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SURVEY

Mobile Devices or Head-Mounted Displays: A Comparative Review and Analysis of Augmented Reality in Healthcare

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ABSTRACT Augmented reality (AR), which combines digital rendering with the real world, has significantly shaped the healthcare system. AR technology can be utilized through a range of devices, broadly grouped into two types: mobile devices and head-mounted displays (HMDs). Mobile devices for AR usually include smartphones, tablets, and smartwatches; on the other hand, HMDs include different models of smart glasses and AR headsets. Each device type offers a unique way to experience AR, making the technology accessible and adaptable for various healthcare applications. However, the differences between using mobile devices and HMDs, and which is preferred under specific conditions, have yet to be determined. To address this, the survey provides a comparative review and analysis of the use of mobile- and HMD-based AR in the context of healthcare. A total of 43 relevant studies published between 2021 and July 2023 were identified from PubMed, ScienceDirect, and SpringerLink based on predetermined keywords and inclusion criteria. Of these, 9 (21%) focused on mobile-based and 34 (79%) on HMD-based AR. We provided a summary for each study, followed by an analysis and comparison of the AR functionalities that drive researchers to adopt the technology, the healthcare purposes researchers aim to address, and the study locations. Additionally, this study summarized the benefits, limitations and challenges, as well as potential future directions for these AR healthcare applications. The objective is to provide a comprehensive overview of both mobile- and HMD-based AR applications in healthcare, which assist individuals in knowing the potential uses of the technology and to aid them in choosing the suitable device for their specific needs.

INDEX TERMS Augmented reality, head-mounted display, mobile devices, comparative review, literature review.

I. INTRODUCTION

Augmented reality (AR), virtual reality (VR), and mixed reality (MR) are revolutionizing contemporary society by merging the boundaries between the physical and digital domains within the broader framework of extended reality (ER) [1]. However, AR, VR, and MR are different with distinct characteristics. VR creates fully digital and simulated environments where users can interact with virtual objects separate from the physical world [2]. This technology is typically accessed through the use of a headset [3]. AR involves superimposing virtual elements onto the real world, which allows users to see both the real world and computer-generated objects simultaneously using mobile devices (i.e., smartphones, tablets, and smartwatches), head-mounted displays (HMDs), computers, or even projectors [2], [4], [5]. MR, on the other hand, combines the elements of AR and VR, enabling users to not only visualize but also interact with virtual objects in a mixed environment between the physical and digital worlds [2]. To ensure an interactive experience, MR is typically achieved using HMDs since they provide superior computational capacities and specialized features.

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Among these technologies, AR has great potential in healthcare [6], education [7], manufacturing [8], marketing [9], and entertainment [10] due to its ability to enhance real-world experiences and its adaptability across different devices. AR became a standard household technology with the release of Pokémon GO, in 2016, on standard mobile devices [11]. In this game, players locate and capture the virtual "Pocket Monsters" at offered real-world locations. This game setting encourages players to navigate the physical world while interacting with virtual elements in the game that can influence their decisions [12]. This was just the beginning of many innovative AR mobile applications, as people started to recognize and harness the significant value of AR beyond the entertainment field. For example, the use of AR mobile applications has become a marketable strategy, attracting user attention, influencing consumer behavior, and enhancing the purchasing experience with products like chocolate bars [13]. This application not only enhances real-world advertising by displaying promotions but also enables users to leave comments and presents a screen that encourages them to dispose of unused chocolate wrappers in trash bins to protect the environment [13]. Furthermore, AR has been sought out for creating novel images and simulations to incite learning in early childhood development [14]. To achieve this, researchers have created an AR mobile application capable of recognizing digital information from images in books, aiding children in grasping complex processes and concepts [14].

As the demand for immersive experiences continues to rise, HMDs have emerged as a pivotal tool in bringing AR to new heights [15]. HMDs often resemble a headset or a pair of glasses, which offer users a more realistic and hands-free interaction with augmented content [15]. A groundbreaking AR HMD device is the HoloLens (1st generation), launched in 2016 by Microsoft [16]. The HoloLens uses a see-through visor to display 3D holographic images and applications in a real environment [16]. The subsequent release of the HoloLens 2 in 2019 brought notable improvements, including enhanced field of view (FOV), improved gesture recognition, and a more user-friendly design [17]. This cutting-edge device has found applications in various industries or as a foundation for improving existing technologies. For instance, research efforts have analyzed the eye-tracking signal quality of the HoloLens 2, revealing recalibration techniques that notably enhance eye-tracking precision and overall signal quality [18]. Another study has implemented the HoloLens 2 in visual mapping applications that included the development of a tabletop map featuring live traffic fluency, weather data, and traffic cameras [19]. Transitioning beyond the HoloLens 1 and 2, various HMD devices such as Google Glass [20], Epson Moverio BT-200 smart glasses [21], VUZIX M400 smart glasses [22], Magic Leap [23], and Apple Vision Pro have been introduced into the AR landscape. This showcases the industry's commitment to pushing the boundaries of AR technology and expanding its potential in diverse applications. Google Glass is a portable and lightweight device that offers voice commands, navigation assistance, and the ability to capture photos [20]. However, the consumer version of Google Glass was discontinued in 2015 mainly due to its privacy concerns [20], and the enterprise edition was discontinued in March 2023. The Epson Moverio BT-200 smart glasses, which are similar to Google Glass, were launched in 2014 with lenses that could each have their own display [21]. The VUZIX M400 smart glasses launched in 2019 differ based on the monocular-see-through design that can be modified based on the user's needs [22]. Magic Leap, Inc. launched their AR headsets, the Magic Leap 1 in 2018 and the Magic Leap 2 in 2022. The Magic Leap 1 is primarily used as a platform for entertainment for early adopters and the development of AR applications for developers [24], while the Magic Leap 2 is positioned as an enterprise-focused AR headset designed and tailored for use in professional and business settings [24]. Besides this, Apple Inc. announced its very first AR headset, the Apple Vision Pro, with a primary focus on entertainment in June 2023, and this product is expected to be available on the market in February 2024 [25].

The healthcare industry has been a key contributor to the further advancements of AR technology [26] because it recognizes the potential to advance medical education [27], improve surgical outcomes [28], enhance medical data visualization [29], and revolutionize various aspects of the industry. An application of AR was used to help medical students throughout their coursework to better understand human anatomy in the biomedical industry [27]. By utilizing AR devices to visualize anatomical structures, medical students can develop a deeper understanding, thereby fostering improved learning outcomes. Additionally, AR technology has been integrated into surgical procedures, offering real-time guidance to surgeons during complex operations [28]. Furthermore, AR-based diagnostic tools and medical imaging applications have revolutionized the way healthcare professionals visualize and interpret patient data, leading to more accurate diagnoses and personalized treatment plans [29]. As technology continues to evolve, the potential applications of AR in healthcare are growing, contributing to more effective and patient-centric healthcare delivery. Due to this, the need to understand the properties and capabilities of AR devices is increasing too. AR devices can be generally classified into two main types: mobile-based devices and HMD-based devices. Mobile devices, such as smartphones, tablets, and smartwatches, offer portability and accessibility but may have limitations in immersive experiences [30]. On the other hand, HMDs require a specialized device purchase but provide a more immersive AR experience with hands-free operation [30]. Given the fact that each type of device contributes unique features and capabilities, it is essential to determine a suitable AR device for specific healthcare applications by knowing its properties and capabilities; conversely, knowing the properties and capabilities of an AR device can inform people about the range of possible applications. However, to the best of the authors' knowledge, there are limited articles that thoroughly compare the distinctions between mobile- and HMD-based AR in healthcare use. Therefore, the objective of this review is to provide a systematic comparison of mobile- and HMD-based AR in healthcare-related studies. Specifically, the research aims to investigate the differences in device functionalities that attract researchers to use them, the healthcare purposes they aim to achieve, and the study locations for mobile- and HMD-based AR applications. It seeks to understand how these differences influence the choice between the two types of AR in healthcare settings. Additionally, this review delves into the applications, hardware, development tools, advantages and limitations of these technologies, as well as their potential impact on the healthcare industry.

II. METHODS

This comparative review largely adheres to the guidelines outlined in the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) reference [31], incorporating most of the administrative information, introduction, and methods.

A. SEARCH STRATEGY

Articles were searched from "PubMed", "ScienceDirect", and "SpringerLink" due to the scopes and paper qualities in medical, engineering, and their related fields, with access dates 07/24/2023, 07/24/2023, and 07/31/2023, respectively. Since this review involves comparing healthcare applications using mobile- and HMD-based AR technology, two sets of keywords were used: ("Smartphone" OR "Tablet" OR "Mobile") AND (Augmented Reality) AND ("Healthcare") represented as K1 for mobile-based AR and ("Head-Mounted Display" OR "HoloLens" OR "Glass") AND (Augmented Reality) AND ("Healthcare") represented as K2 for HMD-based AR. Note that K1 and K2 are the short names or identifiers for the two keywords in the rest of the paper to facilitate easier reference and discussion, shown in Table 1.

B. INCLUSION AND EXCLUSION CRITERIA

We conducted database searches using K1 and K2 keywords and included papers published from 2021 to the day we searched the databases in 2023. The inclusion criteria that determine the eligibility of a paper were: 1) it was a full-text journal or conference paper; 2) it was written in English; 3) it provided clear descriptions of the research question, methods, evaluation, and results; 4) it was related to healthcare; and 5) it utilized mobile- or HMD-based AR technology.

In contrast, a paper was excluded if: 1) it lacked full-text availability or was a review paper, technical note, book chapter, thesis, dissertation, poster, or oral presentation; 2) it was not written in English; 3) it lacked a clear description of the research question, methods, evaluation, or results; 4) it was not related to healthcare; 5) it did not describe mobile- or HMD-based AR, but rather investigated VR or focused on AR technology using other platforms like fixed monitors or projectors for projecting virtual objects into the real world; or 6) it was superseded by later works within the same study, with only the most recent results considered.

C. MATERIAL SELECTION

Following a keyword search in each database, a total of 459 and 377 records related to keywords K1 and K2 were identified, respectively. Figure 1 illustrates the material selection process according to PRISMA [31]. Among the found literature, SpringerLink held the largest number of records, with 272 and 287 identified for K1 and K2, respectively. Besides this, there were 169 records of K1 and 68 records of K2 in ScienceDirect, and 18 records of K1 and 22 records of K2 in PubMed. The identified literature was reviewed to eliminate duplicates, resulting in a total of 421 unique records for K1 and 212 unique records for K2. After removing duplicates, we proceeded to evaluate each paper by thoroughly examining its abstract and considering the inclusion criteria. Literature was excluded if it met any exclusion criteria or did not meet all inclusion criteria. After this, there were 9 (21%) records of K1 and 34 (79%) records of K2 included in this comparative review, which resulted in a total of 43 records.

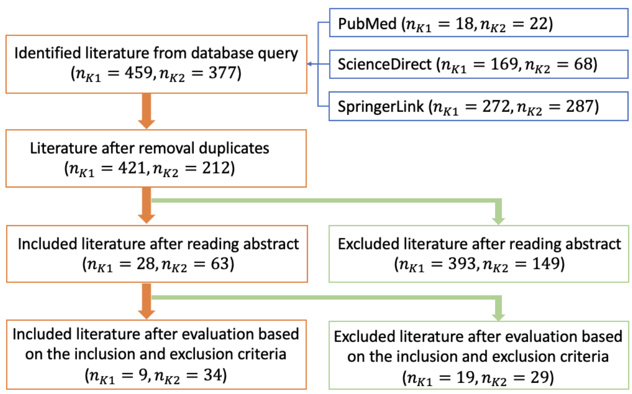


FIGURE 1. Material selection process according to PRISMA [31].

III. RESULTS

This section summarizes the studies and findings of the 9 selected mobile-based AR literature and 34 selected HMD-based AR literature separately, followed by a comparison between them. Table 2 presents the numbers of the included studies by publication year, along with their associated search keywords. Since all the databases were searched in July 2023, the counts were limited to data available up to the access dates in 2023.

A. SUMMARY OF THE MOBILE-BASED AR STUDIES

There were 9 included research studies incorporating mobile-based AR for healthcare applications. Table 3 provides a summary of the studies in terms of publication year, research objective, sample size, the applied functionality of the AR device in the study (AR device functionality), and

TABLE 1. Search keywords and the assigned identifiers.

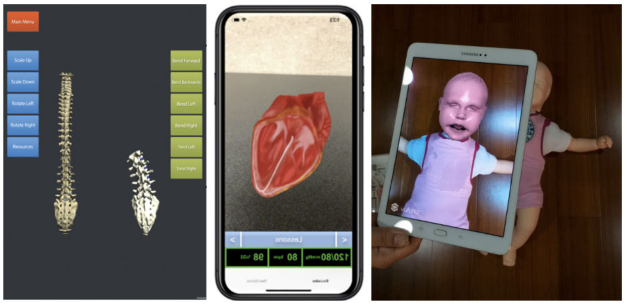
Identifier	Keywords
K1	("Smartphone" OR "Tablet" OR "Mobile") AND (Augmented Reality) AND ("Healthcare")
K2	("Head-Mounted Display" OR "HoloLens" OR "Glass") AND (Augmented Reality) AND ("Healthcare")

TABLE 2. The number of included studies with keywords and their respective counts for the years 2011-2023.

Keywords	2021	2022	2023 (Up to the access dates)	Total
K1	5	2	2	9
K2	13	12	9	34
Total	18	14	11	43

the study purpose related to healthcare (healthcare purpose). The sample size refers to the number of individuals, models, phantoms, cadaver specimens, or measurement runs included in the studies. AR device functionality describes the specific device features that motivate researchers to integrate AR technology into their applications. The healthcare purpose addresses the medical topics or challenges that are solved by research. It is important to note that the AR device functionalities and healthcare purposes were analyzed, summarized, and categorized after a thorough review of all 43 pieces of literature, based on the content of the research and the similarities among the studies. The summarized AR device functionalities and healthcare purposes are discussed in Section III-C. Although the study location is not included in Table 3, this information was also collected, and an analysis of the study locations is provided in Section III-C.

Among the 9 included studies, some investigated the efficacy of mobile-based AR in the treatment and recovery of hospitalized patients [32], [33], [34], [35]. A notable trend was the use of gamification to motivate patients to participate in activities related to physical therapy and stress management during inpatient care [32], [34], [35]. Studies on stress management, specifically conducted with hospitalized pediatric patients, showed improvements in psychological stress through the use of AR books on tablets compared to traditional stress management techniques [35]. Some other studies involved mobile-based AR to aid the patients in performing tasks that were otherwise difficult due to being bedbound [33] or to track progress indicators such as heart rate, steps, duration of use, and hand trembling [34]. Mobile AR systems were also frequently evaluated for their use in healthcare education, where they were commonly employed to visualize 3D anatomical structures or demonstrate procedures that students are expected to perform as healthcare professionals [5], [36], [37]. Such studies investigated fields of healthcare including the visualization of spine movements [36], heart failure [37], and pediatric first aid techniques [5], benefiting physiotherapy and nursing students. Another common feature of these studies is that they developed graphical user interfaces (GUIs) for a better user experience and easier interaction. Figure 2 displays the mobile GUI developed in these studies for education.



(a) (b) (c)

FIGURE 2. Mobile GUIs created in the studies that applied AR to visualize (a) spine movements [36], (b) heart failure [37], and (c) pediatric first aid techniques [5].

The 9 studies incorporated at least 10 smartphones, 5 tablets, and 1 smartwatch with varying specifications as the chosen platforms. Table 4 presents the specified mobile devices involved in the studies with the corresponding specification information, including Central Processing Unit (CPU), Graphics Processing Unit (GPU), resolution, and device release year. The CPU manages the majority of general computing activities, while the GPU is tailored for graphic rendering, with a more robust GPU ensuring smoother, more intricate visuals, and higher frame rates. Furthermore, most devices in the 9 studies run on the Android operating system, except for two iPhones [36], [37] and one iPad [36], which use the iOS operating system, and a smartwatch [34] powered by the WearOS operating system. Note that some devices are not included in Table 4 due to the lack of specified model details in the literature.

In addition to hardware, the development tools including game engines, software development kits (SDKs), and libraries used in the development of mobile applications or programs were also summarized if this information was explicitly provided. This was done to gain a deeper understanding of the development process and the functionalities of the delivered outcome. Table 5 outlines the development tools discussed in all the included studies. They are categorized into three sections: those used in both HMD- and mobile-based studies, those only used in mobile-based studies, and those only used in HMD-based studies.

TABLE 3. Summary of studies adopting AR on mobile devices.

Ref	Year	Research objective	Sample size	AR device functionality	Healthcare Purpose
[35]	2021	To evaluate the impact of reading AR books on salivary cortisol levels in hospitalized pediatric patients in comparison to reading traditional children's books	29 children aged 7-11 and 1 lost during follow up	3D visualization	Assistive system
[33]	2021	To create a multimodal interaction system that allows users to control service robots and devices via touch, eye movements, gestures, voice commands, and AR controls, using a robotic arm equipped with a tablet PC	12 individuals aged 22-54 to test the usability of the AR related feature	Information display; Computer vision and control	Assistive system
[38]	2023	To develop and evaluate an application named MyFootCare for the self-monitoring of diabetes-related foot ulcers	12 patients	Information display; Computer vision and control	Assistive system
[36]	2021	To introduce a vision-based mobile application for instructing students on spine anatomy and accessory movements, as well as to investigate student experiences and engagement with the application	74 final year physiotherapy students	3D visualization	Medical education and training
[37]	2021	To develop an AR application for remote heart failure training for nursing students, and to assess its effectiveness in comparison with traditional recorded video lectures.	14 (control group) and 19 (experimental group) participants	3D visualization	Medical education and training
[5]	2023	To assess the impact of an AR application created for pediatric first aid training on the knowledge and skill proficiency of nursing students	46 nursing students and 49 in control group	Information display	Medical education and training
[32]	2021	To introduce an innovative collaborative framework designed to synchronize shared experiences among multiple AR devices. This framework enables mutual detection and interaction between devices to promote physical activity through gamified scenarios for pediatric patients	N/A	Interactive gaming/ simulation	Gamified scenarios for patients
[34]	2022	To enhance users' physical activity levels and to facilitate regular assessments of their health and cognitive well-being by adopting AR gamification techniques. These techniques engage users in challenges and quests within both virtual and real-world contexts.	18 users aged 20-40 and 15 users aged 40-60	Interactive gaming/ simulation	Gamified scenarios for patients
[39]	2022	To enhance the precision of scalpel placement and depth control for surgeons in External Ventricular Drainage (EVD) surgery by using AR. This improves both the efficiency and intuitiveness of the surgical procedures	4 patients requiring EVD surgery	3D visualization	Surgical assistance

TABLE 4. The smartphone and tablet devices utilized as the AR operating platforms in the included studies (as referenced in Ref).

Ref	Model	CPU	GPU	Resolution	Release Year
[33]	Samsung Galaxy S7	Exynos 8890 Octa	ARM Mali-T880 MP12	1440 x 2560	2016
[34]	Samsung Galaxy A7 2018	Exynos 7885	ARM Mali-G71	1080 x 2220	2018
[38]	Samsung Galaxy S8	Exynos 8895	ARM Mali-G71 MP20	1440 x 2960	2017
[34]	Samsung Galaxy A20	Exynos 7884	ARM Mali-G71 MP2	720 x 1560	2019
[33]	Huawei P9	HiSilicon Kirin 955	ARM Mali-T880 MP4	1080 x 1920	2016
[33]	Huawei Honor 8	HiSilicon Kirin 950	ARM Mali-T880 MP4	1080 x 1920	2016
[34]	Huawei P20 Lite	HiSilicon Kirin 659	ARM Mali-T830 MP2	1080 x 2280	2018
[32]	OnePlus 6T	Qualcomm Snapdragon 845	Qualcomm Adreno 630	1080 x 2340	2018
[34]	TCL 20 5G	Qualcomm Snapdragon 690 5G	Qualcomm Adreno 619L	1080 x 2400	2020
[37]	iPhone 10	Apple A11 Bionic	Apple GPU (3 core)	1125 x 2436	2017
[39]	Samsung Galaxy Tab S5e	Octa-core Qualcomm Snapdragon 670	Qualcomm Adreno 615	1600 x 2560	2019
[32]	Samsung Galaxy Tab S4	Qualcomm Snapdragon 835	Qualcomm Adreno 540	1660 x 2560	2018

The development tools adopted in AR studies using mobile devices can be found in the first two sections. To be specific, 3 studies illustrated that Unity was applied for building 3D environments in which the AR experience took place [5], [32], [39]. ARCore developed by Google first launched in 2018 was widely used for AR application developments on Android devices due to its compatibility [32], [34]. Similarly, Apple first introduced ARKit in 2017 for creating AR content and experiences on iOS devices, which was implemented in the study using an iPhone 10 [37]. Unlike ARCore and ARKit, which create AR experiences on specific platforms, Vuforia, capable of running on various operating systems such as Android, iOS, and Universal Windows Platform, was also used in some studies [5], [33]. Furthermore, OpenCV is an open-source computer vision library for various computer vision tasks such as image processing, image stitching, and object recognition. There was 1 mobile-based study that utilized OpenCV to monitor the patient's health condition through visual indicators, such as the size of diabetes-related foot ulcers [38].

B. SUMMARY OF THE HMD-BASED AR STUDIES

Out of the 43 included studies, 34 adopted HMDs as the AR platforms for healthcare purposes, with summaries available in Table 6. Over half of the studies have examined the use of HMDs in surgical settings, particularly focusing on their role in surgical assistance, such as navigation and guidance during surgeries, as well as in intraoperative planning [4], [40], [42], [44], [46], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60]. A common thread throughout the studies was the superposition of patient data into the surgeon's view to eliminate the need for the surgeon to look up from the patient during the operation to view the data on a traditional screen. Many researchers followed a methodology of having the surgeon choose tool, incision, and suture locations within a preoperative planning phase. The surgeon would then conduct the surgery on a phantom patient model, and an AR application would project the planned locations onto the patient to guide the surgeon through each step of the procedure. Several studies also evaluated the fusion of AR with robot-assisted surgery to give the surgeon a view of the process unobstructed by the robot [40], [44], [55]. Moreover, nearly 40% of the studies investigated the use of HMD-based AR in various types of medical education and training [41], [43], [45], [47], [61], [62], [63], [64], [65], [66], [67], [68], [69]. These studies evaluated the effectiveness of an AR application, often involving interactive 3D models of anatomical structures, in comparison to traditional instructional methods like lecturing and textbook materials. Figure 3 illustrates the common study designs followed in these studies. Of these, some studies focused on the use of AR in learning medical procedures, in which the AR application is a simulation of a medical procedure and the learner was tasked with performing the steps of the procedure by following guided prompts. A noteworthy subset of procedural education studies has concentrated on nursing education. Within this domain, nursing students were immersed in scenarios featuring simulated patients, tasked with applying precise nursing care specialized to the presented symptoms or conditions [63], [64]. Many other studies have found that AR learning enhances learning outcomes compared to conventional methods. This includes increased motivation to learn, higher self-confidence in the acquired abilities, and a greater capacity to apply learned procedures in clinical settings [62], [64], [67]. However, researchers also concluded that AR education tools need further refinement and pre-learning orientation on the use of AR devices, which is necessary for students to properly utilize these tools [65].

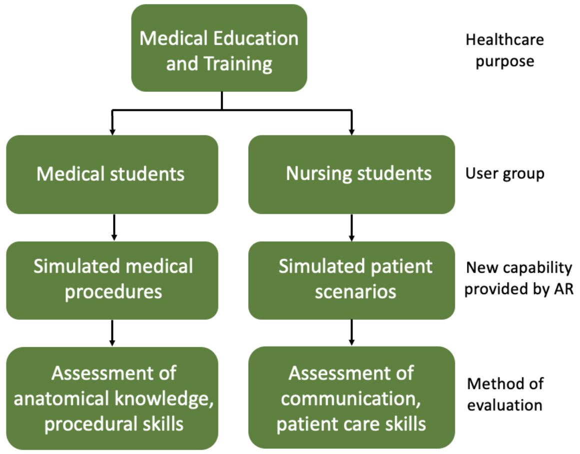


FIGURE 3. Common study designs for applying HMD-based AR in medical education and training.

The included HMD-based studies consisted of at least 6 different models of HMDs including HolenLens 1 and 2, Magic Leap 1, VUZIX M400 Smart Glasses, Epson Moverio BT-200 Smart Glasses, and HTC Vive. The hardware specification information of the devices is provided in Table 7. This includes CPU, GPU, display resolution, release year, horizontal FOV, and weight. Any unclaimed models mentioned in the paper, such as the HTC Vive, were not included in the table. Like mobile devices, the performance of HMDs also depends on the efficiency of the CPU and GPU. A powerful CPU ensures efficient handling of data, while a high-performance GPU is crucial for rendering complex graphics in real-time [72]. Higher-resolution displays enhance visual clarity and contribute to a more realistic AR experience [73]. A wider FOV creates immersive environments by seamlessly integrating virtual elements into the user's natural vision [72]. Additionally, the weight of the headset directly impacts user comfort and overall usability [72]. HoloLens 2 is the most commonly used HMD in the 34 studies. As for the development tools, besides Unity, Vuforia, and OpenCV, there were others exclusively utilized in the HMD-based studies shown in Table 5.

C. COMPARISON BETWEEN MOBILE- AND HMD-BASED AR STUDIES

The comparison between the AR studies employing mobile devices and HMDs in healthcare begins with the AR functionalities, healthcare purposes, followed by comparing the study locations. The AR device functionalities describe the specific features that motivate researchers to integrate AR technology into their applications. We categorized the AR device functionalities into 5 large categories after reading all the studies: 1) interactive gaming/simulation, 2) 3D visualization, 3) information display, 4) computer vision and control, and 5) remote communication and rendering, as shown in Figure 4. Interactive gaming/simulation indicates adding elements of interactivity, immersion, and engagement to gaming experiences and simulations by applying AR

TABLE 5. The development tools including game engines, SDKs, and libraries incorporated in the studies, along with the compatible platforms where they can be employed, descriptions, and key features of the tools.

Ref	Development tools	Platform	Description	Key features of the development tools
Used in HMD- and mobile-based studies				
[5], [32], [39]–[44]	Unity	Cross-platform	A game engine and development platform for creating 3D content and immersive experience	Real-time rendering Animation Simulation
[5], [33], [43]	Vuforia	Cross-platform	An SDK for creating AR applications and software that supports various system	Object recognition Object tracking
[38], [45], [46]	OpenCV	Cross-platform	An open-source computer vision library	Image processing Object tracking
Used only in mobile-based studies				
[32], [34]	ARCore	Android	Known as Google Play Services for AR, an SDK for creating AR software and applications	Motion tracking Scene understanding
[37]	ARKit	iOS	Apple's SKD that enables AR application and experiences development	
Used only in HMD-based studies				
[45]	DirectX	Windows	An Microsoft application programming interface for developing graphics, audio, and multimedia applications.	Graphics rendering Audio processing Multimedia playback
[46]	The Visualization Toolkit (VTK)	Cross-platform	An open-source library for creating 3D data visualization and manipulation applications.	Data visualization
[46]	Insight Toolkit (ITK)	Cross-platform	An open-source software library primarily used for image segmentation and image registration.	Image registration Image segmentation Medical Image processing
[46]	Grassroots DICOM	Cross-platform	An open-source software library and toolkit designed for working with DICOM (Digital Imaging and Communications in Medicine) files and medical image data.	DICOM file support DICOM data parsing
[46]	Qt	Cross-platform	A development toolkit for software development that generates applications and GUIs.	Application development Software development GUI development
[42], [43], [47]	Windows Mixed Reality Toolkit (MRTK)	Windows	An open-source development toolkit created by Microsoft for the development of VR and AR applications.	Application developement Gesture recognition Spatial mapping
[48]	COLMAP	Linux, iOS, Windows	Short for Structure-from-Motion and Multi-View Stereo Community, a pipeline for 3D reconstruction from images.	3D reconstruction

technology. Another typical use of AR is to visualize a 3D object in the real world (3D visualization), enabling users to gain a better understanding of its spatial relationship or structure. Differing from 3D visualization, information display refers to applications that present text, instructions, or guidance in the real world, which were not necessarily in 3D. Computer vision and control describes the use of AR devices for tasks such as image analysis, object detection, object tracking, position optimization, and other control-related functions. Lastly, several studies have utilized AR as a remote communication and rendering tool, which enabled participants to conduct discussions and meetings remotely while viewing the same scene simultaneously through platforms like Zoom. The AR device functionality for each study has been categorized and can be found in Tables 3 and 6 under the column "AR device functionality". Note that a study could be grouped into multiple AR functionalities if it meets the definitions. After analyzing the AR device functionalities, we found that 3 (25%), 4 (33%), 3 (25%), 2 (17%), and 0 (0%) mobile-based applications, as well as 1 (3%), 18 (50%), 10 (28%), 3 (8%), and 4 (11%) HMD-based applications, fell into the 5 categories following the order described above, respectively, as shown in Figure 5a. Among the functionalities, 3D visualization and information display are the two most common reasons that both mobile- and HMD-based studies implemented AR technology. Interestingly, 25% of the mobile applications applied AR for interactive gaming/simulation, but only 3% of the HMD applications did it. Another observation is that 11% of the HMD applications were inspired to achieve remote communication and rending, but none of the mobile studies pursued this. Additionally, 2 mobile-based studies and 3 HMD-based studies adopted the AR technology for computer vision and control. Since there are fewer included studies using mobile devices compared to HMDs, a greater proportion of mobile-based applications (17%) focused on computer vision and control compared to HMD-based applications (8%).

The second trait under comparison is the healthcare purpose served by AR technology. The healthcare purpose

TABLE 6. Summary of studies adopting AR on HMDs.

Ref	Year	Research objective	Sample size	AR device functionality	Healthcare Purpose
[49]	2021	To explore an AR application in craniofacial surgery, with a specific focus on real-time monitoring for the treatment of fibrous dysplasia.	N/A	3D visualization	Surgical assistance
[59]	2022	To assess the feasibility of using AR as a single-step method for cosmetically reconstructing bony defects in the facial skeleton and skull base.	3 experienced neurosurgeons and 6 neurosurgery residents	3D visualization	Surgical assistance
[4]	2021	To introduce a collaborative holographic AR interface that superimposes dynamic internal behavior and planned trajectory information onto surgical scenarios.	1 surgeon	3D visualization	Surgical assistance
[51]	2023	To enhance the precision and efficiency of osteotomy and root-end resection surgeries in endodontics by using an AR device with a 3D dynamic navigation system.	72 3D-printed mandible models	3D visualization	Surgical assistance
[53]	2022	To investigate the efficacy of visualizing 3D single-photon emission computed tomography (CT) and CT imaging data using HMD.	8 styrofoam phantoms and 3 physician evaluators	3D visualization	Surgical assistance
[46]	2023	To compare the AR-assisted navigation system to the conventional method for lumbosacral transforaminal epidural injections, a standard treatment for spinal radiculopathy.	A torso phantom	3D visualization	Surgical assistance
[55]	2022	To develop an AR application that allows for real-time adjustment of intraoperative plans. This application provides surgeons with intuitive visualization of virtual objects overlaid onto real-world surgical sites and anatomy.	N/A	3D visualization	Surgical assistance
[56]	2022	To evaluate the feasibility of using AR for resective maxillary osteotomies in the context of tumor resection in the oral and maxillofacial region.	3 patients with a mean age of 54 years old	3D visualization	Surgical assistance
[40]	2021	To replicate the user interface of an existing surgical robot within an HMD worn by clinicians in orthopedic surgery.	10 clinical surgeons	Information display	Surgical assistance
[50]	2022	To evaluate the safety and feasibility of using AR in comparison to conventional LCD displays in cardiac catheterization procedures.	50 patients using AR and 232 in control group.	Information display	Surgical assistance
[54]	2021	To investigate the application of Hololens 2 device with inside-out tracking in the context of spine surgeries.	2 spine surgeons, 2 engineers, and 8 lumbar cadaver specimens	Information display	Surgical assistance
[42]	2022	To develop and evaluate an AR platform for real-time patient monitoring during surgical procedures.	2 experimental sessions, each consisting of 5 measurement runs.	Information display	Surgical assistance
[58]	2021	To compare the angular accuracy of pedicle screw placement with and without AR navigation.	2 cadaver specimens	Information display	Surgical assistance
[60]	2023	To pilot a HoloLens program to provide expert intraoperative guidance to a Ugandan surgeon in a rural area with limited access to advanced surgical expertise.	1 Ugandan surgeon performing six cases	Remote communication and rendering	Surgical assistance
[48]	2023	To create an AR surgical navigation workflow that continuously corrects for misaligned visualization of registered overlays.	5 users with each placing pins on six glenoids	Computer vision and control	Surgical assistance
[43]	2021	To develop a new suture training system for open surgery to address the limitations of existing training methods by providing trainees with comprehensive information through AR technology.	2 experts performed 5 times for each shape	Information display	Surgical assistance; Medical education and training
[61]	2022	To develop and evaluate an AR assessment tool for anatomical knowledge.	10 students and 6 experts	3D visualization	Medical education and training
[45]	2021	To investigate the potential of combining HMD with haptic feedback from a biopsy phantom to create a realistic simulation of CT-guided medical procedures, which can improve the quality and effectiveness of medical training while remaining cost-effective.	4 trainers and 12 trainees	3D visualization	Medical education and training

TABLE 6. *(Continued.)* **Summary of studies adopting AR on HMDs.**

[62]	2023	To investigates the impact of AR on osteopathic medical student engagement in a 90-minute immersive learning session for anatomical education.	120 students	3D visualization	Medical education and training
[67]	2022	To introduce 2 AR educational tools, VIPER and ARTUR, for patient and student education in radiographic positioning, with a focus on resource efficiency, enhanced engagement, and self-paced learning.	N/A	3D visualization	Medical education and training
[63]	2023	To assess the effectiveness of using an AR device in nursing education, where students interacted with a simulated COVID-19 patient.	30 senior nursing students	3D visualization	Medical education and training; Infection prevention
[68]	2022	To develop an innovative teaching tool that utilizes AR and 3D printed models to provide an accurate and immersive demonstration of norsmal anatomy.	N/A	3D visualization	Medical education and training
[64]	2021	To assess the impact of an immersive 3D interactive video program on the competency of nursing students in nasogastric tube feeding.	45 students with 22 using AR and 23 in control group	Information display	Medical education and training
[65]	2022	To develop and evaluate an HMD system, named AR-CPR, designed to enhance pediatric chest compression performance during cardiopulmonary resuscitation.	28 subjects	Information display	Medical education and training
[41]	2022	To assess the effectiveness of using AR in enhancing adherence to newborn life support guidelines during simulated neonatal resuscitation scenarios.	29 healthcare professionals	Information display	Medical education and training
[66]	2023	To compare 3 different online teaching modalities, clinical case vignettes, patient-testimony videos, and AR teaching using the HoloLens 2, in terms of their impact on knowledge attainment and engagement levels.	252 third-year students	Remote communication and rendering	Medical education and training
[69]	2021	To investigate the use of HoloLens 2 for remote geriatrics teaching to address the growing demand for geriatricians and decreasing student interest in the field.	1 patient and final-year medical students at Imperial College London	Remote communication and rendering	Medical education and training
[47]	2022	To validate the use of AR as an objective tool for evaluating surgical skills through hand and eye tracking.	36 participants performed 4 simulated surgical tasks	Computer vision and control	Medical education and training
[57]	2021	To explore the transformative potential of AR in preoperative planning and intraoperative support for advanced gastrointestinal tumors.	8 patients	3D visualization; Remote communication and rendering	Preoperative planning
[44]	2023	To apply AR to visualize the robot's workspace on a 2D screen by redesigning the system to automatically calculate the optimal robot-patient configuration using rotational workspace and trocar locations.	8 surgical scenarios with varying number of required ports.	3D visualization; Computer vision and control	Preoperative planning
[52]	2022	To apply AR to enhance the understanding and treatment of femoral neck fractures in middle-aged adults.	156 patients	3D visualization	Preoperative planning
[70]	2023	To compare the functionality of 2 HMD-based AR devices for visualizing 3D medical imaging data from the Verima suite.	12 medical personnel	3D visualization	3D medical image visualization
[16]	2021	To assess the use of the HoloLens 2 in a renal medicine ward during the COVID-19 pandemic.	9 patients and 7 staff	Remote communication and rendering	Infection prevention
[71]	2021	To assess an AR-based balance training using Microsoft HoloLens in older adults with impaired balance.	7 older adults aged 66–88	Interactive gaming/ simulation	Assistive system

refers to the specific medical topics or challenges that the research aimed to address and solve. We classified the purposes into 7 categories: 1) surgical assistance, 2) gamified scenarios for patients, 3) assistive system, 4) medical education and training, 5) 3D medical image visualization; 6) preoperative planning; and 7) infection prevention, as shown in Figure 4. Surgical assistance includes surgical guidance, navigation, localization, intraoperative

TABLE 7. The HMDs utilized as the AR operating platforms in the included studies (as referenced in Ref).

Ref	Device	CPU	GPU	Resolution	Release year	Horizontal FOV	Weight
[40], [41], [49], [53], [58], [61], [67]	HoloLens 1	Intel Atom x5-Z8100	Holographic Processing Unit	1280 x 720	2016	30 °	579g
[4], [16], [42], [43], [45]–[48], [51], [52], [54]–[57], [62], [63], [66], [68]–[70]	HoloLens 2	Qualcomm Snapdragon 850	Adreno 630	2048 x 1080	2019	52 °	566g
[44], [59], [70]	Magic Leap 1	NVIDIA Parker SOC	NVIDIA Pascal	1920 x 1280	2018	50 °	316g
[65]	VUZIX M400 Smart Glasses	Qualcomm Snapdragon XR1	Adreno 540	640 x 360	2019	16.8 °	182g
[21]	Epson Moverio BT-200 Smart Glasses	TI OMAP 4460	PowerVR SGX540	1920 x 540	2014	23 °	88g

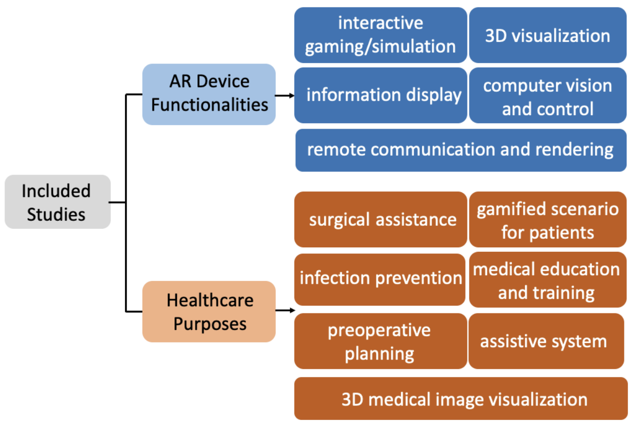


FIGURE 4. The included studies categorized based on the AR functionalities and healthcare purposes.

visualization, and personnel assistance during surgeries. Specifically, surgical guidance, navigation, and localization empower surgeons with invaluable tools to navigate the complexities of the human body and locate target structures; surgical intraoperative visualization provides surgeons accurate and detailed images of the surgical field during a surgery; and surgical personnel assistance uses AR to provide remote labor support to surgical teams. Gamified scenarios for patients refer to the use of game elements in healthcare settings to increase engagement. Assistive systems are designed to help patients accomplish specific tasks. Medical education and training refer to the educational process that people undergo to become doctors, nurses, and other healthcare providers. Unlike the surgical intraoperative visualization, 3D medical image visualization focuses on viewing the medical image in 3D, which does not take place during a surgery. Preoperative planning is used to describe the preparation and evaluation before a surgical procedure. Infection prevention involves the strategies used to prevent and control the spread of infections. Similar to AR device functionality, a study could be classified into multiple healthcare purpose categories if any definition has been satisfied. Figure 5b shows the proportions of the different healthcare purposes in mobile- and HMD-based studies. To be specific, there were 1 (11%), 2 (22%), 3 (33%), and 3 (33%) applications that focused on surgical assistance, gamified scenarios for patience, assistive system, and medical education and training using mobile devices, respectively. No mobile-based studies served the remaining purposes. In contrast, HMD devices were incorporated for a wider range of purposes compared to mobile devices. The only summarized healthcare purpose not found in the HMD studies was gamified scenarios for patients, while 22% of the mobile studies were developed for this purpose. Medical education and training is the purpose that most studies served in both mobile and HMD-based groups. However, one-third of the mobile studies focused on assistive system, while only 3% of the HMD studies had the same purpose.

Another factor that was compared between mobile-based and HMD-based studies is the study location, analyzed by continent. Despite the diversity in culture, societal norms, and healthcare systems within the same continent, there tends to be a general similarity among them when compared to those from different continents. By comparing study locations on a continental basis, we can better understand if regional factors influence the development and application of mobile- and HMD-based AR solutions in healthcare. Figure 5c illustrates the number of included studies conducted on individual continents. Among the studies, 4 (44%) mobile-based literature were conducted in European countries, 2 (22%) in Asia, and 1 (11%) each in North America, the Pacific, and South America. There were 18 (53%) HMD-based studies in Europe, 8 (24%) in Asia, 6 (18%) in North America, and 2 (6%) in the Pacific. Since some of the categories only contain 1 study, we didn't apply the chi-square test to compare the distribution. However, in both mobile- and HMD-based studies, most were conducted in Europe and Asia followed as the second, and no substantial difference was found.

IV. DISCUSSION

The identified studies clearly demonstrate that people recognize the potential and value of AR technology in healthcare. In addition to discussing the use of the technology, these studies also highlighted its benefits and limitations/challenges in the field.

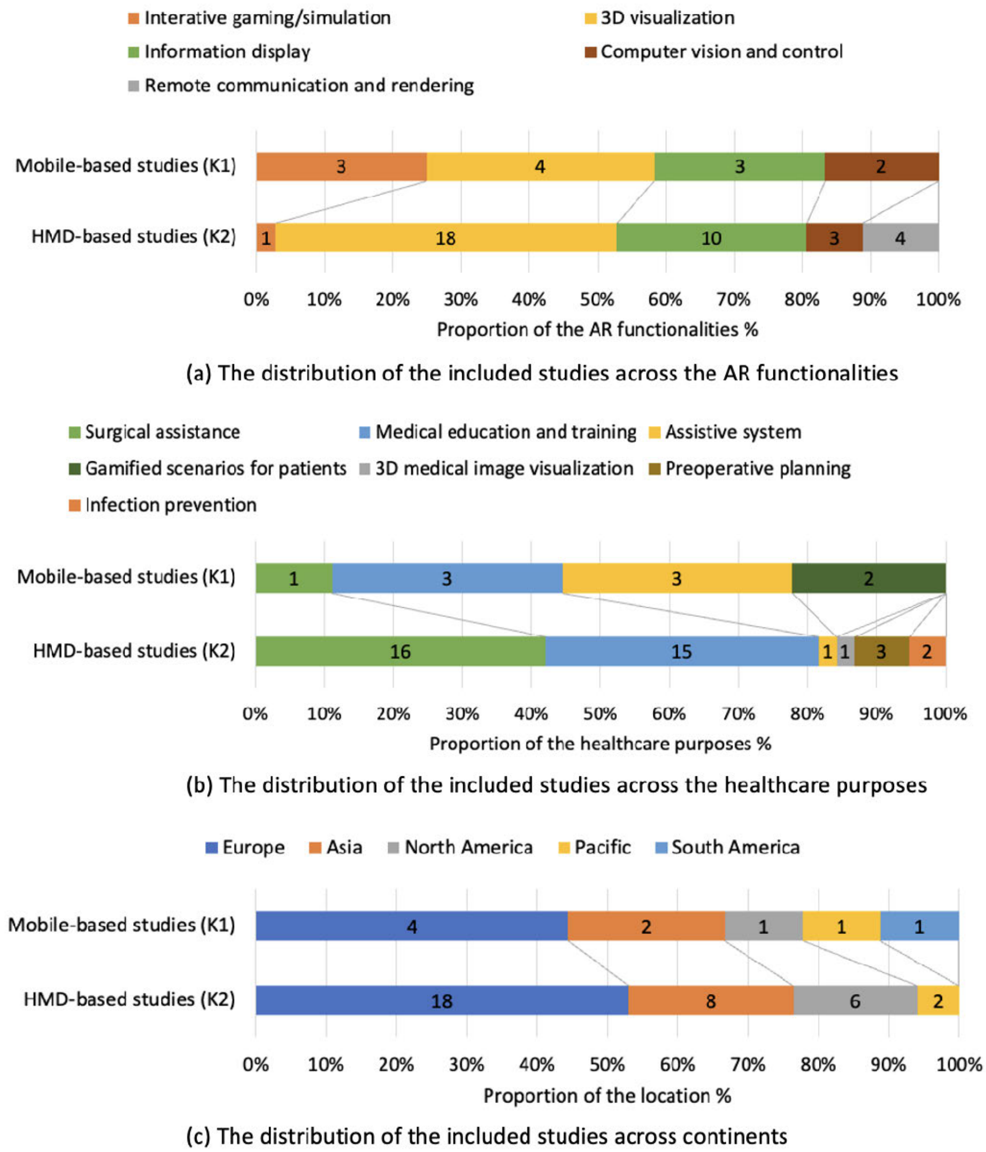


FIGURE 5. **The distribution of the selected studies across the categorized AR functionalities, healthcare purposes, and the study locations.**

A. BENEFITS

The advantages of AR using HMDs and mobile devices largely overlap, with only four recognized exceptions. Among these, three represent advantages unique to HMD-based AR, and one represents an advantage unique to mobile-based AR. The first unique feature of AR using HMDs is permitting free-hand movement [39]. This is due to the inherent nature of the two distinct types of devices - HMDs are head-mounted and do not require users to hold them in their hands, whereas mobile devices are typically handheld unless a stand is employed. The hands-free capability enables surgeons to visualize valuable information as they perform surgeries [4], [51], [58]. Therefore, if someone is considering adopting AR in a procedure that requires hand movement for other tasks, HMDs are the preferred option over mobile devices. The second advantage of using HMDs is their more immersive experience compared to mobile devices, attributable to the direct integration into the user's visual space [45]. Lastly, since only HMD-based studies have achieved remote communication and rendering shown in Figure 5a, the benefits associated with this functionality are exclusive to HMDs based only on the included studies. This functionality was applied during the pandemic to conduct faster and more efficient ward rounds, which helped reduce the risk of infection exposure for healthcare staff [16]. Remote communication of AR devices also enables experts to provide remote assistance to surgeons located in developing countries [60]. The benefit exclusive to mobile-based AR is its portability and light weight. Although not explicitly highlighted in the literature, studies involving HMDs have acknowledged that the weight of HMDs has caused discomfort and pain for users [64], while none mobile-based studies reported this.

There are also numerous benefits to adopting either mobile- or HMD-based AR in healthcare. One of the benefits is its capability to offer 3D visualization [4], [35], [36], [37], [39], [44], [45], [46], [49], [51], [52], [53], [55], [56], [57], [59], [61], [62], [63], [67], [68], [70]. The ability to visualize an organ or tissue in 3D provides intuitive information to surgeons. This, in turn, facilitates the rapid location of the target [39], enhances a surgeon's confidence in decision-making [52], [57], reduces procedure time [53], [54], and improves surgery efficiency, precision, and quality [39], [46], [48], [49], [51]. In a study that compared using AR and standard liquid crystal display in diagnostic right heart catheterizations and coronary angiography, researchers observed that the use of AR's 3D visualization capability decreased fluoroscopy time and radiation exposure [50]. Even when the displayed object is not in 3D, such as when simply showing guidance in text on the display or mobile screen, the use of AR can still aid in understanding, especially in medical education and training [5], [41], [65]. Studies have indicated that incorporating AR into the classroom can enhance adherence to guidelines, thus reduce the time to develop skills for students [65]. The novel technology also boosts motivation for both patients and medical students. For example, gamified scenarios created for patients encourage increased physical activity, promoting a healthier lifestyle [34]. Medical students also expressed satisfaction and a preference for AR technology over traditional teaching approaches due to the motivation it provides [37], [64]. Additionally, the use of AR enables an easy data or information collection approach, and the data may be valuable for people involved. For instance, patient interaction data collected as they use the AR application to encourage more physical activities can be sent to doctors for monitoring, analysis, and evaluation [32], [34]. Medical students can capture screens or record videos during the learning process using AR devices, which allows them to learn at their own pace and on their own schedules [36]. On the other hand, instructors can gather quantitative data to enhance their teaching methods and provide objective feedback [5]. In the assessment of surgical skills, instructors traditionally offer direct observation and feedback to students, which can be potentially subjective. Therefore, obtaining objective data through hand and eye tracking from AR technology is beneficial to medical education [47].

B. LIMITATIONS AND CHALLENGES

This section highlights various constraints and issues associated with implementing mobile- and HMD-based AR technology in healthcare. Note that the limitations and challenges mentioned in this section primarily pertain to AR technology and device use, rather than the study design or setting.

Despite the positive outcomes reported in existing studies, both mobile- and HMD-based studies admitted that significant challenges need to be addressed for AR technology to become a standard platform in clinical settings. This is because the clinical setting demands that the device be both reliable and stable to ensure patient safety and demonstrate usability. However, the current research outcomes do not strongly support its widespread adoption due to the potential integration issues [5], [32], [36], [38], [39], lack of usability evaluation [39], as well as various operational and technical challenges [4], [33], [49], [56], [66]. For example, in a study introducing a novel architecture allowing bedbound patients to control lighting, shutters, and bed position in their hospital rooms by using AR on mobile devices and smart glasses, the limitations were linked to the reliance on wall-mounted markers and sensing range of the devices. This setup made users to approach the wall for interaction, hindering the seamless integration of AR technology for patients confined to their beds [33]. In another study exploring the use of Magic Leap 1 for single-step repairs of facial skeleton and skull base defects, the manual alignment of real objects with holographic projections needed readjustment for each attempt [59]. This was not only time-consuming but also a potential source of error. Furthermore, although AR applied in medical education and training does not require the same rigorous requirements as in clinical settings, it faces unique challenges. It is uncertain to what extent information learned through the AR system is retained over time [5]. In another literature discussing the development and evaluation of an AR knowledge assessment tool, authors acknowledged that developing complex anatomical regions in AR may vary based on personal experiences, resulting in different results for specific anatomical regions [61]. Therefore, standardizing these development processes becomes a crucial consideration to provide constant and reliable implementation across diverse applications.

There are also limitations that depend exclusively on the type of AR device used. A specific AR application designed for foot wound monitoring through smartphone photography reported issues with accuracy and reliability caused by limited camera resolution and the variability of non-standardized photos [38]. Beside mobile devices, HMDs also exhibited limitations and challenges in adopting AR in healthcare. A study highlighted the significant learning curve associated with HoloLens [45]. To be specific, the apparent challenge lies in the potential cognitive load imposed on participants, exacerbated by their inexperience with the HoloLens and the specific operation [63]. Another issue of HoloLens is its weight and fit, which may lead to discomfort, neck strain, and other forms of pain [44], [46], [60], [64], [66], [71]. HoloLens users may also encounter visual discrepancies and interference caused by operating lights, affecting the device's performance [41], [47], [54]. Additionally, HoloLens requires calibration during startup, and the sensitivity of this calibration process may have an impact on usability [71]. Furthermore, since the HoloLens device is not initially designed for medical use, certain features of the HoloLens headset, such as noise cancellation, may impede communication in specific medical scenarios [16]. Although the limitations and challenges specific to other HMDs (like Magic Leap 1, VUZIX M400 smart glasses, and Epson Moverio BT-200 smart glasses) were not found in the included studies, this does not imply that these devices are free from constraints in healthcare applications. This lack of mention is likely because nearly 80% of the included HMD-based studies have focused on using either HoloLens 1 or 2, as shown in Table 7.

V. FUTURE WORK AND CONCLUSION

The future work for mobile- and HMD-based AR in healthcare involves several critical recommendations from researchers. Partial future work for mobile-based AR concentrate on enhancing mobile applications to improve surgical procedure. These enhancements aim to reduce surgical navigation errors and minimize surgical preparation time [32], [39]. Furthermore, the research agenda will expand to conduct testing of the mobile AR system in various environments including medical settings and the homes of patients, while simultaneously ensuring compatibility with other medical devices [33]. For medical training and education using mobile-based AR, there will be a focus to evaluate the extended learning effects of the AR technology in diverse participant groups and healthcare program settings [37]. For HMD-based AR, these recommendations include the development of validation methods to demonstrate the effectiveness of the AR approach in healthcare, increasing the availability of AR headsets to accommodate a larger number of users such as medical students, and enhancing surgical procedure such as guidance accuracy [4], [40], [49], [61]. Lastly, it aims to improve the system's suitability for clinical environments through enhancements in registration and AR display [53].

The integration of advanced AR technology has led to groundbreaking applications in various healthcare fields. The versatility of devices compatible with AR technology contributes significantly to its popularity. This review compared mobile- and HMD-based AR technologies within a healthcare context, focusing on their device functionalities, healthcare purposes, and study locations. We observed differences in device functionalities and healthcare purposes between these two types of AR, but not in their geographic distribution across continents for study location comparison. Compared to AR applications using mobile devices in terms of the healthcare purposes, HMDs were used in a wider range of areas including surgical assistance, assistive systems, preoperative planning, infection prevention, medical image visualization, as well as medical education and training. This observation might be partially influenced by the larger number of HMD-based studies identified. However, we cannot overlook that HMDs offer a hands-free operation and a more immersive experience than mobile devices. On the other hand, mobile devices have the benefit of greater portability, which reduces neck strain and allows for easy data collection as patients perform their daily activities. As for device functionalities, the studies that applied mobile-based AR showed a greater emphasis on creating interactive games or simulation experiences compared to those using HMD-based AR. However, 11% of the included HMD-based studies utilized AR for remote communication and rendering, a functionality not observed in any of the included mobile-based AR studies. Regardless of the device type, the strengths of AR in 3D visualization, information display, along with computer vision and control, have been acknowledged. These capabilities are key factors driving researchers to adopt the technology in healthcare applications. They contribute to a paradigm shift, offering new possibilities across various domains within the field.

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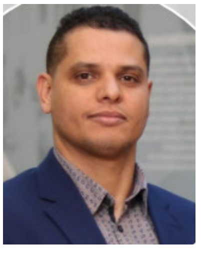

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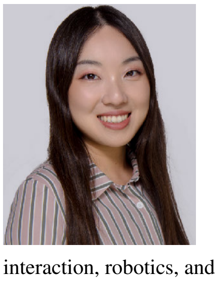

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