# RescuAR: A Self-Directed Augmented Reality System for Cardiopulmonary Resuscitation Training

Hamraz Javaheri[1(✉)], Agnes Gruenerbl[1], Eloise Monger[2], Mary Gobbi[2], Jakob Karolus[1,3], and Paul Lukowicz[1,3]

[1] DFKI GmbH, Kaiserslautern, Germany
Hamraz.Javaheri@dfki.de
[2] University of Southampton, Southampton, UK
[3] University of Kaiserslautern-Landau, Kaiserslautern, Germany

**Abstract.** In recent years, the adoption of augmented reality (AR) technology for healthcare education has gained significant attention. Especially in life-critical situations, such as cardiopulmonary resuscitation (CPR) where sufficient medical training is essential and traditional methods are often limited due to availability constraints. We present RescuAR, a self-directed AR-based CPR training system enhancing CPR skill acquisition and retention by leveraging immersive AR experiences and real-time feedback using sensing modalities.

RescuAR was designed and implemented as a self-directed AR application based on survey findings with 11 healthcare professionals, incorporating both theory and practice phases. To evaluate the effectiveness of RescuAR, a randomized controlled user study was conducted involving $n = 43$ participants, including nurse students and laypeople. The experimental group used RescuAR for CPR training, while the control group underwent traditional teaching and training sessions. The results of the user study revealed that RescuAR significantly improved the overall effective CPR performance, surpassing the outcomes achieved through traditional teaching methods. In conclusion, RescuAR's self-directed and autonomous approach to CPR training shows promising results in improving CPR performance and has the potential to transform CPR education.

**Keywords:** Augmented-Reality · Cardiopulmonary Resuscitation · Self-Education

## 1 Introduction

Cardiopulmonary resuscitation (CPR) plays a crucial role in saving lives during cardiac arrest, a medical emergency with high mortality rates. The timely and effective administration of CPR significantly increases the chances of survival [9]. Therefore, it is vital to ensure that individuals are well-trained in this life-saving technique. Traditional CPR training methods, such as classroom-based instruction and mannequin practice, have been the cornerstone of CPR education for decades. However, these methods


D. Salvi et al. (Eds.): PH 2023, LNICST 572, pp. 166–185, 2024.
https://doi.org/10.1007/978-3-031-59717-6_12

have shown limitations in terms of skill acquisition, retention, and providing immediate feedback on performance.

One prominent challenge in traditional CPR training lies in the gap between knowledge acquisition and practical application. While learners may grasp the theoretical concepts, transferring that knowledge into effective hands-on performance can be challenging [6]. Research has shown that individuals often struggle to translate their theoretical knowledge into practical skills when faced with high-stress situations, such as cardiac arrest scenarios [22].

Furthermore, the ability to receive real-time feedback on performance during CPR training is critical for learners to correct errors, refine their technique, and build confidence. Immediate feedback allows learners to adjust their actions, ensuring the application of correct chest compression (CC) depth, rate, and recoil. However, traditional methods of CPR training often lack the means to provide instantaneous and accurate feedback, leaving learners uncertain about their proficiency and limiting their ability to improve their skills effectively.

To address these challenges and bridge the gap in CPR education, the combination of augmented reality (AR) technology with sensing modalities emerges as a promising solution. AR integrates virtual elements into the real-world environment, offering learners an immersive and interactive training experience, while sensing modalities provide an opportunity for the integration of real-time feedback. By leveraging computer vision and sensing technologies, these systems can analyze the learner's movements and provide immediate feedback on the accuracy and effectiveness of their CPR technique. This real-time feedback enables the learner to make adjustments on the spot, improving the quality and consistency of their compressions. This approach enhances skill acquisition, retention, and performance by overlaying instructional guidance and visual cues onto the learner's view of a CPR scenario [1,10,34].

While existing studies on AR-based CPR training have shown promise in enhancing training experiences and outcomes [3,11,13,16], there is still a need for further research to fully explore the effectiveness of AR in addressing the current limitations of traditional CPR training methods. Although AR has demonstrated potential in providing immersive and interactive training environments, its specific impact on skill acquisition, retention, and performance during CPR training is an area that requires more investigation. Additionally, the design and implementation of AR-based CPR training systems can vary, and it is essential to evaluate the effectiveness of different approaches to optimize their educational value. Furthermore, understanding the potential benefits and challenges associated with incorporating AR technology into CPR training can inform the development of evidence-based guidelines and best practices for its integration.

In this paper, we introduce RescuAR, a self-directed AR-based CPR teaching and training system that addresses the gap between theoretical knowledge and practical applications in CPR education. RescuAR leverages AR technology to provide real-time feedback on performance during CPR training, enhancing the acquisition and retention of crucial CPR skills. We provide a comprehensive overview of the system, covering its pre-design stage, implementation process, and post-development evaluation. The design and implementation of RescuAR are carefully tailored to meet the specific needs of CPR education through survey findings from healthcare professionals. Furthermore, we conducted a user evaluation to assess the impact of RescuAR on learners' ability to acquire and retain essential CPR skills. Our study demonstrated the effectiveness of RescuAR in improving CC depth, frequency, and overall CPR performance, providing valuable insights into the potential of AR as a transformative tool for CPR education and skill development. The findings of this study will contribute to the growing body of research on AR-based medical training and inform the development of more effective CPR training programs that enhance learner performance, confidence, and ultimately save more lives.

## 2 Related Work

In recent years, several approaches have been investigated to improve the effectiveness of CPR training, ranging from traditional classroom-based instruction to advanced technological interventions, such as virtual reality simulations and AR applications [8,14,16,19,29,35].

In a recent study done by Balian *et al.* [3], the feasibility of an AR CPR training system (CPReality) for healthcare providers was tested. Their study results showed that the integration of AR into CPR training has the potential to be a valuable educational strategy that goes beyond simply translating knowledge and skills. However, their study has limitations, including inherent selection bias, a potential learning effect, a lack of baseline CPR performance assessment, and the absence of a control group for comparison. These limitations should be considered when interpreting the study's findings.

Leary *et al.* [21] focused on the limitations of Balian *et al.* work [3] and compared the use of CPRReality training with a standard audio-visual feedback manikin in terms of improvement in CPR quality. The findings of their study indicated that there was no statistically significant difference observed between the two groups. This implies that further, more extensive studies should be conducted to explore whether AR CPR training has the potential to enhance overall CPR quality for both new and re-certifying healthcare providers.

In another study done by Ingrassia *et al.* [13], an AR-based basic life support training system (Holo-BLSD) was proposed and evaluated in terms of feasibility and acceptability. While their study evaluates users' experiences and perceptions through a survey, it does not provide comprehensive evidence or direct comparisons of performance results in comparison to traditional CPR training methods. Therefore, the study may lack the empirical data needed to evaluate the effectiveness and efficacy of the Holo-BLSD system in terms of skill acquisition, retention, and performance outcomes.

In a related study, Johnson *et al.* [15] proposed the use of mixed reality (MR) to support time-critical emergencies. Their work introduced HoloCPR, an MR application that provided real-time instructions for resuscitation through a combination of visual and spatial cues. While their study demonstrated the potential of MR in decreasing reaction time and improving procedural accuracy, it primarily focused on the evaluation of these specific outcomes.

In this study, we aim to contribute to the existing body of research by addressing the limitations and building upon the findings of previous studies in the field. To this end, we provide insights into the design, implementation, and evaluation stages of an AR-based CPR training application suited for wearable AR devices. In addition, we introduce a unique and cost-effective solution for real-time measurement of compression depth, frequency, and recoil during CPR training. Moreover, our study strengthens the evidence supporting the effectiveness of AR-based CPR training by incorporating a control group and baseline performance measurements. By combining these efforts, we hope to enhance CPR training effectiveness and ultimately improve the outcomes of life-saving interventions.

## 3 Methodology

Upon reviewing the existing literature, we identified a gap in the research regarding the detailed exploration of the application design process for AR-based CPR training tools, as well as the limited availability of quantitative data for a comprehensive comparison between these tools and traditional CPR training methods. Motivated by these gaps in the existing literature, our study aims to fill this research void by answering the following research questions:

**RQ1**: What are the required design features and functionalities for an AR-based self-directed CPR teaching and training tool?

We answer this research question by conducting an extensive design survey among healthcare professionals and investigating their professional opinion on the required features and specifications for such training tool.

**RQ2**: Are the performance results of the designed system comparable with traditional teaching methods?

Our objective was to address this question by conducting an experimental trial where we compared the CPR performances of participants, who used the designed system to learn and practice CPR routine, with participants who underwent traditional teaching. We measured their performances before and after teaching sessions in terms of correct depth, correct frequency, and overall effective CPR (correct depth and correct frequency) to develop a better understanding of the efficiency of the designed system.

To this end, we employed a mixed-method design consisting of three consecutive steps: data collection for design requirements, system design and implementation, and system evaluation (Fig. 1).

Initially, a survey was conducted among a group of health professionals to gather valuable insights and identify the design requirements and constraints for an AR-based self-directed CPR teaching and training tool. The survey aimed to understand the preferences, needs, and expectations of professionals regarding CPR training, as well as their perceptions of the potential benefits and challenges of using such an interactive system.

Based on the insights and design requirements identified through the survey, RescuAR, an AR CPR self-training tool, was conceptualized and designed. The primary goal of RescuAR was to enable users to learn and improve their CPR performing skills by providing them with interactive features and real-time data visualization.

To assess the effectiveness of RescuAR, a user study was conducted involving nurse students and laypeople. The participants were randomly assigned to either the experimental group, which utilized RescuAR for CPR training, or the control group, which underwent traditional teaching methods. The CPR performances of participants were evaluated before and after the training sessions, specifically focusing on parameters such as compression depth and frequency. As various studies demonstrated the importance of hands-only CPR in bystanders [4,23], this study's primary objective was to evaluate participants' CPR performances specifically regarding hands-only CC and any effect related to breath technique was neglected.

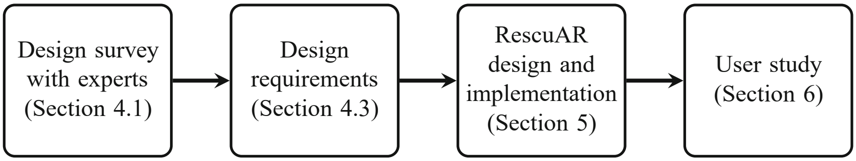



**Fig. 1.** The study flow process starting with the specification of design requirements based on expert survey findings and later evaluation of the designed system in a user study

## 4 Design Requirements for Self-directed AR-Based CPR Teaching and Training Tool

To inform the design of our interactive CPR teaching and training tool, we conducted a survey among experienced healthcare professionals. All professionals were familiarized with the AR device capabilities that will be used for the study prior to conducting the survey. The purpose of the survey was to identify the key requirements (RQ1) for developing an AR-based self-directed learning system that could effectively support CPR education. By gathering insights from these professionals, we aimed to create a tool that addresses the specific needs and challenges of learners in the context of CPR training.

### 4.1 Design Survey

The survey employed a combination of open-ended and multiple-choice questions. To provide a more structured approach the questions were categorized into five categories: User needs and requirements, user interface and design, instructional content, interaction and feedback, and miscellaneous.

While the questions under the user needs and requirements category focused on the participants' opinions on the features and functionalities that are considered essential for an AR-based CPR training app, the user interface and design questions focused more on the appearance and aesthetic aspects of the app.

In the instructional content section, several questions were asked to gather insights regarding the content, flow, and delivery mode of the teaching materials. Participants were asked to provide feedback on the clarity and comprehensiveness of the instructional content, as well as their preferences for the organization and sequence of the material. Additionally, participants were asked about their preferred delivery modes, such as text, images, videos, or interactive elements. Furthermore, more detailed questions focused on finding the most effective teaching methods for acquiring correct CPR skills such as correct CC depth and frequency, along with suggestions for optimization.

Under the interaction and feedback section, participants were asked to express their preferences for input methods, such as voice commands, button interactions, and gestures. Additionally, participants were asked to indicate their preferred methods of real-time feedback from app, whether visual, audio, or haptic.

Lastly, the miscellaneous section encompassed more general questions, allowing participants to share their opinions on gamification aspects of the AR-based CPR training app. Additionally, participants were given the opportunity to provide any overall suggestions or feedback they deemed relevant to the development of the app.

By capturing diverse perspectives from healthcare professionals, the survey played a crucial role in informing the design and development of an effective AR-based CPR training app.

### 4.2 Participants

A survey was conducted among 11 healthcare professionals. The participants' demographic characteristics, including their professional backgrounds and relevant experience, are summarized in Table 1.

**Table 1.** The participants' characteristic distributions

| Characteristics | |
|---|---|
| Age (years), Median (IQR) | 39, (32–48) |
| Female | 2 |
| Male | 9 |
| Non-Binary | 0 |
| Experience in healthcare (years), Median (IRQ) | 20 (14–23) |
| Tried or Familiar with AR (yes) | 6 (54%) |

IQR, interquartile range; AR, augmented reality

### 4.3 Survey Findings

The open-ended questions in the survey were analyzed using qualitative data analysis methods to evaluate the responses and gain deeper insights into participants' perspectives. The analysis process involved systematically reviewing the open-ended responses, coding them for key themes and patterns, and organizing the data into meaningful categories. Through this approach, we were able to identify common themes, explore variations in participants' experiences and opinions, and gain a comprehensive understanding of the topics under investigation. The qualitative analysis provided valuable qualitative data that complemented the quantitative findings, allowing for a richer and more nuanced interpretation of the survey results. These results highlighted the essential design elements and interaction methods that were considered crucial for an effective CPR training application based on the professionals' expertise and daily experiences in the healthcare field.

**Instructional Content, Routine, and Design Elements.** The survey respondents provided valuable insights and reached a consensus on several key aspects of the CPR training application design. They emphasized the importance of incorporating a combination of audio, scripted text, and a virtual human teacher within the app to effectively deliver theoretical materials and provide personalized guidance and support. Additionally, participants strongly favored the use of animated human avatars as a demonstration tool for CC and breath techniques compared to other methods such as 2D videos of real persons performing CPR or audio instructions and verbal cues. The dynamic and interactive nature of animated avatars was perceived as more engaging and effective in conveying the correct techniques for CPR training. In terms of the teaching routine, participants suggested that it should begin with a theoretical representation of the concepts, followed by hands-on practice. They further recommended that the teaching of compression depth and frequency should be initially conducted separately before combining them in the training sessions. Lastly, participants highlighted the significance of enabling repetitive theoretical and practical sessions. They emphasized the importance of incorporating functionality to navigate through the different stages of the training. This feature would provide users with the ability to easily access previous and next steps, facilitating repetitive practice sessions. The opportunity for repetitive practice allows learners to review and reinforce their CPR skills, ultimately improving their performance and confidence.

**Input and Interaction.** Regarding input and interaction, the survey respondents expressed a strong preference for the integration of interaction methods through physical buttons or verbal communication via voice commands. Both methods were considered intuitive and practical for engaging with the app during training sessions. The respondents emphasized the advantages of voice commands, as they enable users to perform actions without the need for manual input, allowing them to focus on performing CPR on the manikin. This hands-free interaction was seen as a convenient and efficient way to engage with the app. On the other hand, physical buttons were identified as a suitable option for environments with high noise levels or crowded settings. Furthermore, participants expressed the belief that using virtual buttons or hand gestures for interaction would not be suitable for this task, as they would require users to have prior knowledge of how to interact with such input methods.

**Methods for Frequency and Depth Acquisition.** The survey respondents highlighted the crucial role of immediate and real-time feedback during hands-on training sessions for acquiring the correct frequency and depth in CPR. Among various types of feedback, the combination of audio and visual feedback emerged as the most preferred method for both frequency and depth acquisition.

In terms of frequency acquisition, healthcare professionals recommended the inclusion of audio elements to facilitate proper timing during CPR. They expressed the belief that incorporating the iconic “Stayin’ Alive” sound, which aligns with the required rhythm for CPR, would enhance the training experience. However, to promote stronger muscle memory and improve precision, professionals also suggested the inclusion of a metronome sound.

For correct depth acquisition, the respondents emphasized the importance of incorporating a simple graphical visualization, similar to the devices used in traditional teaching setups to provide visual cues on the depth of CC. Participants pointed out the importance of optimizing the orientation and location of the visualization within the user’s field of view to ensure clarity and accuracy during CPR training. They recommended that the depth display be positioned near the manikin’s chest within the user’s field of view, in a fixed position to maintain proper posture during performance. However, considering that CPR is a highly physical activity and individuals may have different preferences, participants suggested that it would be beneficial if the position of the depth display could also be adjustable by the user based on their personal preference. This customization feature would allow users to optimize their viewing experience and ensure optimal training engagement.

## 5 RescuAR System Design and Implementation

Based on survey findings, an AR-based system prototype was developed with the aim of creating an immersive multi-sensory CPR teaching and training tool, incorporating audio, visual, and tactile elements, to enhance the learning experience and real-time feedback to foster a comprehensive understanding of the CPR technique.

The application was designed and developed using the Unity 3D game engine [31]. Microsoft HoloLens [25] was used as a wearable AR device to run the application.

The system consisted of two main parts: RescuAR application, and a standard CPR manikin [20] covered with custom pressure sensors. The RescuAR application utilized real-time data streams from the CPR manikin to provide feedback on compression rate, depth, and recoil. A local wireless communication scheme facilitated seamless interaction between the manikin and the application, enabling accurate and immediate feedback on CPR performance.

### 5.1 RescuAR Application

The formulation of the CPR training app’s prototype design was based on the results derived from both quantitative and qualitative data collected through the survey. According to the survey participants, a two-phase delivery of teaching material was found to be appropriate. They recognized that understanding the underlying principles and concepts of CPR is crucial in order to perform the techniques accurately and confidently. Hence the application routine was divided into two distinct phases: Theory and practice. During the initial theory phase, the application focused on imparting the fundamental principles of CPR. The subsequent practice phase emphasized hands-on practical training. The flow chart of the application routine is presented in Fig. 2.

Given that the primary objective of this study was to evaluate participants' performance specifically regarding CC, the instructions pertaining to rescue breaths were exclusively included in the theoretical section and not incorporated into the practical training. This deliberate decision allowed for a more targeted assessment of participants' proficiency in CC, aligning with the study's primary focus.

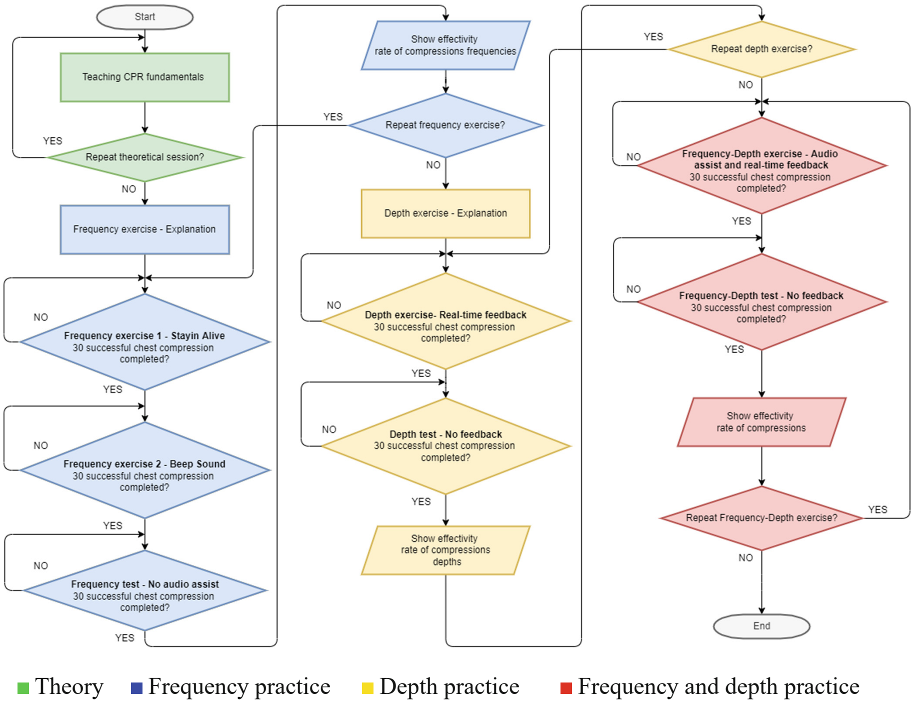
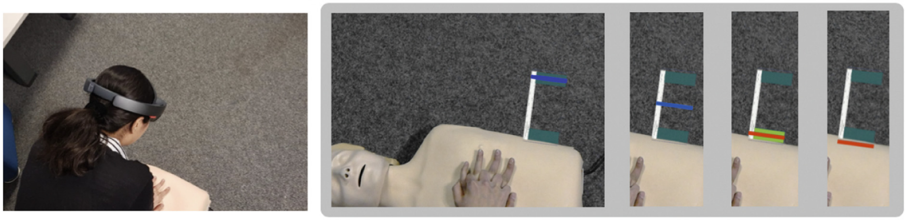



**Fig. 2.** The flowchart explaining the routine of RescuAR CPR tutorial and training application

**Theory Phase.** During the theoretical phase, users were introduced to the fundamentals of CPR (airway, breathing, and circulation techniques) based on European resuscitation council guidelines [26] through an engaging virtual teaching experience. A virtual teacher avatar was designed in following the survey results and served as the guide, delivering the essential CPR basics both audibly and visually. To enhance comprehension, the information was presented not only through the avatar's spoken instructions but also as easily understandable written scripts. This method was deemed to be the most suited approach for this application by survey participants. The communication between the virtual teacher and the participant was facilitated using voice commands. The virtual teacher provided the voice commands at the end of the conversation to reduce the need for memorization. For example, the virtual teacher would say, "If you

(a)



(b)

**Fig. 3.** Third-person and first-person (in-app) views of RescuAR application. (a) Theoretical phase. (b) Practical phase

feel like you need further practice, you can let me know at any time. Just use the word 'repeat!"'

To ensure a clear understanding of proper technique, animated 3D avatars were employed to visually demonstrate the correct posture and hand positioning during CPR (Fig. 3). By utilizing 3D virtual models and realistic placement within the room, participants were able to walk around the models and observe the CPR technique from different angles, providing a more immersive and interactive 3D training experience that cannot be achieved using 2D displays. By combining audio instruction, written scripts, and animated avatars, the theoretical phase of the training aimed to maximize participant comprehension and knowledge acquisition.

The application commenced with a calibration phase, which involved scanning the environment and room using the capabilities of the HoloLens and Mixed Reality Toolkit (MRTK) to obtain a spatial mesh of the environment. We utilized plane-finding methods to detect suitable surfaces for the placement of virtual teacher avatars and other demonstrative avatars. Colliders were added to the room mesh to create a more realistic movement area for the teacher avatar.

**Practice Phase.** The second phase of the application focused on practical training to cultivate the essential muscle memory required for CPR proficiency. Based on the feedback from survey participants, separate hands-on practice addressing each essential criterion of CPR was emphasized as important. As a result, two key criteria, frequency and depth, were targeted individually and then combined to ensure comprehensive learning.

To teach the correct frequency of CC, two distinct audio cues were employed. Initially, the iconic “Stayin’ Alive” song, known for its rhythm matching the recommended CPR procedure (104 bpm), was utilized to encourage participants to perform CC in sync with the song’s beats. Subsequently, a metronome sound with the same frequency (104 bpm) rate was introduced to enhance learner focus and synchronization.

Regarding CC depth, a trial-and-error approach was adopted to instill the appropriate technique. To align with the preferences of professionals who recognized the benefits of using a design similar to standard commercial devices, real-time feedback on compression depth was provided through a visual depth panel resembling CPRmeter devices [24]. This allowed learners to assess their performance and make adjustments accordingly (Fig. 3). The application allowed for the repositioning of the virtual depth feedback panel using the manipulation gesture of HoloLens. To address the shaking effect occurred during CPR performance, we implemented a functionality to fixate the depth feedback panel to the corner of the field of view. Participants could enable or disable this feature using a voice command. To eliminate the need and urge to look at the teacher avatar during chest compressions, which could be affected by the shaking effect, the visual rendering of the avatar was disabled during the practice session and reappeared after the completion of the stage. This effect was also explained by the teacher to the user to avoid any confusion. Additionally, a click sound reminiscent of the standard CPR dummy’s internal clicker (which had been previously removed to avoid confusion) indicated the moment when the correct depth was achieved.

Upon completion of training for both frequency and depth criteria, a final session provided an opportunity for learners to combine both elements, aiming to perform CC with the correct frequency and depth in a synchronized manner. This comprehensive training approach equipped participants with the necessary skills to deliver effective CC during CPR.

### 5.2 CPR Manikin

To acquire information such as depth, frequency, and pressurized position of the CC on the manikin, a single FSR (Force-Sensing Resistor) was used. The sensor was attached beneath the skin layer of the CPR manikin’s chest plate, precisely positioned in the center of the chest where the hands should be placed during correct CPR (Fig. 4). To facilitate seamless data acquisition and control, the pressure sensors were directly connected and managed by an Arduino Pro Mini board [2]. The analog signals generated by the embedded sensors were transformed into digital signals through the Arduino platform. Subsequently, these digital signals originating from the sensors were transmitted via a serial port to a local computer for further utilization and analysis.

To calculate the depth of chest compressions, we adopted the method proposed by Tsou *et al.* in their study [32]. This method utilizes Hooke’s law to calculate the depth based on the pressure applied to the chest spring. We assumed the spring inside the dummy to be a linear spring due to the same diameter along its entire length. We converted the FSR readings to Newton to calculate the spring constant. Before the experiment, we measured the spring constant using the FSR force value and the spring displacement using the following formula:

$$x = \frac{F}{k}$$

Where $F$ is the force applied to the compression spring (reading from the pressure sensor converted to Newtons, $N$), $k$ is the spring constant ($\frac{N}{m}$), $x$ is the displacement of the spring ($m$).

The accuracy of the employed method for calculating the depth of CC was verified against a commercial CPRmeter device [24] to ensure the validity of the measurements.

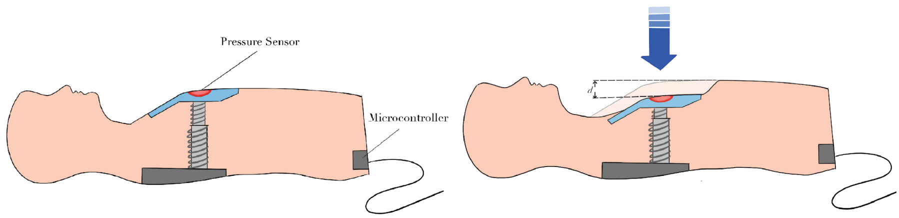



**Fig. 4.** Placement of Pressure sensors and controller inside the manikin. $F$ = Applied force to the spring ($N$), $k$ = spring constant ($\frac{N}{m}$), $x$ = displacement of the spring ($m$)

## 6 User Study and System Evaluation

To evaluate the effectiveness of our designed RescuAR system, we conducted a user experiment. The study took place in two different experiment centers, Southampton University Southampton, UK, and German Research Center for Artificial Intelligence (DFKI) Kaiserslautern, Germany. The primary objective of this experiment was to assess and compare the CPR performance of participants who used the RescuAR system with those who underwent traditional CPR training methods (RQ2).

### 6.1 Study Design

The study utilized a randomized controlled trial design to investigate the effectiveness of different teaching methods for CPR training. Participants were randomly assigned to either the experimental or a control group.

**Experimental Group.** The experimental group received a self-directed CPR teaching and training session using the RescuAR system (Application and the CPR manikin). The teaching session began by calibrating the HoloLens for each individual and starting the application. Each participant completed the teaching and training session without any time limit.

**Control Group.** The control group underwent a traditional CPR teaching and training session, which involved classroom-based instruction and practice using the CPR manikin. The same manikin as the experimental group was used in the control group to avoid any biases. A certified teacher was recruited to provide essential information on performing CPR based on European resuscitation council guidelines [26]. The session began with a theoretical introduction to the airway, breathing, and circulation techniques, followed by a demonstration from the teacher on the correct CPR procedure using the CPR manikin. Participants were then given the opportunity to practice CPR on the same manikin under the observation of the teacher. The teacher interrupted and gave feedback whenever they felt essential. Throughout the session, participants were encouraged to ask questions, repeat the training, and perform additional CC cycles if they desired. No time constraints were applied during teaching and training session. To minimize bias between the groups, the training sessions were conducted on an individual basis.

Both groups received instruction on airway, breathing, and circulation techniques. However, during the data recording session, participants were only asked to perform chest compressions, as the main focus of our study was to evaluate the quality of chest compressions in terms of depth and frequency while neglecting the potential effects of the breath technique. No device or extra feedback method was used during data recording. The performances of participants were assessed before and after the study to measure their baseline CPR skills and the improvements achieved through the assigned teaching training method. By comparing the performance improvements between the experimental and control groups, the study aimed to evaluate the impact of RescuAR system on enhancing CPR skills.

### 6.2 Study Protocol

This protocol was reviewed and approved by the ethical committee of Southampton University. All of the participants were informed about being free to participate in the research and nondisclosure of personal information. They all agreed and signed written informed consent. Upon written consent, the experiment protocol was performed in five ordered stages: (1) Demographic survey, (2) baseline CPR recording (3) randomized group assignment (4) teaching and training session, and (5) post-training CPR recording. The survey collected demographic and characteristic information including age, gender, experience background in CPR, and familiarity with wearable AR devices. After completion of the survey participants were asked to perform two cycles of 1-minute hands-only CPR. Participants rested at least two minutes between each cycle. Later all participants were randomly divided into two experimental groups to receive teaching and training session. After the teaching session participants rested at least for 10 min to avoid the effect of tiredness on their performance. Later they performed another two cycles of 1-minute hands-only CPR (without usage of any feedback device or extra help) with at least two minutes rest between each cycle. As various studies demonstrated the importance of hands-only CPR in bystanders [4,23] this study only focused on the evaluation of hands-only CPR performance, and any effect regarding performing rescue breath was neglected.

### 6.3 Participants

Total of 44 persons volunteered to participate in this study. Among those, 43 persons' data were included and one person's data were excluded from the study due to data corruption. After exclusion, the experimental group consisted of 22 volunteer participants and the control group contained 21 participants. The participants were nurse students and laypeople who were randomly assigned to study groups. The nurse students were recruited by Southampton University and laypeople were recruited by DFKI. All participants were required to be aged above 18. Characteristics of participants are presented in Table 2.

**Table 2.** The participants' characteristic distributions

| Characteristics | Control | Experimental |
|---|---|---|
| Age (years), Median (IQR) | 22, (20–24) | 21, (19–24) |
| Female | 5 (23%) | 9 (41%) |
| Male | 16 (77%) | 13 (59%) |
| Non-binary | 0 (0%) | 0 (0%) |
| Nurse Student | 9 (43%) | 9 (41%) |
| Laypeople | 12 (57%) | 13 (59%) |
| With prior knowledge | 8 (38%) | 11 (50%) |
| Tried or Familiar with AR (yes) | 2 (9%) | 1(4%) |

IQR, interquartile range; AR, augmented reality; With prior knowledge, who is CPR certified and/or completed a first aid course

### 6.4 Data Collection and Analysis

Over two 1-minute cycles, two CC measurements were recorded before and after the teaching session using the same sensor-equipped CPR manikin described in Sect. 5.2 with a sampling rate of 100 Hz. The effective CPR performances of the participants were analyzed according to the latest evidence-based guidelines for resuscitation officially published by European Resuscitation Council [28]. These guidelines suggest an effective CPR as follows:

- CC in a frequency of at least 100/min but not exceeding 120/min.
- CC with a depth of at least 5 cm but not exceeding 6 cm

In this study, the percentage of effective CPR performance of a participant was calculated based on the percentage of the time that the participants complied with all the above-mentioned guidelines at the same time while doing CPR.

Statistical analysis was performed using IBM SPSS Statistics for Windows, Version 22.0 [7]. Numerical data were presented as means ± standard deviations. To compare the improvement in two groups before and after teaching sessions, Paired t-test was used. To compare the outcomes between two study groups, Chi-square test (for categorical data) and Student's t-test (for numerical data) were used. A two-sided $p$-value less than 0.05 was considered significant in all analyses.

## 6.5 Results

**RescuAR Evaluation.** The participants in the experimental group showed significant improvements in performing correct depth and frequency. While the calculated $p$-value for CC depth improvement was 0.003, the $p$-value for frequency improvement was below 0.0001. A comparison between both criteria before the experiment session showed that more participants had issues finding the correct frequency (39.8% ± 36.9% correct frequency) than the correct depth (58.7% ± 39.8% correct depth). Even though for most of the participants, both depth and frequency were improved after the tutorial and training session, the frequency improvement rate was higher (73.8% ± 28.2%) than the improvement rate in CC depth (84.3% ± 23.2%).

Moreover, the results showed that the overall effective CPR performance of the experimental group significantly increased ($p < 0.0001$) after teaching session with RescuAR. While the mean of participants' performance was 23.3% ± 27.2% before the teaching session, it was improved to 61.3% ± 27.4% after training with the proposed system.

**Experimental Group vs. Control Group.** The study analysis showed no significant difference regarding characteristics distribution between the two groups concerning sex ($p = 0.332$) and knowledge backgrounds ($p = 0.543$) of the participants. Based on the findings, RescuAR helped to achieve higher effective CPR rates compared to traditional teaching. Analyzing the final performances of both groups' participants, it was observed that, even though both groups had no significant difference in doing effective CPR before the teaching session (control = 20.3% ± 25.4%, experimental = 23.3% ± 27.2%, $p = 0.594$), the experimental group performed significantly better than the control group after the teaching session (control = 40.4% ± 28.5, experimental = 61.3% ± 27.4%, $p = 0.019$) (Fig. 5).

Moreover, performance degradation only occurred in some of the control group's participants, and all participants in the experimental group showed improvement after the teaching session (Fig. 6).

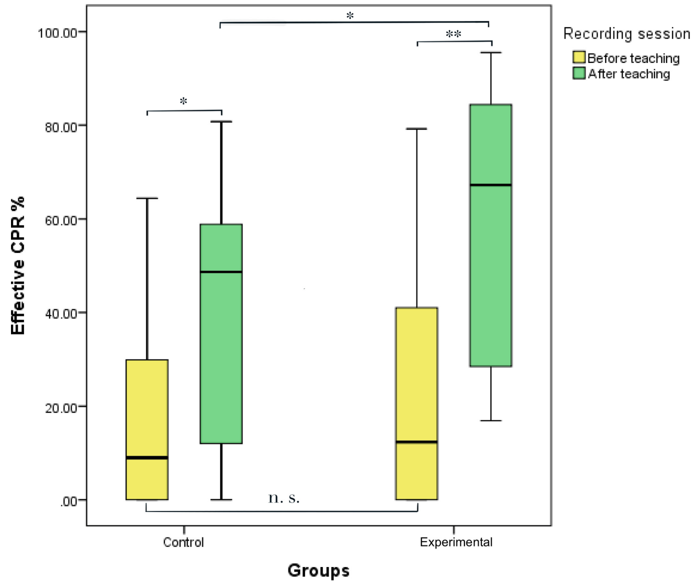



**Fig. 5.** The figure demonstrated the statistical analysis of control and experimental groups - n.s. = no significant difference between indicated groups ($p < 0.05$) * = Significant difference between indicated groups ($p < 0.05$), ** = Significant difference between indicated groups ($p < 0.01$)

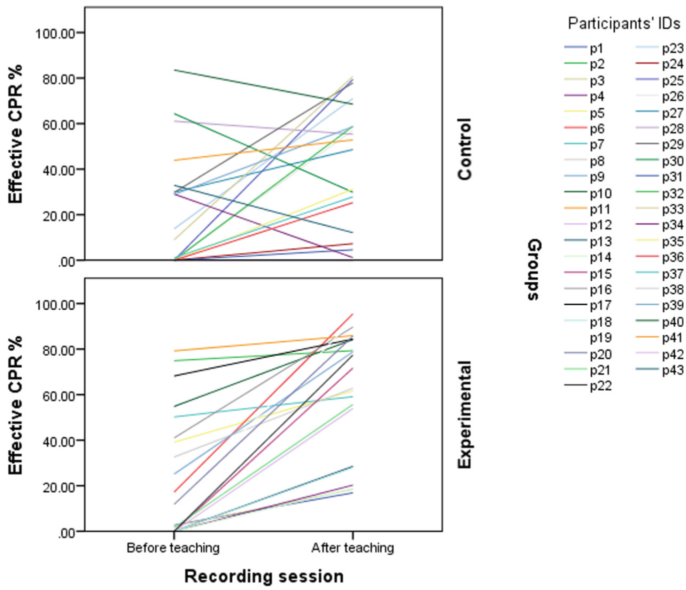



**Fig. 6.** Participant's performance lines before and after teaching sessions

## 7 Discussion

The results of our study provide compelling evidence of the effectiveness of RescuAR in self-directed CPR teaching and training. The significant improvements observed in both compression depth and frequency among participants in the experimental group demonstrate the positive impact of RescuAR on CPR skills. Moreover, the experimental group exhibited significantly higher improvements in effective CPR performance compared to the control group, underscoring the comprehensive benefits of RescuAR's AR-based approach. These findings suggest that traditional CPR teaching methods may have limitations in adequately addressing crucial aspects of skill acquisition and retention.

Acquiring physical skills like CPR relies on developing accurate muscle memory, and timely intervention is crucial to prevent the formation of incorrect habits. However, accurately assessing learner performance is challenging for teachers without measurement devices. Even with measurement systems, the timing and manner of intervention can impact learner performance. Previous research has explored the use of measurement systems to provide insights for teachers, but their effectiveness is influenced by various factors, including intervention timing and the method used [10,34].

Our system showed that using real-time feedback modalities integrated into the teaching routine could help to overcome this challenge. These findings align with previous research highlighting the benefits of audio-visual feedback in CPR education [10,18]. Furthermore, our approach for real-time detection and visualization of CC depth and frequency helped to seamlessly integrated the real-time feedback into the training routine overcoming the limitations caused by using commercial CPR feedback devices such as hand injuries due to the placement of the device, or instability of using smart devices for measurement during CC [1,12].

Moreover, successful teaching requires sufficient dedicated time to achieve specific skills or abilities. However, in a traditional setting, time constraints and variations in individual capabilities make it challenging to provide adequate attention to each student. In a crowded classroom setup, many students may hesitate to ask questions or request repetitions during training sessions. This can hinder their learning experience and limit their understanding of the subject matter. **A self-directed approach — as implemented in RescuAR — promotes active participation, encourages question asking, and allows students to engage with the material at their own pace**.

Additionally, instructors themselves differ in their approaches and abilities to teach and evaluate effectively [17]. Consequently, evaluations or presentations dependent on human teachers may lack objectivity and standardization. To address these challenges, previous studies have attempted to unify teaching routines and enhance training sessions using various technologies. Some studies focused on teaching CPR principles through videos [5,27,33]. While unifying teaching is essential, learners' active engagement also plays a significant role in improving outcomes [30]. For instance, de Sena *et al.* found that although video-based teaching improved CPR skills, participants preferred more interactive and engaging self-training over passive video-based instruction [30]. Our study demonstrates that merging approaches can provide an efficient alternative for CPR education. **By utilizing a virtual teacher with programmed curricula,**

**we standardized teaching routines without diminishing learners' interest, promoting verbal communication between teacher and student**.

In line with the findings of Balian *et al.* [3], our study further substantiates the potential of AR in CPR training. By incorporating a control group and measuring baseline performance, we provide additional evidence to support the effectiveness of AR for CPR training. This strengthens the understanding of the benefits and possibilities that AR technology offers in enhancing CPR education through various designs and implementations.

Although Leary [21] did not find a statistically significant difference between CPRReality training and a standard audio-visual feedback manikin, our study demonstrates significant improvements in CPR performance within the experimental group, suggesting the advantages of our AR-based approach in enhancing CPR quality compared to traditional methods.

### 7.1 Limitations

While our system design and study results provide valuable insights, it is essential to acknowledge its limitations. Certain technical issues, such as loss of environment mapping, occasional teacher avatar misplacement, and limited field of view, were identified during the experiment indicating the need for further optimization. Additionally, the study's controlled environment and participants' awareness of evaluation may have influenced their performance, necessitating further validation of the app's real-world applicability in diverse settings with participants unaware of being evaluated. Furthermore, further research is needed to assess the long-term durability and retention of the improved CPR performance observed in our study. Lastly, our study primarily focused on compression depth and frequency as key performance indicators, future studies could consider incorporating a more comprehensive assessment, including other critical elements such as hand placement, posture, and breath technique.

## 8 Conclusion

In conclusion, our study provides compelling evidence of the effectiveness of RescuAR, an AR-based CPR teaching and training app, in improving compression depth, frequency, and overall CPR performance. The insights gained from our study inform the development of guidelines and best practices for incorporating AR technology in CPR training programs. Policymakers, educators, and healthcare professionals can use this information to establish standards and recommendations for the implementation and utilization of AR-based training tools. This includes considerations such as the design of instructional content and feedback mechanisms, and the integration of AR training into existing curriculum frameworks. While this study primarily focused on the fundamental teaching of CPR, our future work will delve into exploring the integration of more realistic and immersive simulation scenarios. By incorporating advanced training systems, we aim to investigate ways of providing learners with a comprehensive and realistic training experience that prepares them for a wider range of CPR situations and challenges. By doing so we aim to contribute to expanding the field of research on medical training and inform the development of more effective CPR training programs that enhance learner performance, confidence, and ultimately save more lives.

**Acknowledgement.** This research was supported by HumanE-AI-Net.

## References

1. An, M., Kim, Y., Cho, W.K.: Effect of smart devices on the quality of CPR training: a systematic review. Resuscitation **144**, 145–156 (2019)
2. Arduino: Arduino pro mini (2018). https://www.arduino.cc/
3. Balian, S., McGovern, S.K., Abella, B.S., Blewer, A.L., Leary, M.: Feasibility of an augmented reality cardiopulmonary resuscitation training system for health care providers. Heliyon **5**(8), e02205 (2019)
4. Berg, R.A., et al.: Assisted ventilation does not improve outcome in a porcine model of single-rescuer bystander cardiopulmonary resuscitation. Circulation **95**(6), 1635–1641 (1997)
5. Braslow, A., Brennan, R.T., Newman, M.M., Bircher, N.G., Batcheller, A.M., Kaye, W.: CPR training without an instructor: development and evaluation of a video self-instructional system for effective performance of cardiopulmonary resuscitation. Resuscitation **34**(3), 207–220 (1997)
6. Brown, T.B., et al.: Relationship between knowledge of cardiopulmonary resuscitation guidelines and performance. Resuscitation **69**(2), 253–261 (2006)
7. Corp., I.: IBM SPSS statistics for windows (version 22.0) (2017). https://www.ibm.com/products/spss-statistics
8. Everson, T., Joordens, M., Forbes, H., Horan, B.: Virtual reality and haptic cardiopulmonary resuscitation training approaches: a review. IEEE Syst. J. (2021)
9. Greif, R., et al.: European resuscitation council guidelines 2021: education for resuscitation. Resuscitation **161**, 388–407 (2021)
10. Gruber, J., Stumpf, D., Zapletal, B., Neuhold, S., Fischer, H.: Real-time feedback systems in CPR. Trends Anaesthesia Crit. Care **2**(6), 287–294 (2012)
11. Higashi, E., Fukagawa, K., Kasimura, R., Kanamori, Y., Minazuki, A., Hayashi, H.: Development and evaluation of a corrective feedback system using augmented reality for the high-quality cardiopulmonary resuscitation training. In: 2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC), pp. 716–721. IEEE (2017)
12. Hong, J.Y., Oh, J.H., Kim, C.W., Lee, D.H.: Hand injuries caused by feedback device usage during cardiopulmonary resuscitation training. Resuscitation **107**, e3–e4 (2016)
13. Ingrassia, P.L., et al.: Augmented reality learning environment for basic life support and defibrillation training: usability study. J. Med. Internet Res. **22**(5), e14910 (2020)
14. Issleib, M., Kromer, A., Pinnschmidt, H.O., Süss-Havemann, C., Kubitz, J.C.: Virtual reality as a teaching method for resuscitation training in undergraduate first year medical students: a randomized controlled trial. Scandinavian J. Trauma, Resuscitation Emerg. Med. **29**(1), 1–9 (2021)
15. Johnson, J.G., Rodrigues, D.G., Gubbala, M., Weibel, N.: HoloCPR: designing and evaluating a mixed reality interface for time-critical emergencies. In: Proceedings of the 12th EAI International Conference on Pervasive Computing Technologies for Healthcare, pp. 67–76 (2018)
16. Jung, C., et al.: Virtual and augmented reality in cardiovascular care: state-of-the-art and future perspectives. Cardiovascular Imaging **15**(3), 519–532 (2022)

17. Kaye, W., et al.: The problem of poor retention of cardiopulmonary resuscitation skills may lie with the instructor, not the learner or the curriculum. Resuscitation **21**(1), 67–87 (1991)
18. Kirkbright, S., Finn, J., Tohira, H., Bremner, A., Jacobs, I., Celenza, A.: Audiovisual feedback device use by health care professionals during CPR: a systematic review and meta-analysis of randomised and non-randomised trials. Resuscitation **85**(4), 460–471 (2014)
19. Kuyt, K., Park, S.H., Chang, T.P., Jung, T., MacKinnon, R.: The use of virtual reality and augmented reality to enhance cardio-pulmonary resuscitation: a scoping review. Adv. Simul. **6**(1), 1–8 (2021)
20. Laerdal: Little Anne CPR dummy. Official page (2018). https://www.laerdal.com/de/
21. Leary, M., McGovern, S.K., Balian, S., Abella, B.S., Blewer, A.L.: A pilot study of CPR quality comparing an augmented reality application vs. a standard audio-visual feedback manikin. Front. Digital Health **2**, 1 (2020)
22. LeBlanc, V.R.: The effects of acute stress on performance: implications for health professions education. Acad. Med. **84**(10), S25–S33 (2009)
23. Leong, B.: Bystander CPR and survival. Singapore Med. J. **52**(8), 573 (2011)
24. Medical, L.: CPRmeter 2 (2023). https://laerdal.com/de/products/medical-devices/cpr-feedback-devices/cprmeter-2/
25. Microsoft: Hololens. Official page (2018). https://www.microsoft.com/en-us/hololens
26. Olasveengen, T.M., et al.: European resuscitation council guidelines 2021: basic life support. Resuscitation **161**, 98–114 (2021)
27. Paglino, M., et al.: A video-based training to effectively teach CPR with long-term retention: the scuolasalvavita. it ("schoolsaveslives. it") project. Internal Emerg. Med. **14**(2), 275–279 (2019)
28. Perkins, G.D., et al.: European resuscitation council guidelines 2021: executive summary. Resuscitation **161**, 1–60 (2021)
29. Ricci, S., Calandrino, A., Borgonovo, G., Chirico, M., Casadio, M.: Virtual and augmented reality in basic and advanced life support training. JMIR Serious Games **10**(1), e28595 (2022)
30. de Sena, D.P., Fabrício, D.D., da Silva, V.D., Bodanese, L.C., Franco, A.R.: Comparative evaluation of video-based on-line course versus serious game for training medical students in cardiopulmonary resuscitation: a randomised trial. PLoS ONE **14**(4), e0214722 (2019)
31. Technologies, U.: Unity 3D game engine (version 2018.4.36f1) (2018). http://www.unity.com
32. Tsou, J.Y., Kao, C.L., Hong, M.Y., Chang, C.J., Su, F.C., Chi, C.H.: How does the side of approach impact the force delivered during external chest compression? Am. J. Emerg. Med. **48**, 67–72 (2021)
33. Wanner, G.K., Osborne, A., Greene, C.H.: Brief compression-only cardiopulmonary resuscitation training video and simulation with homemade mannequin improves CPR skills. BMC Emerg. Med. **16**(1), 1–6 (2016)
34. Yeung, J., Meeks, R., Edelson, D., Gao, F., Soar, J., Perkins, G.D.: The use of CPR feedback/prompt devices during training and CPR performance: a systematic review. Resuscitation **80**(7), 743–751 (2009)
35. Yigitbas, E., Krois, S., Renzelmann, T., Engels, G.: Comparative evaluation of AR-based, VR-based, and traditional basic life support training. In: 2022 IEEE 10th International Conference on Serious Games and Applications for Health (SeGAH), pp. 1–8. IEEE (2022)