Cardiopulmonary resuscitation simulator with real-time feedback
Simulador de reanimación cardiopulmonar con realimentación en tiempo real

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Abstract- Cardiac arrest is a problem that causes a large number of deaths worldwide each year. However, cardiac arrest is a potentially reversible condition if quality cardiac resuscitation is initiated immediately, and an automated external defibrillator is used. In general, the simulators used in training courses do not allow objective assessment of the cardiopulmonary resuscitation (CPR) maneuver. Typically, these simulators have only audible feedback on the depth of compressions. Thus, both the students while practicing and the instructors while assessing the maneuver, must evaluate and correct the resuscitation guided by what they perceive with their own eyes and not on the basis of objective information. In this project, a clinical simulator with real-time feedback has been developed to facilitate the learning and an objective evaluation of the CPR maneuver taught in training courses.

Keywords: Cardiopulmonary resuscitation, cardiac arrest, clinical simulator.

Resumen- El paro cardiaco es un problema que causa anualmente un gran número de muertes en todo el mundo. Sin embargo, una parada cardiaca es un estado potencialmente reversible si se inicia inmediatamente una reanimación cardiaca de calidad y se utiliza un desfibrilador externo automático. En general, los simuladores utilizados en los cursos de formación no permiten evaluar objetivamente la maniobra de reanimación cardiopulmonar (RCP). Normalmente, estos simuladores solo cuentan con realimentación sonora sobre la profundidad de las compresiones. Así, tanto los alumnos mientras practican como los instructores mientras valoran la maniobra, deben evaluar y corregir la reanimación guiados por lo que perciben a simple vista y no en base a información objetiva. En este trabajo, se ha desarrollado un simulador clínico con realimentación a tiempo real, con el que se pretende facilitar el aprendizaje y la evaluación objetiva de la maniobra de RCP impartida en cursos de formación.

Palabras clave: reanimación cardiorrespiratoria, paro cardiaco, simulador clínico.

1. INTRODUCTION

The Cardiopulmonary Resuscitation (CPR) maneuver was born in 1960 (Kouwenhoven et al., 1960; Safar, 1965) which supported the creation of the CPR protocols. Organizations such as the American Heart Association, the European Resuscitation Council and the Spanish Cardiopulmonary Resuscitation Council (Abella, 2016) made these protocols available globally which means that they are applied around the globe.

Cardiopulmonary resuscitation is a set of maneuvers which objective is to reverse sudden cardiorespiratory arrest in a patient. When performed correctly, it can restore breathing and spontaneous blood circulation (Yan et al., 2020). CPR consists of two main components: chest compressions and rescue breaths, which provide ventilation to the patient. The chest compressions are performed at the center of the chest where the sternum is located, with the objective to restore blood circulation. The rescue breaths, on the other hand, aim to deliver oxygen to the lungs (Olasveengen et al., 2021). During chest compressions, the person performing the CPR should be positioned on their knees, beside the person who experienced the cardiac arrest, as shown in Figure 1 (a). The sternum should be pressed using the heel of one hand, while the other hand is placed on top, weaving them as shown in Figure 1 (b). Both arms should remain extended throughout the chest compressions, maintaining a vertical position relative to the patient.

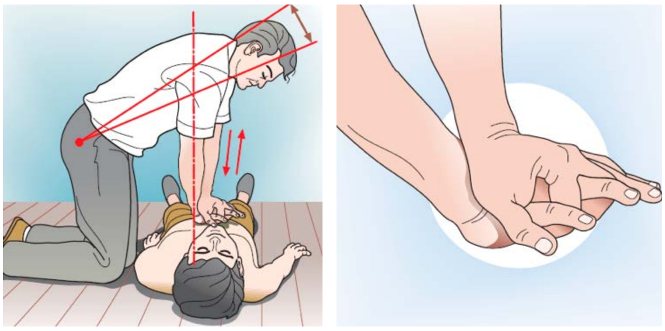
(a) (b)

Figure 1. CPR maneuver: (a) position of the rescuer person; (b) position of the hands to perform a high-quality CPR.

To assess the effectiveness of chest compressions, three parameters should be considered: the compression rate, the compression depth, and the complete thoracic decompressions. For evaluating rescue breaths, two parameters are considered: breath frequency and insufflated air volume. Consequently, a

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high-quality CPR must meet the following criteria (Meaney et al., 2013):

- Interruptions must be minimized during CPR to maintain a minimum rate of 80% along the entire assistance period.
- Maintain a chest compression frequency of 100 to 120 compressions per minute.
- Ensure compression depths between 5 cm and 6 cm. Compressions exceeding 6 cm may lead to rib fractures, myocardial hematoma, or damage to visceral organs. Survival rates improve with deep compressions within the recommended range, indicating a dose-effect relationship between compression depth and patient survival.
- Place the patient on a firm and even surface to optimize chest compression mechanics.
- Ensure thoracic decompression after each compression without detaching the hands from the patient's chest.
- Provide rescue breaths with an air volume between 5-8 ml/kg and maintain a frequency below 12 breaths per minute.

A high-quality CPR can double or even triple the patient's survival rate (Association, 2022). Therefore, it is crucial for the general population, clinicians, and bystanders to acquire and learn how to perform high-quality CPR.

Typically, basic mannequins are used in CPR training and skill stations for medical students. However, these mannequins do not provide real-time feedback, making it challenging to objectively evaluate compliance with the protocols. While high-fidelity mannequins capable of real-time feedback exist in the simulation landscape for CPR, they are often not utilized due to their high cost.

As a result, a low-cost, high-fidelity simulator has been developed to assess the adherence to CPR protocols effectively.

2. CONTEXT & DESCRIPTION

To design and develop the low-cost CPR simulator with real-time feedback, the following tasks have been performed:

- Sensors: introduce in a low-fidelity CPR mannequin a distance sensor and a flow sensor. These sensors were used to capture the relevant parameters of the CPR maneuver, such as the compression depth and the ventilation volume.
- Data: the data captured by the sensors were processed to extract valuable information regarding the key parameters that define a high-quality CPR. Algorithms were developed to analyze and show the sensor data accurately.
- Database: a comprehensive database was designed and developed to store all the gathered data during the simulation. This database allows for efficient data management and analysis, supporting further research and evaluation.
- Web Interface: a user-friendly web interface was designed and developed to provide real-time feedback to the users. This interface displays the captured data and provides visual representations and metrics to assess the quality of the CPR performance.
- Validation: a validation study was conducted to evaluate the CPR simulator developed.

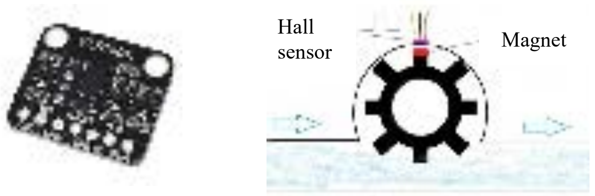
A. Hardware design

The low-cost simulator used for this project is the Prestan Adult CPR mannequin shown in Figure 2. This mannequin includes a sound device known as a clicker, which emits a sound when the compression depth exceeds 5 cm. Moreover, the mannequin is designed with a built-in block that restricts compressions from exceeding 6 cm in depth. The selection of the Prestan CPR mannequin was based on its affordability and its adaptability to include additional components, such as the distance and flow sensors previously mentioned. Additionally, an additional piece was inserted to allow compressions that exceed the 6 cm depth. By doing this, the physical restriction of the Prestan mannequin is removed supporting a better learning of the technique.

Figure 2. Low fidelity mannequin used: Prestan Adult CPR.

To capture the necessary information to evaluate the CPR performance, two sensors were employed: the VL6180X distance sensor (Figure 3(a)) and the YF-201 flow sensor (Figure 3(b)). The VL6180X distance sensor, a laser-based sensor, measures the frequency, depth, and decompression of the chest compressions. It emits a beam of light perpendicular to the object to determine its distance accurately (Prototyping, 2022). The YF-201 flow sensor, a turbine type flowmeter, measures the airflow passing through a turbine per unit of time (Mechatronics, 2022). It is positioned within the mannequin using a plastic tube, securely attached at one end to the mannequin's mouth and at the other end to the flow sensor. This configuration allows to measure of air insufflation during rescue breaths.

To manage and process the data from the sensors, an Atmel SAM3X8E ARM Cortex-M3 microcontroller is used. It enables the collection and analysis of relevant information to evaluate the quality of CPR performance. The gathered data from the sensors need to be stored in a database, which is hosted on a server. In addition, the server hosts the web interface for the simulator. To achieve these objectives, a Raspberry Pi 4 Model B is used, serving as both the database server and the platform for the web interface. To accomplish this, the distance sensor collects data regarding the frequency and depth of chest compressions and decompressions. The frequency of chest compressions is determined by analyzing the data received from the distance sensor whereas the depth of the compressions and decompressions are automatically measured by the sensor. On the other hand, the flow sensor provides information about the airflow delivered to the patient. However, to assess the effectiveness of rescue breaths, it is necessary to determine the volume of air delivered. Since flow is the change in volume over time, the volume of air provided is obtained from the flow data.



(a) (b)

Figure 3. Sensors used: (a) distance sensor (Prototyping, 2022), (b) flow sensor with its components (Mechatronics, 2022).

The data obtained from the sensors are gathered into a database that will be placed in a server. Additionally, this server will also host a web interface that will be created to manage the CPR simulator.

B. *Software design*

A LAMP web server has been set on the Raspberry Pi. It includes Linux as operating system, Apache as the web server, MariaDB for the database management. PHP is the programming language used generating an HTML which is directly sent to the user. This infrastructure is shown in Figure 4, and it is appropriate for dynamic web interfaces which is the objective for this CPR simulator as the information must be processed and shown in real-time to the user.

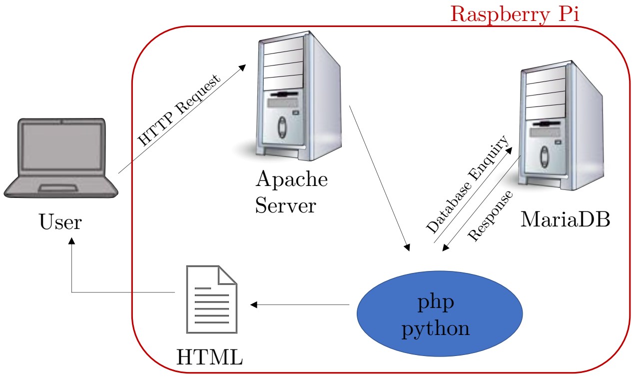
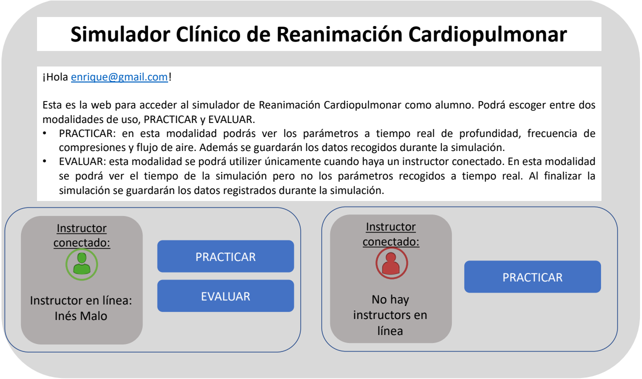


Figure 4. Infrastructure implemented in the Raspberry Pi.

Other languages used to create the web interface are JavaScript, CSS and HTML. The web interface considers two different modes: a training mode and an evaluation mode as shown in Figure 5.

As our focus is to evaluate how well CPR protocols are followed, the evaluation mode is described. First, a trainer creates a clinical case that will be assigned to a specific trainee. Then, the trainee must log in into the simulator. Once this is done, a panel with actions that should be taken prior to start the CPR is shown.



Simulador Clínico de Reanimación Cardiopulmonar

¡Hola enrique@gmail.com!

Esta es la web para acceder al simulador de Reanimación Cardiopulmonar como alumno. Podrá escoger entre dos modalidades de uso, PRACTICAR y EVALUAR.

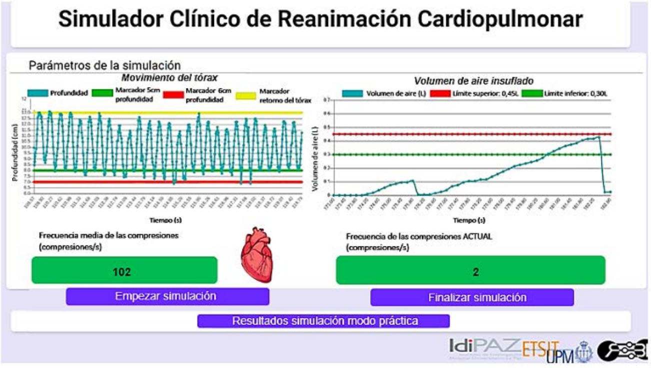
- PRACTICAR: en esta modalidad podrás ver los parámetros a tiempo real de profundidad, frecuencia de compresiones y flujo de aire. Además se guardarán los datos recogidos durante la simulación.
- EVALUAR: esta modalidad se podrá utilizer únicamente cuando haya un instructor conectado. En esta modalidad se podrá ver el tiempo de la simulación pero no los parámetros recogidos a tiempo real. Al finalizar la simulación se guardarán los datos registrados durante la simulación.

Instructor conectado:
Instructor en línea: Inés Malo

Instructor conectado:
No hay instructors en línea

Figure 5. Web interface in which a welcome message is shown with the explanation of the two modes available. As the interface is only available in Spanish, it is shown in this language.

Once those actions are accomplished, the simulation with the mannequin starts showing the information about chest compressions and rescue breaths in real-time, see Figure 6. This information is only shown to the trainer. Moreover, once the simulation is finished, a pdf document is generated including all the CPR relevant information. This allows to objectively evaluate the CPR maneuver.



Simulador Clínico de Reanimación Cardiopulmonar

Parámetros de la simulación

Frecuencia media de las compresiones (compresiones/s): 102

Frecuencia de las compresiones ACTUAL (compresiones/s): 2

Figure 6. Information about the simulation parameters: chest compressions and ventilations in real time.

C. *Pilot study*

To evaluate the CPR simulator developed, a pilot study was performed at Hospital Universitario La Paz with residents who participated in a basic life support training in September 2022. Along the course, the residents received instructions on various techniques, including CPR compressions. Therefore, one of the skill stations used our simulator to assess their performance in delivering chest compressions. A total of 84 trainees attended the basic life support training courses, and all of them had the opportunity to perform chest compressions using the simulator. During all the simulations, it was ensured that the CPR simulator was on a firm and even surface by all the trainees.

Additionally, a usability questionnaire was fulfilled by all the participants after the use of the CPR simulator. This questionnaire had 10 questions, as shown in Table 1, that could be rated from 1, strongly disagree to 10, strongly agree.

Table 1. Questions included in the usability questionnaire based on a 7-points Likert scale.

Questions	
Q1.	Do you consider that the CPR simulation is useful to learn the CPR maneuver?
Q2.	Do you consider that the CPR simulation is useful as a training method?
Q3.	Do you this that the simulator encourages learning?
Q4.	How would you rate your experience with the simulator?
Q5.	Do you think that the simulator support critical reasoning and decision making?
Q6.	Do you consider that the data gathered from the simulator: depth, compressions and flow of insufflated air are adequate?
Q7.	Do you consider that the information is shown effectively in the web interface?
Q8.	Do you think that the simulator supports an objective evaluation of the CPR maneuver?
Q9.	I consider that the simulator is easy to use and understand.
Q10.	In general, I am satisfied with the CPR simulator.

3. RESULTS

All the trainees performed the CPR maneuver without any interruptions, complying with the minimum assistance rate of 80%. However, the median depth of the chest compressions performed by the trainees was 6.15 cm, exceeding the maximum depth of 6 cm, as shown in Figure 7. Regarding thorax decompression, 10.85 cm was the one needed to perform a correct decompression. As shown in Figure 7, the median value achieved for thorax decompression during the simulations was 10 cm. This indicates that the trainees were not able to adequately decompress the thorax of the simulator. Finally, in terms of the frequency of chest compressions, it is worth noting that, despite some exceptions illustrated in Figure 7, the median value of 115 compressions per minute falls within the recommended range of 100 to 120 compressions per minute.

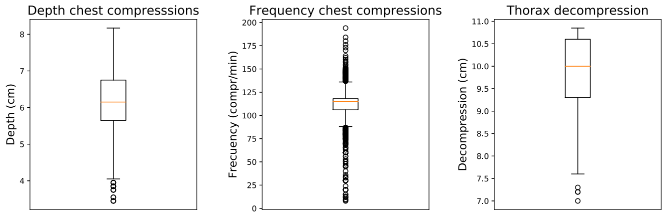


Figure 7. Depth of the chest compressions, frequency of the chest compressions and thorax decompression performed during the 84 simulations.

With respect to the usability questionnaire, from the 84 participants, 78 rated a 9 or 10 in all the questions. In fact, only 4 participants rated below 5, which is somewhat agree, some questions, providing some areas for improvement such as including auditive feedback in the simulator or improving the real-time graphs to be even more intuitive. Nevertheless, all the participants scored with 6 and 7 the question number 10 which relates to the general satisfaction of the simulator.

4. CONCLUSIONS

A robust, simple, interactive, and pedagogical tool has been developed for training in CPR protocols. This tool allows trainees to improve their skills through realistic scenarios, enabling students to practice and objectively evaluate their CPR maneuvers in a safe environment. Finally, it allows trainers to objectively evaluate trainees based on parameters gathered by the simulator.

Additionally, based on the results of the pilot study, it is observed that there is a need for further training and improvement in CPR protocols. These results highlight the importance of continuous training and education in CPR techniques. While CPR protocols have been integrated into medical education for a considerable period, this study suggests that there is still room for improvement.

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