based on using AI, physical simulator and scenario based simulation systems to the users. A virtual session is created with the help of VR app which is connecting individuals or group members to the real tutor. The real tutor is also connected with VR app which is controlled by applying the AI algorithms. Physics simulator helps in producing the realistic behavior of the virtual objects. The AI-based performance assessment module helps in assessing the patient performance and tracks the progress of patients/user by using AI algorithms. The database web server stores data about the users, 3D models and scenarios. The web admin panel is used to provide access and controlling mechanism to both VR app and database.

During this pandemic, the role of immersive technological adoption has significantly accelerated due to its interactive and immersive nature. The applications of various immersive technologies in the context of battling COVID-19 in the different healthcare departments are discussed below.

A. Medical education, training and proctoring

Providing nursing and medical education to the students created unpresented challenges for the healthcare professionals during the pandemic [138,139]. Immersive technologies have a wide range of applications in providing quality care and necessary training to the medical staff or students. The rise in the VR-based training market from $216 million in 2018 to the expected growth of 6.3 billion till 2022 is clear evidence of its application [137]. The recent pandemic forced medical institutions to think of using technologies to deliver education without face-to-face communication. This pandemic also resulted in the closure of medical institutions by giving birth to many issues related to medical education and training. However, immersive technologies have shown productive outcomes in providing medical training or education to healthcare professionals and students in a risk-free environment in this pandemic. These tools and technologies provide rich sources of information and learning through immersive-based applications and smart VR devices like 3D goggles and headset during the training of the medical students. The current immersive technologies have shown a significant contribution in grasping the complex content easily due to their visual and interactive capabilities in remote learning during a

pandemic [140]. The immersive technologies provided social distancing by imparting training with low-cost, accurate, graphical and interactive learning experiences to the medical students located at remote sites. The immersive virtual technologies have introduced a novelty in teaching the learning process by eliminating the conventional teaching method. The immersive simulation has been proved to enhance the technical and non-technical skills gaining compared to conventional methods of learning in the orthopedic area [141]. In the medical field, anatomy is the type of subject that conventional teaching approaches cannot adequately deliver as it consisted of dissection parts and protection to be demonstrated. In this COVID-19 crisis. However, the VR can be adopted to teach the medical students anatomical parts and 3D views of these parts through rotation, magnification, and virtual dissection to understand the structures fully. It has been observed that using VR as teaching technology has produced good results in comparison to conventional teaching methods [142]. During the pandemics, the VR has been utilized for Omni-learning which means learning anytime, anywhere and by anyone [29]. It became possible to provide real-time training during COVID-19 through the applications of virtual reality where students were not required to be physically present. VR simulation-based education (SBE) could be considered the most acceptable feasible option to provide an illusion of a realistic medical environment. Similarly, VR360° videos could improve the learning skills and knowledge acquisitions at best level [143]. The VR-based SBE is also an excellent option to provide online training to orthopedic surgeons with risk-free education confidently and efficiently [144].

VR technology has been applied by clinicians to understand the effects of disease on the lungs of COVID-19 infected patient in George Washington University Hospital. They also used Oculus headsets to address the complex challenges of coronavirus and resenting their condition visually. According to physicians, VR technology provided a good view of COVID-19 disease radiographically to the medical experts. This technology helped to quantify the damage brought by this disease by observing the amount of damage caused to the lungs. VR technology also enabled the healthcare professionals to study this disease from different angles [145]. VR technology assisted in providing physician training to the physicians and patients [10]. In the University of Washington, the researchers and healthcare professionals deployed virtual technology to deliver mindfulness strategies to patients where patients leveraging VR headsets received instructions from the medical experts [145]. Another instance of VR/AR application was also seen in Kanas City University, where VR/AR technologies have been adopted for the learning and teaching process. Keeping in view, the productivity, finally university made it a part of the curriculum by integrating the sophisticated technologies in the courses [146].

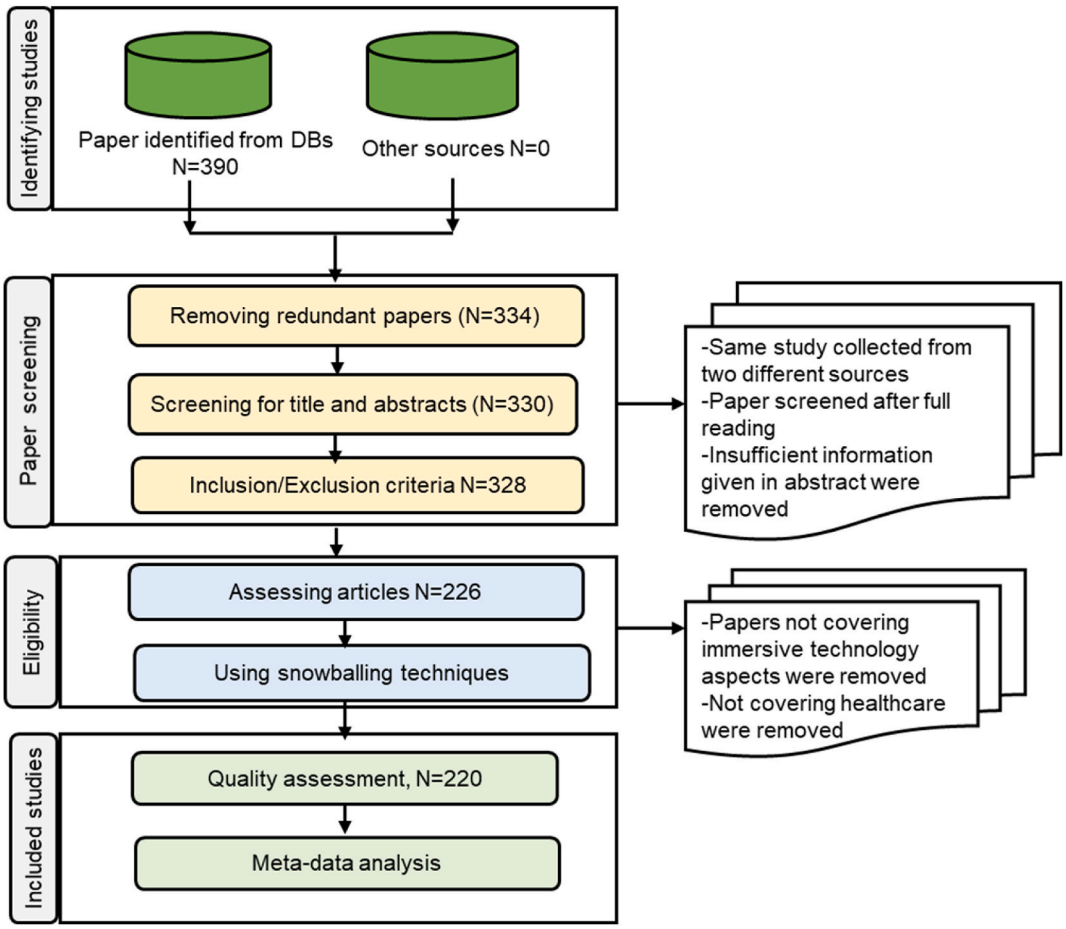

Fig. 1. Flow of research methodology.

Similarly, in New York, over 40,000 paramedic staff including students and retired persons, trained as part of healthcare forces during this pandemic by using modern VR technology [147].

Similarly, in the current COVID-19 situations, the AR technology was utilized immensely due to its video streaming feature which enabled the surgeons in improving the level of training and delivering the medical training to fresh surgeons and patients [148]. AR technology has been applied during the pandemic for learning-teaching purposes. Award-winning app with the assistance of AR-based HoloAnatomy has been adopted by 185 first-year students during the closure of classes at Case Western Reserve University. It provided complete detail in a 3D way and learning was not only limited to the availability of cadavers and medical toolboxes [149]. The headset based leveraging MR technology has also been used for rounds in the wards in the COVID-19 pandemic. This tool helped in providing the education opportunities by reducing the number of people, minimizing the usage of PPEs and saving the precious time of students and doctors in areas where high element of risks were involved [150]. AR also has been applied to provide fruitful surgical education for limited operating with the benefit of lessening the number of surgeons in theatre and hence mitigating the risk of viral transmission [141].

The president of CGS enterprise learning, Doug Stephen shared four use cases of AR technologies in the medical education [151]. The first use case is that AR improved the success rate of operations or brain surgery in the operating theatre. Microsoft HoloLen has been applied to overlay images to provide a 3D view of brains so the surgeon can interact with digital imaginary by bringing the successful outcomes. Secondly, in this pandemic, the AR-based diagnostic equipment known as HemoCue has been deployed with a smartphone to provide remote collaboration, interaction, higher fidelity, and offline training. Thirdly, the medical devices are expensive and bulky, so it is impractical to carry, thus AR allowed them to use virtual devices for tangible information. The fourth use case is related to integrating the AR with MR technologies to furnish more functionalities and features. The VR technology in collaboration with AR and smartphone technology can be used as feedback mechanism. The AR technology-based mobile apps introduced gamification tools to present information in interesting ways such that elder people could be informed about the COVID-19 interestingly. These gamification tools enable the elder people to get educated about the awareness and battling of pandemic [152].

Similarly, medical professionals applied the AR for providing the effective and efficient training related to the new machinery and medical equipment or any other necessary procedure. This training method is more helpful, when experienced staff and training are scarce and quickly delivered. According to Harry Hulme, AR is an important tool for testing healthcare workers and equipment changeovers. The AR-enabled method helped in reducing training time and accelerated the procedure of equipment changeovers [153]. AR provided innovative and interactive methods in the classroom in solving assignment especially in STEM curriculum. Medical schools used AR models for training surgeons and nurses about the complex medical procedure of neurosurgery to the simple need placement. The AR has been found as a perfect use case in training and education as it reduces distraction and improves the awareness about the task at hand [154].

B. Virtual surgery and operating procedures

Getting access to the healthcare services can be put some financial burden on the patients and their caregivers [155]. The immersive technology has the potential to provide seamless healthcare services. These technologies enabled the surgeons to perform virtual mock surgeries and operations in their virtual spaces without any pressure and stress. Immersive technological tools virtually connected to the healthcare professionals enable them to mimic the real-world case by providing remote interactive and immersive experiences. Before COVID-19, the surgeons used to be flying around the world for proctoring cases. But, the ExplORer system run by AR technology has been adopted by the surgeons for zooming, sharing and guidance on the remote screen. In this system, the medical professional can login from their home or room and the virtual pointer allows medical proctors to highlight items on the screen and draw on fluoroscopy images. It also warns doctors for what to look for while planting the device on the human body [156]. The operating room (OR) personnel system supported by AR glasses, hologram and apps were utilized by specialists in spine surgery of 12 patients during the tele-monitoring, teaching and surgical planning due to limited OR environment in COVID-19 emergencies [157]. The AR technology was utilized for the first time during the surgical intervention, when a 59 years old COVID-19 positive patient suffering from diabetes, hypertension and other chronic diseases was operated due to his deteriorating health condition. The AR tele-surgery platform known as Proximie™ was employed for obtaining consent from the expert doctors. In this tele-surgery procedure, two remote surgeons as consultants were involved. This platform enabled the surgeons to use AR tools for incision on televised operative field on screen. This platform provided audio-video feedback in real time and remote mentorship as well. After operating the

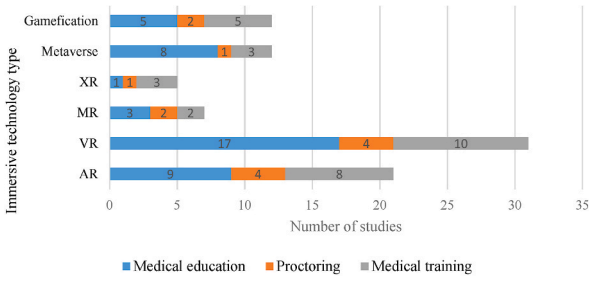

Fig. 2. Applications of immersive technologies for medical education, proctoring and training.

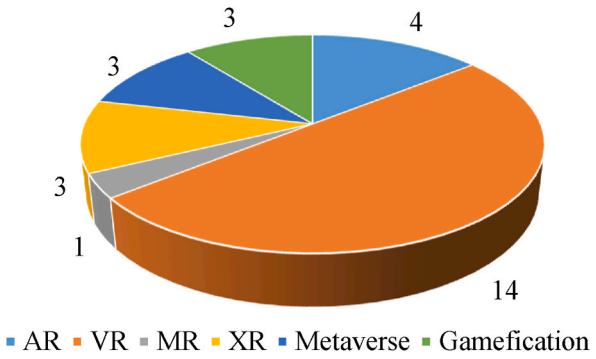

Fig. 3. Immersive technologies applications for mental health.

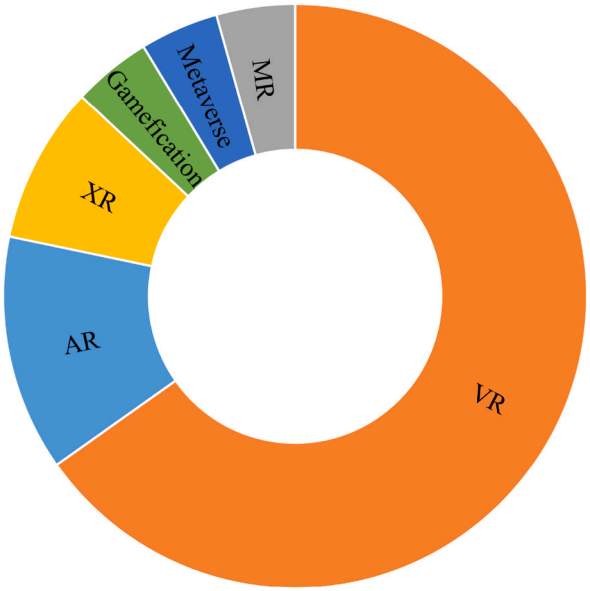

Fig. 4. Immersive technologies adoption for stress management.

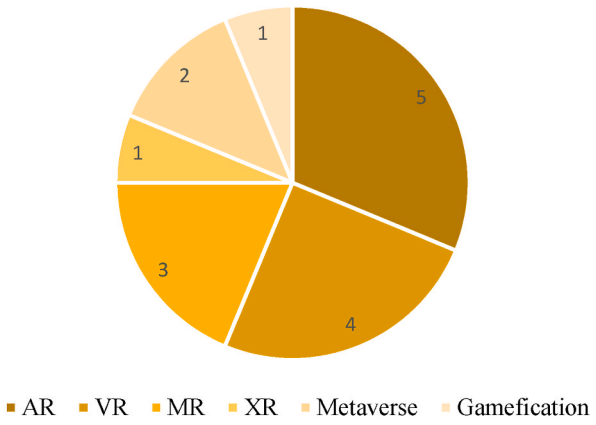

Fig. 5. Number of research studies using immersive technologies for social distancing.

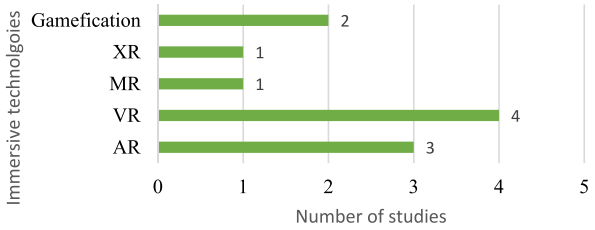

Fig. 6. Number of studies using immersive technologies for physical fitness.

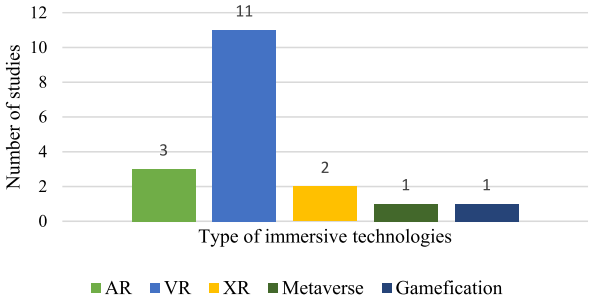

Fig. 7. Number of studies using immersive technologies for cognitive rehabilitation.

condition of patients improved with uneventful recovery [158]. The visual demonstration of Proximie™ platform is given in Fig. 10 [158]. In the current COVID-19 pandemic, the application of AR and immersive simulation played the role of catalyst in orthopedic surgery, trauma, and elective surgery. The AR provided real-time access to hands-free operating room resources by promoting education and telemedicine and tele-monitoring in surgeries [159].

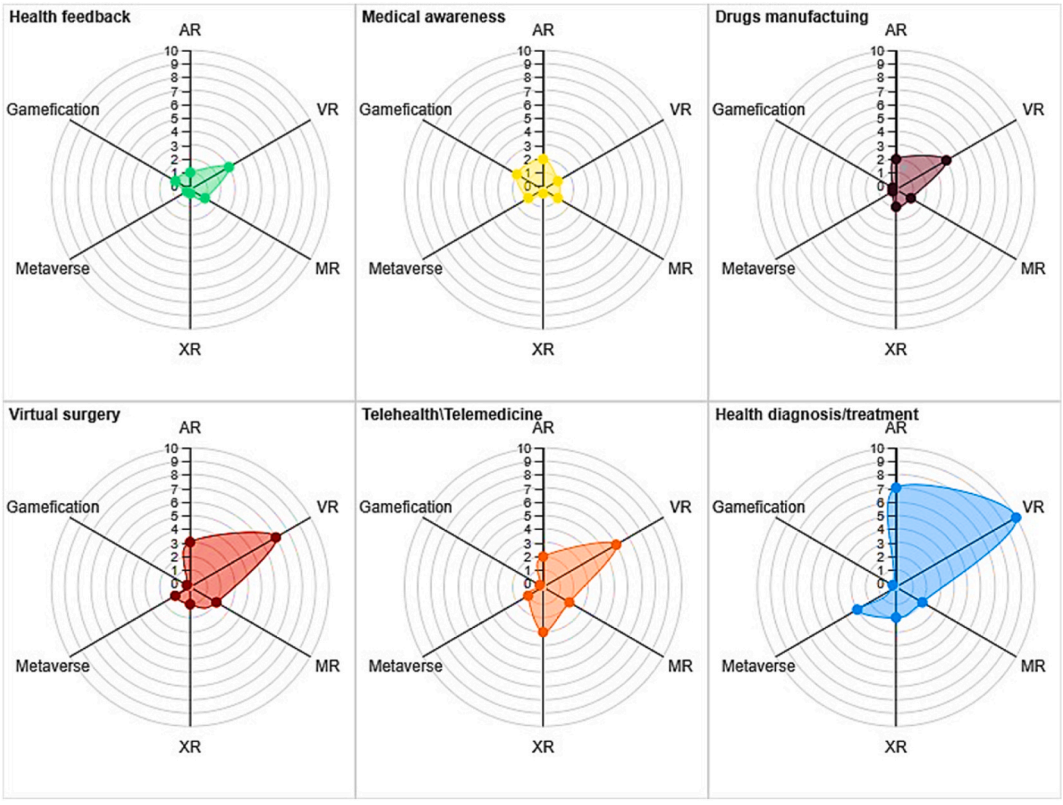

Fig. 8. Immersive technologies contribution for healthcare purpose.

Table 2
Existing literature highlighting applications of immersive technologies for healthcare aspects.

Ref	Immersive technology	Healthcare Domain Covered											
		Medical education	Training	Mental health	Social distancing	Physical fitness	Cognitive rehabilitation	Virtual surgery	Drug manufacturing	Health feedback	Diagnosis/ Treatment	Telehealth	Stress management
[44]	VR	×	×	✓	×	×	✓	×	×	×	×	×	✓
[45]	XR	✓	✓	×	×	×	×	×	×	×	×	×	×
[46]	XR	×	×	✓	×	×	✓	×	×	×	×	×	✓
[47]	XR	✓	✓	×	×	×	×	×	×	×	×	×	×
[48]	VR	×	×	✓	×	×	✓	×	×	×	×	✓	×
[49]	VR/AR/Game	×	×	✓	×	×	×	×	×	×	×	×	×
[50]	VR	×	×	✓	×	×	×	×	×	×	×	×	✓
[51]	VR	×	×	×	×	×	×	×	×	×	✓	×	×
[23]	MR	✓	×	×	×	×	×	✓	×	×	×	✓	×
[52]	VR	×	×	×	✓	✓	×	×	×	×	×	×	×
[53]	VR/AR	×	✓	×	×	×	×	✓	×	×	×	×	×
[54]	VR	×	×	✓	×	×	✓	×	×	×	×	×	✓
[55]	Metaverse/VR	×	×	✓	×	×	×	×	×	×	×	×	×
[56]	VR	×	×	×	×	×	×	×	×	×	×	✓	×
[57]	VR	×	×	×	×	✓	×	×	×	×	×	×	×
[58]	Gamification	×	×	✓		✓	✓	×	×	×	×	×	×
[59]	VR	×	×	✓	×	×	×	×	×	×	×	✓	×
[60]	VR	✓	×	×	×	×	×	×	×	×	✓	×	×
[61]	VR/Games	×	×	×	×	×	✓	✓	×	×	×	✓	×
[62]	VR	×	×	×	×	×	✓	×	×	×	×	✓	×
[63]	VR	×	×	×	×	×	✓	×	×	×	×	✓	×
[64]	VR	✓	×	×	✓	×	×	×	×	×	×	×	×
[65]	VR	×	×	✓	×	×	✓	×	×	×	×	×	✓
[66]	VR	✓	✓	×	×	×	×	×	×	×	×	×	×
[67]	VR	×	✓	×	×	×	×	×	×	×	×	×	×
[68]	VR	×	✓	×	×	×	×	×	×	×	×	×	×
[69]	VR/AR	✓	✓	✓	×	×	×	×	×	×	×	×	×
[70]	VR	×	✓	×	✓	×	×	×	×	×	×	×	×
[71]	VR	×	✓	×	×	×	×	×	×	×	×	×	×
[36]	VR	×	✓	✓	×	×	✓	×	×	×	×	×	✓
[72]	VR	×	✓	×	×	×	×	×	×	×	×	×	×
[73]	VR/Games	×	×	✓	×	×	✓	×	×	×	✓	×	×
[74]	VR	✓	✓	×	×	×	×	×	×	×	×	×	×
[75]	MR	✓	✓	×	×	×	×	×	×	×	×	×	×
[76]	VR	✓	✓	×	×	×	×	×	×	×	×	×	×
[77]	VR	✓	✓	×	×	×	×	×	×	×	×	×	×
[78]	VR	✓	✓	×	×	×	×	×	×	×	×	×	×
[79]	VR	✓	×	×	×	×	×	×	×	×	×	×	×
[80]	AR	✓	×	×	×	×	×	×	×	×	×	×	×
[81]	MR	✓	×	×	×	×	×	×	×	×	×	×	×
[82]	AR	✓	×	×	×	×	×	×	×	×	×	×	×
[83]	VR	×	✓	×	×	×	×	×	×	×	×	×	×
[84]	VR	✓	×	×	×	×	×	×	×	×	×	×	×
[85]	VR	×	×	✓	×	×	✓	×	×	×	×	×	✓
[86]	VR	×	×	✓	×	×	✓	×	×	×	×	×	✓
[87]	VR	×	×	✓	×	×	✓	×	×	×	×	×	×

(*continued on next page*)

Table 2 (*continued*)

Ref	Immersive technology	Healthcare Domain Covered											
		Medical education	Training	Mental health	Social distancing	Physical fitness	Cognitive rehabilitation	Virtual surgery	Drug manufacturing	Health feedback	Diagnosis/ Treatment	Telehealth	Stress management
[88]	VR	×	×	×	×	×	×	×	×	×	×	×	✓
[89]	VR	×	×	✓	×	×	✓	×	×	×	×	×	×
[90]	VR	×	×	✓	×	×	✓	×	×	×	×	×	×
[16]	AR/Game	×	×	✓		✓	×	×	×	×	×	×	×
[91]	VR	×	×	✓	×	×	✓	×	×	×	×	×	✓
[92]	MR	×	×	✓	×	×	✓	×	×	×	×	×	✓
[93]	VR	×	×	✓	×	×	✓	×	×	×	×	×	×
[94]	VR	×	×	✓	×	×	✓	×	×	×	×	×	×
[95]	MR	✓	×	✓	×	×	×	×	×	×	×	×	×
[96]	VR	✓	×	✓	×	×	✓	×	×	×	×	×	✓
[97]	VR	×	×	×	×	×	✓	×	×	×	×	×	✓
[98]	VR	×	×	✓	×	×	✓	×	×	×	×	×	×
[99]	VR	×	×	×	×	×	✓	×	×	×	×	×	×
[100]	VR	×	×	✓	×	×	✓	×	×	×	×	×	×
[101]	AR	×	✓	×	×	×	×	×	×	×	×	✓	×
[102]	AR	×	×	×	✓	×	×	✓	×	×	×	×	×
[103]	MR	×	×	×	×	×	×	✓	×	×	×	×	×
[104]	MR	✓	×	×	×	×	×	✓	×	×	×	×	×
[105]	AR	✓	×	×	×	×	×	×	×	✓	✓	×	×
[106]	MR	✓	×	×	×	×	×	×	×	×	×	×	×
[107]	VR/AR	✓	×	×	×	×	×	×	×	×	×	×	×
[108]	XR	×	×	×	×	×	×	×	×	×	✓	×	×
[109]	AR	×	×	×	×	×	×	×	×	×	✓	×	×
[110]	VR/AR	✓	✓	×	×	×	×	×	×	×	×	×	×
[111]	VR	×	×	×	✓	×	×	×	×	×	×	×	×
[112]	VR/AR	×	×	×	×	×	×	×	×	✓	✓	×	×
[113]	VR	×	×	✓	✓	×	×	×	×	×	×	×	×
[114]	AR	✓	×	×	×	✓	×	×	×	×	×	×	×
[115]	VR Games	×	×	×	×	×	✓	×	×	×	×	×	×
[116]	XR	×	×	✓	×	×	✓	×	×	×	×	×	×
[117]	Metaverse	✓	×	×	×	×	×	×	×	×	×	×	×
[118]	Metaverse	✓	×	×	×	×	×	×	×	×	×	×	×
[119]	Metaverse	×	✓	×	×	×	×	×	×	×	×	×	×
[120]	MR	✓	×	×	×	×	×	×	×	×	×	×	×
[121]	Metaverse	✓	×	×	×	×	×	×	×	✓	✓	✓	×
[122]	Metaverse	✓	✓	×	×	✓	×	×	×	×	×	×	×
[123]	Metaverse	✓	✓	✓	×	×	×	✓	×	✓	✓	✓	×
[124]	Metaverse	×	×	×	×	×	✓	×	×	×	×	×	✓
[125]	Metaverse	×	×	×	×	×	×	×	✓	×	×	×	×
[126]	Metaverse	×	×	×	×	×	✓	×	×	×	×	×	✓
[127]	Metaverse	✓	×	×	×	×	×	×	×	×	×	×	×
[128]	Metaverse	×	×	×	✓	×	×	×	×	×	×	×	×
[129]	Metaverse	×	×	×	✓	×	×	×	×	×	×	×	×
[130]	Metaverse	×	×	×	✓	×	×	×	×	✓	×	×	×
[131]	Metaverse	✓	×	×	×	×	×	×	×	×	×	×	×
[132]	Metaverse	✓	×	×	×	×	×	×	×	×	×	×	×
[133]	Gamification	✓	×	×	×	×	×	×	×	×	×	×	×

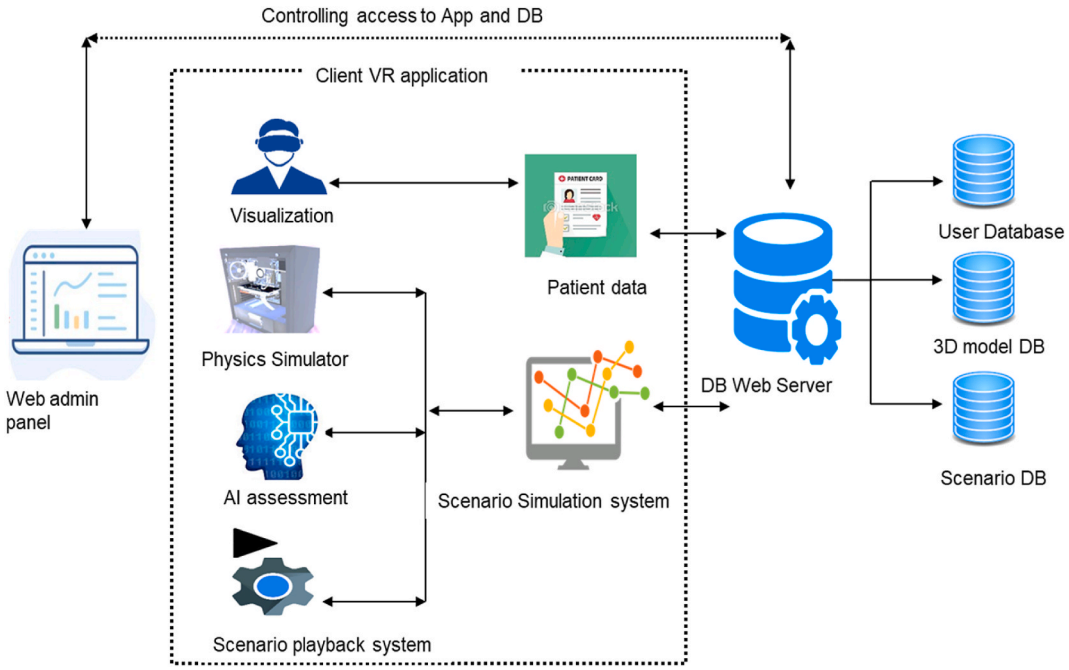

Fig. 9. VR-based healthcare system architecture.

Likewise, the VR platform enabled the surgeons to virtual help each other at a remote distance in layering live video to reach the operative field of local surgeons in real time and provided the visual instructions in the shoulder arthroscopy [141]. VR allowed the surgeons to carry out various mock surgeries in their virtual space [160,161]. VR technology helped them in eliminating the deficiency in their skills quickly and enabled them to become more skillful in their profession. According to the Harvard Business Review report, the application of VR technology has improved the surgical performance of surgeons by 230 % compared to conventional surgery methods [162]. VR allowed them to perform virtual surgeries without using costly equipment. VR software provided a complete guide about the steps that are to be taken to complete surgery in the right sequences by using haptic controllers. The VR software applications were also applicable to explain the procedure of surgery related to patients. The major VR use cases are surgical training, planning regarding pre-surgical planning and medical device marketing [137].

According to a recent study, VR has the potential to improve the patient safety. The training done via VR can improve the patient outcomes, like 83 % improvement has been achieved in the performance related to hip arthroscopy [147]. VR provided a flexible immersive architectural designs for healthcare professionals to perform remote surgeries. The VR-based architecture [137] for the surgery is depicted in Fig. 11. In this architecture, the VR-based client application gets data from a database web server and the outputs are displayed on a user's visualization module or head-mounted display. The function of the web admin panel is to perform access management and database management tasks. The data about MRI and CT scan is converted into 3D models where surgeon can navigate to get a patient or trainee ready by looking at the different angles. The script editor is used to adjust the difficulty experienced by the trainee. The playback system allows to replay the surgery to analyze the performance of trainee or to show the patient about the plan of surgery. Similarly, the performance of trainees can be evaluated against the certain metrics and feedback about their skills level is provided by using AI assessment model. Physics simulator helps in producing the realistic behavior of the virtual objects.

C. Mental health and stress management

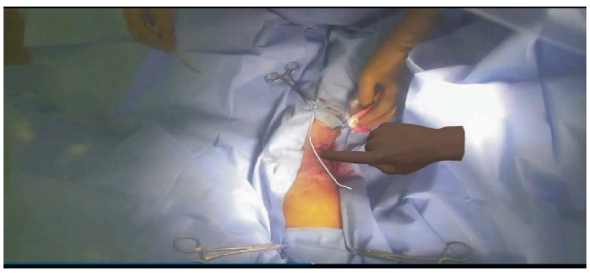

Fig. 10. Proximie™ platform using AR technology during incision.

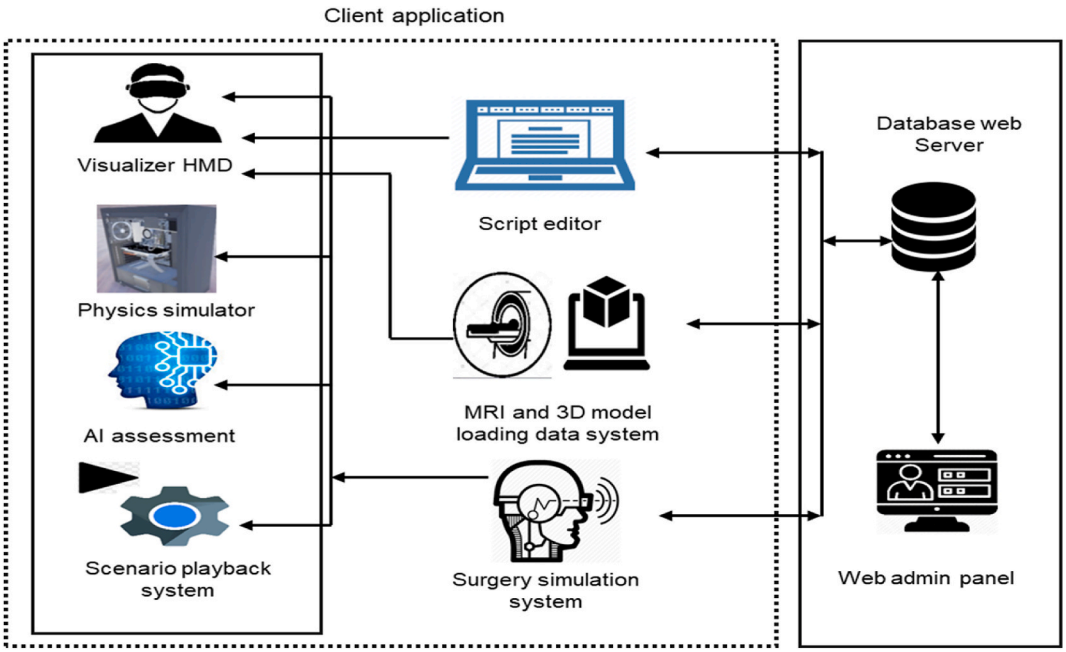

Fig. 11. VR-based surgery system architecture.

Social distancing maintained due to COVID-19 has led to mental disorders [13]. A wide range of psychological disorders such as fear, stress, insomnia, depression and anxiety arose due to the mobility restrictions and lockdown measures [163]. According to the survey report [164], it has been reported that 31 % of Americans suffered from depressions and anxiety while 11 % committed suicide amidst the COVID-19 pandemic. Although, the medication's physical discomfort has been treated by medication however the excessive fear related to COVID-19 had not been mitigated. For this purpose, many applications of immersive technologies have been witnessed in dealing with mental health disorders such as stress, fear and anxiety. The role of immersive technologies became more viable under these circumstances in the pandemic. For example, the VR has been found very helpful in reducing the pain, steading nerve and enhancing the mental health. VR technology could be proven as a good option for its application at home without involving trained clinicians [164]. Different rehabilitation techniques have been proposed but VR techniques brought more immediate results, value-added responses, less resource consumption and an eco-friendly environment [165,166]. During the pandemic, far-reaching growth has been observed in VR-based tele-rehabilitation process and different approaches have been adopted to improve the mental health conditions. For example, the framework-based on the application of VR technology has proven to be cost-effective, real-time data analysis and decision-making for cognitive rehabilitation [62]. In healthcare, VR has been employed for virtual exposure treatment to address the issues related to mental disorders. For example, the Bravemind system driven by VR technology has been applied to treat the mental stress disorders. This system yielded significant results in case of handling stress, anxiety and fears among the people. This technology put the stressful patients in a controlled environment and handled the mental disorders like fear and anxiety in commanding ways. Infinadeck has also been considered as another good choice for physical treatment and rehabilitation of patients from different traumas [148]. Similarly, the MIND-VR protocol was presented to alleviate the anxiety and stress during COVID-19. This protocol has been found as low-cost, easy to use, easily accessible, user-friendly, bi-lingual and informative. Both patients and healthcare workers used this protocol during COVID-19 emergency [167]. While handling the mental health problems, exposure therapy was considered the best choice to recover from this phobic situation of COVID-19. In this respect, Zhang et al. [168] presented VR-based exposure therapy known as Virtual Reality Exposure Therapy (VRET). This therapy is a part of behavioral therapy where patients were subjected to exposure to a thing that they are more intimidating. In this therapy, the major role of VR is to simulate a real environment where patients are exposed to reduce the anxiety and fear caused by COVID-19. The VRET had many advantages in the current COVID-19 outbreak. It helped in alleviating the fear and anxiety emerged due to COVID-19 by minimizing the feeling of isolation. This was an innovative method and emerged very effective method for dealing with mental health disorders. It improved the medical condition of patients in the modern research. It also enhanced patients' memory; after the treatment procedure, the patients were able to recall what happened during the pandemic and diminished the anxiety effects to some extent. This therapy provided a virtual controlled environment and patients were immersed in the virtual world. This therapy was also seen as helpful in removing the negative cognitions. It helped to develop a therapeutic behavior and created a sensory feeling of physically involved in it [168]. Similarly, another therapy known as VR biofeedback using *EaseVR* has been applied to overwhelm patients' minds and bodies, who were suffering from chronic pain. This type of therapy yielded significant outcomes in reducing depression and anxiety for the short term but also had sound effects after the treatment completion [164]. The VR-based therapy has been used to address anxiety and stress in the COVID-19 patients in Italy. For example, Schiavonia, hospital in Italy was supplied with the VR

headset to improve the emotional and psychological well-being of hospital staff, health workers and patients suffering from COVID-19 disease. A virtual healthcare system with the collaboration of Yale, Stanford and Harvard universities was developed. The proposed virtual healthcare system uses feelings that are originated from happiness and positive memories to fight against the anxiety. In this virtual healthcare system, the patients will be teleported to a location, where they felt happy [169]. The patients participate in the guided breathing exercise. The proposed virtual healthcare system allows the nursing staff and clinicians to get connected with the other medical experts during the interviewing process. Users can virtually visit the place by using VR technology to view footage of it from 3D imaging libraries like Google Street View. After that, they discuss their selected memory with the clinical staff connected with them. The clinical staff also have access to the video on a tablet, enabling them to relive the event and bring the happy memories into their present setting.

Similarly, the VR-based apps also have been used for dealing with the mental health problems. These apps have shown enormous applications in the peak hours of the pandemic. The VR apps produced the conducive effects in handling stress situations arose due to the lockdown [170]. Similarly, AR-based games i.e. Harry Potter and Pokémon GO, promoted mental and physical health amidst the coronavirus pandemic. These games have been adopted by people for virtual socialization, sustaining physical activities, mental structures and temporal routine during the COVID-19 pandemic [16]. Additionally, the AR-based games promoted learning, enjoyment, and motivation among the students [171].

D. Social distancing and physical fitness

It was not possible to stay close to each other in the pandemic situation due to the highly contagious nature of this lethal virus. However, it was also imperative to keep the wheel running but due to COVID-19. However, it was a herculean task to allow the people to work together as they used to do in the everyday situations. Different technologies and apps were adopted to keep social distancing by performing the routine tasks. The role of immersive technologies was only limited to the training and educating doctors, patients and students but it was far beyond it. These technologies also had the potential to the keep social distancing during the pandemic. Similarly, patients suffering from chronic diseases or hospitalized used VR tools such as goggles or headsets to get the feeling of the immersive and home environment. It also allowed them to talk or interact with family people through 360^{O} camera. The mobility restrictions and lockdown during COVID-19 not only affected mental and physical health but also physical fitness. Aerobic exercise became more imperative to keep both physical and mental health. In this regard, the immersive technologies also played an immense role in sustaining the overall fitness. Although, during the pandemic, many people have opted to use treadmill however its results were found as boring and monotonous. To solve this dilemma, immersive technologies offered a wide range of applications in physical fitness. Immersive technologies could allow to explore new places, locations and outer spaces to make physical exercise captivating. These technologies provided Omni-directional treadmill known as Infinadeck, which can be used to create virtual environment for walking. Some other features compared to common treadmills is it provides the speed of 6 mph by providing 360^{O} paths for running. It also helps maintain social distancing by patients and can benefit isolation if used with proper sanitation techniques after surgery [148].

During the peak hours of pandemic, people changed their life routines such as shopping, meeting and socialization. AR/VR technologies also enabled people to do small business or work from home to avoid virus transmission in proximity thus providing a good platform for smooth business activities by following the lockdown protocols. AR/VR has proved its applications and functions to get connected virtually with each other. AR provides holographic technology, and VR brings new ideas to handle the pandemic of COVID-19. These technologies collaboratively have enabled people with new opportunities to perform remote activities such as work, entertainment and exercise [172]. A major use case of AR is related to remote assistance and collaboration during the pandemic. AR provided an enhanced version of the live-video sharing experience among the users. The feature of AR technology to bring tools that enable to track the movement of user's device camera with the help of computer vision technological support. These tools also enabled users to add annotations and collaborate with users under the supervision of experts connected from home. It helps in reducing the traveling, staffing and maintaining the social distance in this pandemic [153]. Similarly, AR-enabled devices and applications enable users to participate in remote collaboration by sharing design review, 3D modeling and supporting information according to their view [153]. MR-based HoloLens headset was adopted in a joint venture by Tech giant and NHS Trust in the UK to treat COVID-19 patients. It kept doctors safe and secure by enabling them to send the live videos to a computer screen in a nearby room at an adequate distance. This technological addition led to the viable results like reducing the amount of time spent in hazardous areas up to 83 %, less usage of PPEs and keeping social distancing with patients [147].

E. Cognitive rehabilitation

Immersive technologies brought tailor-made rehabilitation healthcare services in the current pandemic. The VR technology added the virtual and immersive experiences to provide the rehabilitation services. VR has been employed for the physical, cognitive, and neurological therapies [173]. In physical therapy, the VR technological solutions assisted in repairing the cognitive impairments/-disorders such as dementia and hyperactivity. Physical therapy has shown a success rate for improvement in these medical conditions [174]. VR helped in improving the memory, learning skills and attention. In physical therapy, VR applications improved the weakness of muscle and training of mobility function in case of limb injuries. In neurological rehabilitation, VR technologies helped the patients to retain postural balance and motor skills. They were commonly used for stroke rehabilitation, recovery from brain and spinal cord damages. In the current COVID-19 situations, severely ill COVID-19 patients may likely develop Post-Intensive Care Syndrome (PICS) after recovering from COVID-19. It leaves physical, psychological, and mental disorders. Thus, VR technology conveyed remote treatment, tailored-made rehab and fast administrating solutions for the treatment therapy of PICS-COV patients. VR has shown

fast-growing applications in rehabilitation and offered immense ways of treatment and therapy for stroke patients. VR allowed consistent therapy for patients suffering from stroke and kept them connected [175]. A project known as VR4REHAB [176] has been launched for the rehabilitation motto with the support of AR and VR technologies. These immersive technologies enabled the expediting patient recovery, optimizing the rehab protocols and easy reintegration of patients in the daily life. The VR presented innovative solutions for COVID-19 rehabilitation. Another framework presented Varela-Aldás et al. [62] helped in providing the social distancing by treating the patients suffering from cognitive disorders. VR application for rehabilitation and therapy at domestic level produced new possibilities such as increasing client involvement, better results and less cost [174]. Immersive technologies presented sophisticated systems models for handling healthcare data. For instance, the VR-based architecture for rehabilitation in the healthcare industry is given in Fig. 12 [137]. This architecture is similar to the other architectures presented by VR in the different healthcare departments but it has extra modules such as a training simulator and rendering engine to support input, processing, and output components. In this architecture, the users' data is given via input with the help of haptic or motion tracking devices or sensors. The input data is processed with the help of processing software and then forwarded to the different modules such as training simulator, Physics simulator, rendering engine and AI-driven performance assessment and feedback. The training simulator module is responsible for implementing VR algorithms. Physics simulator helps in producing the realistic behavior of the virtual objects. While the rendering engine function is to produce 3D graphics. The AI-based performance assessment module helps in assessing the patient performance and tracks the progress by using AI algorithms. The database web server stores data about the users, 3D graphics, patients' profiles, training programs etc. The web admin panel has the functionality to provide access and controlling mechanism to the database.

F. Drug manufacturing and designing

The pervasive nature of immersive technologies also enabled them to contribute in the different areas of pharmacy. The immersive technologies flourished in by providing better molecular biology and drug manufacturing results during the global pandemic of coronavirus. Similarly, immersive technologies allowed the researchers to view the structure of proteins and to understand the effect of the mutation. Immersive technologies have shown more accuracy and efficiency in identifying drug-like ligands than traditional methods such as diversity-oriented and fragment methods. These technologies proved their role in maintenance, drug validation, production standalone or with the support of other technologies. AR technology with artificial intelligence (AI) could address many challenges by supporting workflow solutions that allow efficiency and safety in drug manufacturing and remote collaboration. AR technology also showed major role in repairing, maintaining and identifying the equipment malfunctions visually. VR has been applied

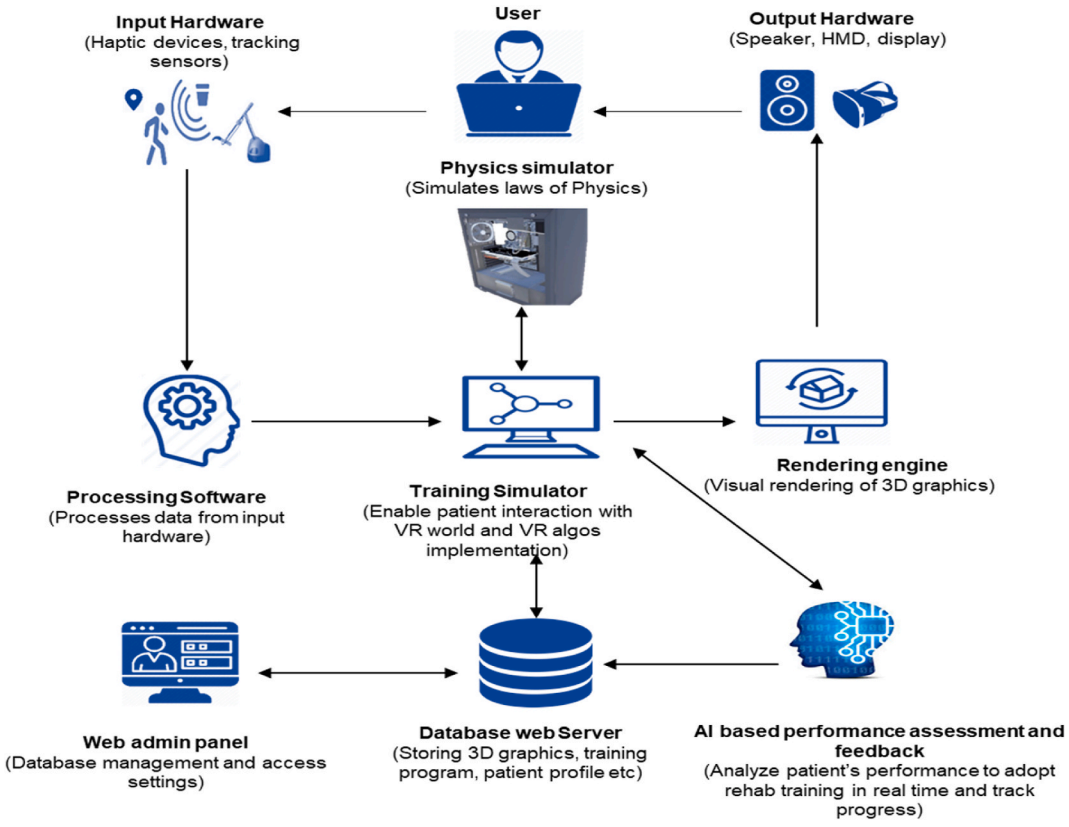

Fig. 12. VR-based architecture for patient rehabilitation.

for molecular visualization, drugs designing and analysis. According to Bristol scientists, VR helped in manufacturing anti-viral drug against the SARS-CoV-2 virus more quickly [177]. The physicians created a VR-based simulated environment to consult patients by checking patients' unpleasant style, venomous drug intake, obesity, metabolic dysfunctions, effects of smoking and drinking on the liver and lungs [135]. During the peak hours of the pandemic, different efforts around the world have been made for drug designing and molecules visualization for binding with SARS-CoV-2 enzymes. In this regard, an open-source framework using VR has been presented. This proposed framework is known as iMD-VR [178] and it provided support to the researchers to visualize and explore the dynamics of molecules of coronavirus enzymes. Scientists found this framework helpful in drug discovery as it brought the collaboration despite remote working and maintaining the social distancing. This framework also assisted the researchers to understand about the drugs fitting into enzymes and their functions. Another immersive technology driven framework was presented by Deek et al. [179] for building protein complexes in flexible ways.

The overall picture of the applications of immersive technologies in dealing with the challenges in the healthcare department during the COVID-19 emergency is given in Fig. 13. In this figure, we see that immersive technologies bring enormous potentials to provide possible solutions to the problems related to the healthcare domain. Immersive technologies provide a set of products, tools and apps to enhance the medical care system in medical education, training, social distancing, stress management, surgery and cognitive rehabilitation during the COVID-19 critical phase.

As, previously mentioned the immersive technologies provided a galore of options such as games, apps, platforms, frameworks, hardware, and various tools that have been applied in the healthcare domain to address the current coronavirus. The immersive technology-based apps played a dominant role in bringing social distancing, training, stress management, awareness, guidance, virtual visits, drug development, meeting and connecting healthcare staff to provide remote treatment during the COVID-19 emergencies. The major applications or the functions of different immersive technology products such as platforms, tools, games, software (apps) and hardware-based solutions in the healthcare sector during the pandemic are given in Table 3.

6. Issues in the application of immersive technologies during pandemic and their solutions

Although, the immersive technologies played a dominant role in healthcare domain during the COVID-19 pandemic but still there are some issues that are needed to be addressed in the mainstream adoption of the immersive technologies to achieve the most optimal medical benefits. The identification of these challenges and limitations [198,199] related to immersive technologies will enable the healthcare decision makers to apply and improve their applications in the healthcare environment. Following are some of the issues along with the proposed solutions affiliated with deployment of the technologies in healthcare.

A. Security and Privacy issues

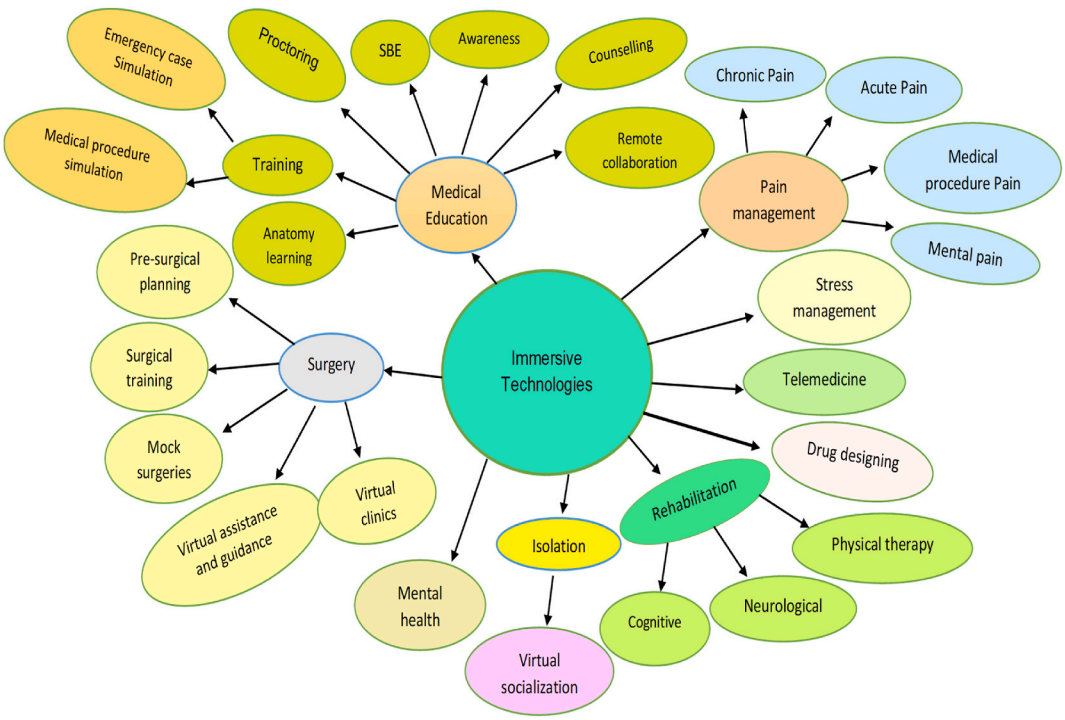

Fig. 13. Applications of immersive technologies in the healthcare industry.

Table 3
Immersive technology products use in the healthcare domain during pandemic.

Product name	Product type	Applications in healthcare	Ref
iMD-VR	Platform	This framework is based on VR tools to foster protein complexes in drug manufacturing.	[179]
Audioshield Thrill of The Fight Pistol Whip Hot Squat Rise to Glory. Holopoint BoxVR Beat Saber Knockout League	Gamification	All these musical games are used during physical exercise and can be used for calorie burning. These games provide a variety of workouts.	[180]
VR Health Exercise Tracker	App	It is the first metabolic testing and calorie tracking app.	
YUR.watch	Smartwatch	It measures heart rate, tracks fitness, and estimates calories.	
HoloAnatomy	App	This app is used to provide training to medical students.	[181]
True3D	Platform	Provides visualization and interaction with patient tissues and users can see holographic images of results.	
Academy's mobile learning (WHO)	App	This app has virtual workshops, guidance, training, sequential procedure for removing PPEs and tools to battle COVID-19.	[182]
Spatial MeetinVR Glue FrameVR Mozilla Hubs Big screen Engage Rumii AltspaceVR	App	These apps are used for meeting with features such as user-friendly, client presentation, multiple platform support, and brainstorming sessions.	[183]
MIND-VR	Platform	This platform is used in Italian hospitals to deal with the stress and anxiety of healthcare workers during the COVID-19 emergency	[167]
VRET	Platform	The platform can be used to tackle the fear and anxiety and remove the fear of being isolated.	[168]
VRHealth	Platform	It innovatively removes hot flashes.	[184]
Proximie	Platform	A tele surgery platform used for incision	[158]
BBC's Civilizations	App	This app brings a virtual museum, views of civilization and cultures in the room during the lockdown.	[185]
JigSpace		A learning app that provides 3D object and figures	
Froggipedia		This app is helpful for medical students to learn about the anatomy of frogs, and fingers can be used for dissection.	
Pokémon Go Ingress Zombies Ghost Snap	Game	AR based game to keep people busy and distracted during COVID-19 lockdown.	
TeamViewer Pilot	App	This App is applied for connecting people anytime, anywhere and anytime.	[186]
Sodar AR AroundMe 1point5	App	Social distancing app to prevent the spread of the COVID-19 and provide isolation. It sends an alert when an infected person gets too closer.	[187]
DEEP VR	Game	The game has applications to control fear and stress by biofeedback mechanisms.	[188]
SoundSelf		It supports and creates mindfulness.	
Healium	App	It monitors the internal wave of the brain and heart rate to control anxiety and stress.	
Psious	Platform	It is applied in Spain to control stress and anxiety by therapy.	
Magic Wand	App	This app helps in buying items without touching them.	[189]
YOU-AR-OK	App	This app is used in Canada to check mental health during COVID-19.	[190]
HoloPatient Remote	App	It allows nursing and medical student to acquire remote virtual training during the pandemic. It is also used for providing remote treatment to patients.	[191]
Holo Lens	Device	A smart healthcare device for viewing X-ray and treating patients.	[192]
Snap Safe lens	App	This is a smartphone-based app that allows users to stay away from each other during the lockdown in the UK.	[193]
Anatomy 4D	App	This is the most suitable app for teaching human anatomy to medical students.	[194]
ARangement-covid	App	It is used for road safety and direction of traffic to keep social distancing.	[195]
CHILzone	Platform	It is used by patients for control and feels relaxed by using 3D printing and tap into creativity.	[196]
PROteinVR	App	VR-based apps are applied for protein 3D visualization in drug manufacturing.	[197]

The application of immersive technologies enabled the researchers and healthcare practitioners to get access to the sensitive data related to the patients. There are potential threats of cyber risks, where the attackers can maliciously get access to the virtual environment and manipulate the user's data. Although immersive technologies provide attractive ways of sharing screen and videoconferencing remotely but they bring new challenges such as server delay and less-security. Therefore, before deployment the institutions should have polices supported by contact agreement with the existing providers [200]. There are very few extended reality (XR) devices existing in the consumer market that are compliance with health regulatory policies [201,202].

- **Possible solution**

While handling the personal and sensitive data related to the patients and avoiding the unauthorized access, Proniewska et al. [203] suggested his solution based on HoloView application that is tailored to run on HoloLens. In dealing with the security concerns the other proposed solution can be reckoned as the HoloView application [203].

B. Cost/Pricing issues

We know that immersive technologies provided innovative and immersive experiences to overcome healthcare issues during the current pandemic, but their prices are still an open issue. According to a survey report the price of manufacturing VR/AR devices led the way [204,205]. Similarly, the XR technologies use complex electronic sensors, networks and displays, which lead to the prohibitive cost factor [206]. Establishing and building VR programs necessitates a hardware of high quality, computer of high speed, efficient VGA cards, precise tracking system, high resolution displays and highly specialized accessories [207]. The immersive technology tools are very expensive such as the expense of high-end HMDs (e.g., Microsoft Hololens has created multiple constraints [200]. Besides, the high-fidelity holographic devices/equipment may be practical and accessing during the and after the Coronavirus pandemic but still its incorporation is hampered by the price issue.

- **Possible solution**

The major applications of immersive technologies have been witnessed around online surgery and medical training. The application of cost-effective VR headsets for the mass access the in medical training is one major example of it. Apart from providing cost-effective options, they have a range of features and functions that can be practically deployed to fulfil an array of educational requirements in the healthcare environment. The suggested list of most popular and low-cost headsets are HTC Vive and Oculus GO [29]. Low-cost headsets like Google Cardboard can also be used with VR and AR technologies for neurosurgery in the low and middle income countries [208]. A wider diffusion of hardware platforms and use of open software might consistently reduce the issues related to the cost of immersive technology equipment. Similarly, a major investment is made in these technologies in the recent times. Similarly, the companies with support of manufacturers are contemplating to develop the most cost-effective VR/AR devices. Sony's VR headset is also recommended as the biggest platform in virtual world because of its low price and preinstalled user base of PlayStation 4 owners [209].

C. Connectivity and network Issues

A high-speed internet connection is of paramount importance to improve the tele-rehabilitation and remote monitoring provided the therapist but in some areas it may not be available [13]. By using the immersive technologies, the margin of latency and error is very marginal in healthcare environment as sensitive data related to patients is transmitted. Similarly, the existing traditional networking technology is not sufficient to provide seamless connectivity to the emerging immersive technology applications. Furthermore, it is uphill task to identify such a network architecture and integrating the most sustainable network functions related to the VR/AR technologies as the traditional network are not sufficient enough to meet the emerging needs of VR/AR technologies. There are also several other challenges related to the networking when it comes to the adoption of VR/AR technologies. This list of these challenges include the identification of required VR/AR interface from the network, caching policies, QoS specification, rate adoption mechanism, transport layer protocols and other security mechanisms [210].

- **Possible** solutions

Addressing network and connectivity issues, it is imperative to provide network based solution that supports new network generation such as 5G with low delay and faster data transmission for VR/AR emerging applications. The overall solution should be based on studying beyond the traditional network domain to integrate the fundamental user navigation of VR data capture, next generation task interaction, encoding and network. Additionally, the consideration needs to be paid out to the advancement regarding way of measuring specifications and also unification, the actual mapping of quality of service (QoS) to quality of experience (QoE) assessment setting and evaluating platform for openly available benchmark data set to expedite the research along with promoting standardization and repeatability. The implementation of 5G network can be very effective for VR landscaping. First, 5G brings new opportunities for VR network such as the peak data rate of 5G is likely to reach 10 Gbps and thus the delay in service will be less than 5 ms which is a major improvement in transmission rate and delay in comparison to 4G [5]. Second, the arrival of new characteristics such as mmWave, edge computing, device-to-device (D2D) communication provide a scalable and adaptive communication mechanism for promoting and deploying VR technologies. Therefore, the significant rise in the performance of VR devices and 5G networks have laid a solid foundation for the adoption and application of VR technologies on huge scale [211]. 5G will bring stability to AR/VR technology by providing opportunity to access the better quality content.

Mobile Edge Computing (MEC) can also be thought as a solution because it is providing 5G network architecture that is supporting the VR application. The MEC server is responsible for holding AR data and object caches to provide high bandwidth, low latency and content delivery [210].

D. Usability and user awareness issues

In major cases the healthcare professionals are unaware about the about the usability on new technologies [212]. Usability is also considered as important challenge related to VR application by clinical researchers in the healthcare environment [198,213]. If the problems related to usability are not identified and addressed by a suitable and targeted evaluation approach then the applications will get sway away from achieving the main goal [213]. It is also important for the clinicians and patients to be aware about the potential consequences of adopting these technologies in the healthcare department. According to the research the COVID-19 virus contaminates after 72 h on surface [214]. Another issue related to using VR equipment or hardware is about "hardware quarantine". If VR/AR hardware equipment is shared among the users or patients, then it is likely the virus can easily be transmitted through this equipment if not handled in a proper way.

- Possible solutions

Before launching any new VR/AR technology or hardware it has to be tested or evaluated in a certain environment by healthcare professionals. The evaluation methods like Heuristics evaluation, Walk-through and user experience evaluation methods can be applied to check the usability and performance issues related to the VR/AR applications [215]. The work presented by Kharoub et al. [216] addressed the usability issues and interface design problems of immersive technologies by using mixed method approach. Similarly, Zhang et al. [217] also suggested various approaches related to the usability assessment of VR applications in healthcare domain. While using VR/AR headsets or other equipment, it is indispensable to disinfect by avoiding the spread of infection. It can be done by using disinfectant wipes along with additional masks. Similarly, decontamination systems can be applied that are using nano-coating and ultraviolet light to offer supplementary benefits [200]. The successful implementation of VR technology also requires that users such as healthcare clinicians and patients must be given a prior training about VR/AR devices for gaining the most productive outcomes.

E. Designing and technical issues

There are technical and designing issues in the mainstream adoption of immersive technologies in the current pandemic. These barriers limit the deployment of VR/AR technologies. Therefore, technical issues require serious attention of the researchers and healthcare professionals to provide better healthcare services during the pandemic and post COVID-19 era. A clear visualization is also

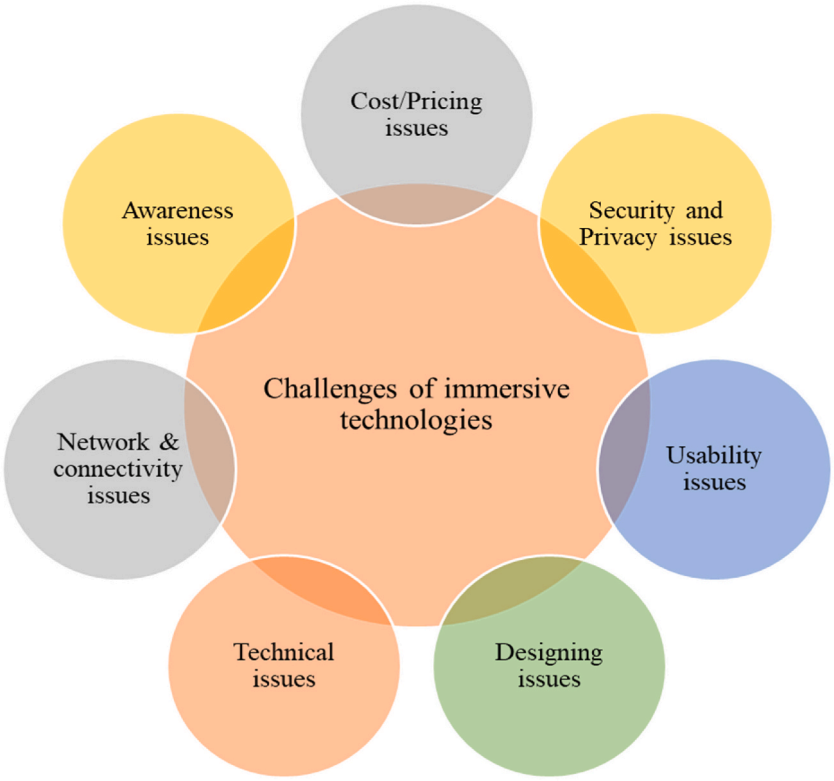

Fig. 14. Summary of the challenges faced by immersive technologies during the pandemic.

a major concern due to the multiple sources of data [218]. The biggest challenge in adoption of immersive technology is related to Field of View (FOV). VR/AR devices have FOV of 90° in comparison to normal human vision such as 120° vertical and 190-degree horizontal. Because, the VR/AR devices must be capturing as much as large FOV to offer better immersive experience. The VR/AR devices such as headsets or eyeglasses become less comfortable with large FOV due to their bulky size such that wearing these devices for prolonged period of time become more irritating. The VR/AR headsets are not designed to keep the immersive experience factors like poor quality of display, lacking acoustics and processing power issues [204]. Some of these challenges are related to the natural part of product design. The other limitations of VR/AR devices are related to brightness, display quality, latency and user experience [204, 207]. Low resolution display is also a major concern in VR system that significantly affects the viewing experience. According to several research studies, it is also observed that VR/AR technologies may also cause vertigo which may arise as a result of physiological conditions in the people [219].

- **Possible solution**

FOV is important for viewing and immersive experience in the healthcare environment. A broader FOV can be considered as the tentative solution to view the projected image in VR/AR devices. It can be easily achieved but viewing experience is affected by screen-door effect. A simple and direct solution of this problem is to increase the resolution of display, however this solution is also hampered by high expenses and transport rate. Bu, still there exists a trade-off between resolution density and FOV [220]. Similarly the work presented by Kharoub et al. [216] can be used to enhance the FOV by providing better user experience and interaction. Mobile VR is also another good simulation approach for providing better immersive experience [221].

The summary of various challenges faced by immersive technologies in the healthcare domain during the pandemic are given in Fig. 14.

7. Discussion

In this discussion, we are highlighting that how the deployment of immersive technology has changed the shape of healthcare sectors and what are the major challenges that need to be considered for the smooth adoption of these technologies. From the findings of this study it is obviously clear that the adoption of cutting-edge immersive technologies amidst the COVID-19 pandemic in the healthcare sector is quite considerably noticeable. Immersive technologies have the potential to present various platforms, architectures, games, apps, and hardware devices to provide medical services and facilities to the people involved in healthcare sector during the peak hours of the pandemic. Immersive technology spectrum contributed to every sphere medical area.

In this study, we observed that immersive technology played a crucial role in providing training to the medical personnel and students in more effective, efficient and innovative ways. As, during the COVID-19, it was hard to continue the teaching and learning of medical education. The immersive technologies had the potential to stimulate the learning by environment by bringing realistic scenario and favorable outcomes. Similarly, immersive technologies also made it possible for the medical experts and surgeons to perform virtual surgery or telemedicine services. In the current COVID-19 pandemic, the application of AR and immersive simulation played the role of catalyst in orthopedic surgery, trauma, and elective surgery. However, the successful adoption of immersive technologies is connected with addressing challenges like high costs, hardware requirements and making major investment in these products. The success of adoption of immersive technologies also hinges around the provision of proper training to medical practitioners. The medical personnel need to understand the current and future applications of immersive technology generally and particularly to deal with challenges caused by the pandemic.

Similarly, immersive technology also has shown remarkable outcomes during its adoption for other healthcare aspects such as mental health, stress management, cognitive rehab, therapy session, neurological and psychological disorders. Immersive technologies brought tailor-made rehabilitation healthcare services in the current pandemic. This technological transformation has shown fast-growing applications for the mental rehabilitation and offered immense ways of treatment and therapy for stroke patients. These immersive technologies enabled the expediting patient recovery, optimizing the rehab protocols and easy reintegration in daily life. The VR presented an innovative solution for COVID-19 rehabilitation. Immersive tech supported the optimizing rehabilitation protocols, accelerating patients' recovery, promoting treatment adherence and easy reintegration into daily life. Immersive technologies presented sophisticated systems for handling healthcare data. The VR-based architecture for rehabilitation in the healthcare industry can provide modules such as training simulator and rendering engine to support for the input, processing, and output components. Immersive technology can be more effective in providing online mental health related sessions, but it still has some security and health regulatory concerns. The usability and adoptability of immersive technologies in the healthcare sector is resisted by awareness issues, budgetary problems, technical problems and hardware quarantine. Similarly, it is also difficult to deploy the right network infrastructure and its integration with these technologies. These different challenges can be overcome by providing good training to the medical staff, using immersive technology supporting better FOV. The application of HolovView devices can be effective in case of budgetary issues.

Social distancing was the only solution to avoid the spreading of the virus. The medical personnel adopted the immersive technologies to provide remote consultation and treatment without getting infected by the virus and maintaining the physical contact. Immersive technologies allowed the medical experts to provide health care services like diagnosis, treatment, in emergency situations. Although, immersive technologies can be proven as game changer due to their multiple purpose support but there are some concerns where the remote treatment can be hampered. These concerns are related to availability of specialized hardware devices for both medical personnel and patients. Similarly, persistent internet connectivity and literacy about using immersive technology is also

essential considerations for providing better healthcare services remotely during the pandemic. For producing better accuracy and immersive experience in the medical diagnosis and treatment, the VR display devices should be designed with large field of view (FOV).

The pervasive nature of immersive technologies made it ideal candidate for the drug development in the pharmacy sector. These technologies flourished by providing better molecular biology and drug manufacturing results during the global pandemic of coronavirus. Virtual reality has been applied for molecular visualization, drugs designing and analysis. The application of immersive technology is resisted by different challenges such as the hardware quarantine which is a major problem of consideration by the various stakeholders in the healthcare setup. Similarly, usability and technical problems are also challenges that require some consideration. These different types of issues can be handled by the hardware testing methods such as evaluation method, heuristics approach and user-experience can be proven effective in judging the usability of these devices. The disinfection of VR/AR devices can also lead to reduce the spreading of COVID-19 virus in the medical laboratories during drugs designing and analysis.

8. Conclusion

A remarkable turnaround has been observed during the COVID-19 in the applications of digital technologies in the healthcare industry. But, the significant contribution of immersive technologies to address the challenges of the COVID-19 emergency in the healthcare domain is noticeable. Immersive technologies already played a dominant role in healthcare in the pre-COVID-19 scenario, but a sharp rise has been witnessed in the adoption of these technologies during the pandemic. The immersive technologies contributed towards the healthcare industry during the COVID-19 outbreak in a different ways to alleviate the effects of a pandemic to much extent. Immersive technologies supporting different apps, hardware platforms, tools, devices, platforms, architectures and with other technologocal support helped in overcoming this pandemic. These technologies covered almost every field related to the healthcare industry ranging from medical training to the cognitive rehabilitation. These technologies enabled healthcare professionals to experience immersive, interactive, 3D modeling, simulation, feedback, collaborative, efficient, effective and flexible means to perform different healthcare tasks during current pandemic of COVID-19. This review clarifies that immersive technologies have lessened the onus on the medicalcare system through creative and innovative ways but there are some limitations affiliated with their adoption that must be addressed prior to take full advantage of them.

In this study, we pinpointed the various application of immersive technologies for all the specturm of healthcare. We also identified some serious challenges and provided solutions to address the impetus in implementing these technologies during the COVID-19 pandemic. Despite of the barriers, the immersive technoloiges due to their pervase nature have the great potential to extend and enhance the healthcare systems during the pandemic and post COVID-19 pandemic. This study is very helpful for healthcare professionals or other stakeholers to understand the current applications and to deal with challenges which may arise in the future pandemics.

Availability of data and materials

All the data generated or analyzed during this study are included and displayed in this article.

CRediT authorship contribution statement

Habib Ullah Khan: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization. **Yasir Ali:** Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Conceptualization. **Faheem Khan:** Writing – review & editing, Resources, Formal analysis, Validation. **Mugahed A. Al-antari:** Writing – review & editing, Validation, Funding acquisition, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mugahed A. Al-antari reports financial support and administrative support were provided by Sejong University. Mugahed A. Al-antari reports financial support, administrative support, and article publishing charges were provided by National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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