Translational study on cardiopulmonary resuscitation: from skills acquisition and retention to impact in clinical practice

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Doctoral Thesis in

Clinical and Health Services Research

Faculty of Medicine of the University of Porto

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Porto | 2025

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This thesis is constituted by two original papers. Under the scope of this thesis, other research papers and conference abstracts were published.

<u>Core Research Papers</u>

- **Nicolau, A.**, Jorge, I., Vieira-Marques, P., & Sa-Couto, C. (2024). Influence of Training With Corrective Feedback Devices on Cardiopulmonary Resuscitation Skills Acquisition and Retention: Systematic Review and Meta-Analysis. JMIR Medical Education, 10, e59720.

  2023 Journal Quartile – Q1 (3.2 Impact Factor)

- **Nicolau, A.**, Bispo, I., Lazarovici, M., Ericsson, C., Sa-Couto, P., Jorge, I., ... & Sa-Couto, C. (2024). Influence of rescuer position and arm angle on chest compression quality: An international multicentric randomized crossover simulation trial. Resuscitation plus, 20, 100815.

  2023 Journal Quartile – Q1 (2.1 Impact Factor)

<u>Related Research Papers</u>

- Jorge, I., Sá-Couto, C., & **Nicolau, A.** (2022, June). Development of an Objective Measurement System for Quality Assessment of Chest Compressions. In 2022 17th Iberian Conference on Information Systems and Technologies (CISTI) (pp. 1-6). IEEE.
- Sá-Couto, C., & **Nicolau, A.** (2019). General public's knowledge regarding basic life support: A pilot study with a Portuguese sample. Acta Médica Portuguesa, 32(2), 111-118.
- Sa-Couto, C., **Nicolau, A.**, Marques-Costa, R., & Vieira-Marques, P. (2018). CPR personal trainer: a low-cost training tool with objective feedback. Resuscitation, 130, e107.

- Sá-Couto, C., Ferreira, A. M., Almeida, D., **Nicolau, A.**, & Vieira-Marques, P. (2018). Evaluation of skills acquisition using a new low-cost tool for CPR self-training. Porto Biomedical Journal, 3(1), e8.
- **Nicolau, A.**, Sá-Couto, C., Sousa, I., Vieira-Marques, P. (2021) *[Abstract]* Cardiopulmonary resuscitation skills self-training with a novel automated-feedback device: impact in compressions performance. In Selected Abstracts from the 26th Annual Meeting of the Society in Europe for Simulation Applied to Medicine. Adv Simul 6 (Suppl 2), 10.

<u>Related Oral Communications</u>

- **Nicolau, A.**, Bispo, I., Lazarovici, M., Ericsson, Tempfli, J., Kim, S., Jorge, I., Vieira-Marques, P., Sa-Couto, C. Exploring the influence of rescuer position on chest compression quality: an international multicentric pseudo-randomised manikin trial. SESAM Annual Meeting 2024, Prague, Czech Republic
- **Nicolau, A.**, Sá-Couto, C., Jorge, I. Impact of a short-single, technology-based self-training cycle on CPR knowledge and skills acquisition: a quasi-experimental study. SESAM Annual Meeting 2023, Lisbon, Portugal.
- **Nicolau, A.**, Sá-Couto, C., Sousa, I., Vieira-Marques, P. CPR skills self-training with a novel automated-feedback device: impact in compressions performance. SPSim/RIEM Conference 2022, Lisbon, Portugal
- **Nicolau, A.**, Sá-Couto, C., Sousa, I., Vieira-Marques, P. Cardiopulmonary resuscitation skills self-training with a novel automated-feedback device: impact in compressions performance. SESAM Annual Meeting 2021 (virtual).

Abbreviations

AED - automated external defibrillator

BLS - basic life support

BMI - body mass index

CC - chest compression

CI - confidence interval

CONSORT - Consolidated Standards of Reporting Trials

cpm - compressions per minute

CPR - cardiopulmonary resuscitation

IHCA - in-hospital cardiac arrest

IQR - interquartile range

OCS - overall compression score

OHCA - out-of-hospital cardiac arrest

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses

RCT - randomized controlled trial

ROSC - return of spontaneous circulation

SBAS - Stanford Brief Activity Survey

SCA - sudden cardiac arrest

SD - standard deviation

SE - standard error

SWiM - Synthesis Without Meta-Analysis

WHO - World Health Organization

Acknowledgements

The work presented in this thesis is the result of the collaboration, help, support and teachings of many. It was a long and challenging journey, rich in knowledge, curiosity and passion for science. I thank everyone who, in some way, was present on this journey. In particular:

To **Carla Sá Couto** for, since 2015, believing in me. Thank you for all your academic and personal support, and for being a huge inspiration.

To **Pedro Vieira Marques** for all the advice and support in this and many other projects. Thank you for your patience and all your understanding.

To **Inês Jorge** for all her enormous collaboration on this thesis. Thank you for the excellent friendship we have built.

To **Ingrid Bispo**, **Marc Lazarovici**, **Christoffer Ericsson** and **Pedro Sá Couto** for your significant support and for helping to bring this thesis to fruition.

To **Cristina Granja** for the additional motivation and support.

To the **Faculty of Medicine of the University of Porto Simulation Center staff** for your collaboration and support over the years.

To **André Pardal** for your tireless support and friendship since 2012.

To my **parents**, **grandparents**, **brother** and **in-laws** for being the greatest support in all the challenges. Thank you for your understanding over the years and for believing in this journey.

To my wife, **Diana Santos Silva**, for always being by my side, in all circumstances, since 2009. For loving me every day. For listening and understanding me. For making me happy. I owe you everything. "*Como sempre, para sempre.*"

To my son, **Duarte**. You haven't been born yet but I am eternally grateful and eager for your arrival. In the last few months, you have given me the motivation and energy that I needed. You're my everything.

Abstract

Effective cardiopulmonary resuscitation (CPR) is a cornerstone of life-saving interventions during cardiac arrest, yet its success depends on the quality of chest compressions. This thesis investigates two critical aspects of CPR performance: the effectiveness of corrective feedback devices in enhancing skills acquisition and retention, and the influence of rescuer positioning and arm angles on compression quality. By adopting a translational approach, it bridges the gap between cognitive learning and practical performance, providing insights that span training methodologies and real-world clinical practice.

A systematic review and meta-analysis were conducted to evaluate the impact of corrective feedback devices on CPR training among both laypeople and healthcare professionals. The findings indicate that these devices significantly improve skills acquisition and retention over time, with longer training durations yielding superior outcomes.

A simulation trial explored rescuer positioning and arm angles, revealing that a 90° arm angle and elevated positioning optimize compression depth and effectiveness. Conversely, kneeling on a bed was associated with poorer chest compression quality, underscoring the importance of ergonomic support during resuscitation.

The results of this research emphasize the need for a multifaceted approach to enhance CPR quality. Integrating feedback technologies that deliver real-time metrics on chest compression depth, rate, and recoil can ensure adherence to resuscitation guidelines and promote sustained high performance. These devices must also guide ergonomic adjustments to improve rescuer efficiency and reduce fatigue, with designs that prioritize durability, portability, and cost-effectiveness for broad implementation.

Resumo

A ressuscitação cardiopulmonar (RCP) eficaz é a pedra angular das intervenções que salvam vidas durante a paragem cardiorrespiratória, mas o seu sucesso depende da qualidade das compressões torácicas. Esta tese investiga dois aspetos críticos do desempenho da RCP: a eficácia dos dispositivos de feedback corretivo na melhoria da aquisição e retenção de competências e a influência do posicionamento do socorrista e dos ângulos dos braços na qualidade das compressões. Ao adotar uma abordagem translacional, esta tese preenche a lacuna entre o treino e o desempenho prático, fornecendo informações que abrangem as metodologias de formação e a prática clínica do mundo real.

Foi realizada uma revisão sistemática e uma meta-análise para avaliar o impacto dos dispositivos de feedback corretivo no treino de RCP entre leigos e profissionais de saúde. Os resultados indicam que esses dispositivos melhoram significativamente a aquisição e a retenção de competências ao longo do tempo, com as durações de treino mais longas produzindo resultados superiores.

Um ensaio simulado explorou o posicionamento do socorrista e os ângulos do braço, revelando que um ângulo de braço de 90° e um posicionamento elevado otimizam a profundidade e a eficácia da compressão. Por outro lado, a posição ajoelhada numa cama foi associada a uma pior qualidade de compressão torácica, sublinhando a importância do apoio ergonómico durante a reanimação.

Os resultados desta investigação enfatizam a necessidade de uma abordagem multifacetada para melhorar a qualidade da RCP. A integração de tecnologias de feedback que forneçam métricas em tempo real sobre a profundidade, a frequência e o *recoil* da compressão torácica pode garantir a adesão às diretrizes de ressuscitação e promover um alto desempenho sustentado. Esses dispositivos também devem orientar ajustes ergonómicos para melhorar a eficiência do socorrista e reduzir a fadiga, com designs que priorizem a durabilidade, a portabilidade e a relação custo-benefício para uma ampla implementação.

Chapter 1

Introduction

Preface

This doctoral thesis has been submitted in fulfilment of the requirements for the PhD degree in Clinical and Health Services Research at the Faculty of Medicine of the University of Porto.

The motivation to contribute to the topic of cardiopulmonary resuscitation training first emerged during my master thesis in Bioengineering, inspired by the desire of developing technology that would enable anyone to acquire cardiopulmonary resuscitation skills. The project began with an assessment of the general public knowledge on basic life support [1], which served as a foundation for the development of training equipment for cardiopulmonary resuscitation (CPR) maneuvers [2]. Ultimately, we evaluated the tool’s impact on skill acquisition [3], demonstrating that a low-cost, feedback device for self-directed CPR training could provide an alternative or a complementary extension to traditional training methods.

Building upon this groundwork and motivated by the increasing adoption of CPR training devices with corrective feedback, this thesis conducts a systematic review of these tools and their effectiveness in enhancing skills acquisition and retention. Recognizing that the quality of CPR maneuvers depends on factors beyond the rescuer's knowledge and skills, this thesis further explores the other aspects of the rescuer's technique. Specifically, it investigates how the position and angle of the rescuer's arms influence the quality of CPR performance.

This first chapter provides a brief introduction to the topic, outlining the rationale and objectives of the research. Chapters two and three present the core publications that form the foundation of this thesis: (1) “Influence of Training With Corrective Feedback Devices on Cardiopulmonary Resuscitation Skills Acquisition and Retention: Systematic Review and Meta-Analysis”; (2) “Influence of rescuer position and arm angle on chest compression quality: An international multicentric randomized crossover simulation trial”. The fourth chapter discusses the key findings of this research, critically examines its limitations, and offers recommendations for future work in this domain.

Rationale

Cardiac Arrest

Cardiac arrest is a medical emergency that occurs when there is a loss of functional cardiac mechanical activity in association with an absence of systemic circulation, disrupting blood flow to the brain, lungs, and other vital organs [4]. It is a critical condition requiring immediate intervention to prevent death or severe complications.

The causes for cardiac arrest can be categorised into cardiac (i.e. acute myocardial infarction, lethal arrhythmia, cardiomyopathy, valvular heart disease, congenital heart disease, etc) and non-cardiac causes (trauma, bleeding, asphyxia, hypoxia, drug overdose, hypoglycaemia, hypothermia, epilepsy, septic shock, dehydration, etc) [4]. Cardiac arrest can also occur in seemingly healthy individuals, sometimes triggered by factors like intense physical activity or sudden stress [4].

The restoration of spontaneous and regular heartbeat and breathing is defined as return of spontaneous circulation (ROSC). Post-arrest hypotension and shock is common in patients surviving cardiac arrest, possibly resulting from acute myocardial injury, myocardial stunning, vascular dysfunction due to systemic inflammatory response, reperfusion injury, metabolic perturbations, and trauma from cardiopulmonary resuscitation (CPR) [5].

The incidence and survival rate from cardiac arrest varies between healthcare institutions and countries around the world. It also depends on the location and onset of the emergency, whether it occurs as an in-hospital cardiac arrest (IHCA) or as an out-of-hospital cardiac arrest (OHCA).

In Europe, the overall incidence of OHCA where CPR is attempted is 56 per 100 000 population, per year, with a survival rate of 8% [6]. Observed incidence rates of IHCA vary with a median of 1.5 per 1 000 admissions in the United Kingdom, 1.7 per 1 000 admissions in Sweden [7]. The survival rate from IHCA also vary from 18% in the United Kingdom, and approximately 30% in Denmark and Sweden [8].

Cardiac arrest management requires immediate, high-quality intervention from rescuers, who may be either healthcare professionals or laypeople. Optimizing the critical steps of the chain of survival promotes improved patient outcomes. These steps include the activation of the emergency response, the provision of high-quality CPR and early defibrillation, the provision of advanced resuscitation and effective post-ROSC care, as shown in Figure 1 [9].

Figure 1 - Chain of Survival for IHCA and OHCA.

<u>Cardiopulmonary Resuscitation</u>

CPR is a lifesaving technique used to maintain circulation and oxygenation in individuals experiencing cardiac arrest. It involves chest compressions to promote blood circulation to vital organs and, if possible, rescue breaths to provide tissue oxygenation. Research indicates that bystander CPR can double or even triple the chances of survival, highlighting its pivotal role in emergency response [10].

High-quality CPR is a key aspect for maximizing the chances of survival of the patient in cardiac arrest. Several components have been established as contributors to high-quality CPR, as shown in Table 1 [9].

Table 1 - Key aspects for high-quality Adult CPR.

Topic	Recommendations
Positioning and Location	Resuscitation should be performed, as soon as possible, where the victim is found, if high-quality CPR can be performed safely.
	Ideally, CPR should be performed on a firm surface and with the victim in the supine position.
	The rescuer should place the heel of one hand on the lower half of the victim's sternum, and the heel of the other hand on top of the first.
	The rescuer should optimize a 90-degree arm angle perpendicular to the victim's chest [11].
Compression Fraction, Pauses and Ventilation	Pauses in chest compressions should be as short as possible, no more than 10 seconds during ventilations or rhythm check.
	If there are more than one rescuer, it is reasonable to switch chest compressor approximately every 2 minutes (around 5 cycles of compressions and ventilations, at a ratio of 30:2), to prevent decrease in quality of compressions due to fatigue.
	Without an advanced airway, it is reasonable to pause compressions to deliver 2 breaths, each given over 1 second.
	After shock delivery, the rescuer should resume chest compressions immediately.
Compression Depth and Rate	Rescuers should perform chest compressions to a depth of at least 5 cm, and less than 6 cm.
	Rescuers should perform chest compressions at a rate of 100 to 120 compressions per minute (cpm).
	Rescuers should allow for complete chest wall recoil.
Feedback and Monitoring	Audiovisual feedback devices can be used during CPR for real-time performance optimization.

Both healthcare professionals and laypeople can perform CPR. While healthcare professionals are extensively trained in advanced resuscitation techniques, bystanders play a vital role in out-of-hospital emergencies [9,10]. Hands-only CPR, which involves only chest compressions without rescue breaths, is recommended if the rescuer is untrained or unwilling to provide mouth-to-mouth ventilation, or in cases where delivering rescue breaths may pose a risk or cause significant delay in starting chest compressions [9].

Training CPR

While the technique may seem straightforward, effective CPR requires proper training and regular practice [10].

Most cardiac arrests occur outside of hospitals, often in homes or public spaces [6]. In such situations, bystander intervention is crucial. Yet, many people hesitate to act due to a lack of confidence or knowledge [1]. Proper CPR training can empower individuals to take action during these critical moments, increasing survival rates and reducing long-term complications for victims [10].

One of the most common ways to learn CPR is through in-person training courses offered by organizations such as the Red Cross, the American Heart Association (AHA), the European Resuscitation Council (ERC), or local healthcare institutions. These courses provide hands-on practice with mannequins supported by certified instructors.

CPR training methodologies have evolved significantly, incorporating technology and evidence-based practices to enhance learning outcomes [10]. Traditional classroom training remains a cornerstone, emphasizing direct instructor guidance and peer collaboration. Participants practice chest compressions and rescue breaths on mannequins, often with devices that provide feedback [12].

Proficiency in CPR requires regular practice, as skills can deteriorate over time without reinforcement [13]. Experts recommend taking a CPR refresher course every two years to maintain certification and stay updated on the latest guidelines [10]. However, more frequent practice may be beneficial, particularly for individuals who are not regularly exposed to CPR scenarios. Some training programs offer annual skill checks or shorter refresher sessions to help participants retain their knowledge and confidence.

Feedback Devices

CPR training feedback devices have emerged as essential tools in modern resuscitation education [10]. These devices provide real-time, objective feedback on the quality of CPR performance, enabling trainees to refine their technique and build confidence [10].

Traditional CPR training relies heavily on instructor observation and subjective evaluations. While experienced instructors provide valuable guidance, human assessment can sometimes miss subtle errors in compression depth, rate, or hand placement [14,15]. CPR training feedback devices fill this gap by offering precise, data-driven insights. As research increasingly highlights the critical role of high-quality CPR in improving outcomes, the need for accurate performance assessment has become more apparent.

CPR training feedback devices come in various forms, ranging from integrated features within training mannequins to standalone monitors. These devices typically measure key metrics such as: (1) compression depth; (2) compression rate; (3) chest wall recoil; and (4) hand placement.

Many feedback devices provide visual, auditory, or haptic cues to alert trainees when their performance deviates from recommended guidelines. They vary in complexity and design, catering to different training environments and budgets. Common types include [12,16]: (1) Integrated Mannequins: Many modern mannequins come equipped with built-in feedback sensors. (2) Standalone Monitors: Compact and portable, standalone monitors attach to traditional mannequins and offer a cost-effective solution; (3) Wearable Devices: Some systems use wearable sensors to track hand placement and movement, offering flexibility for training in unconventional settings; (4) Mobile Apps: Paired with mannequins or standalone sensors, mobile apps provide detailed reports, performance tracking, and even gamification elements to make learning more engaging.

Prior to 2015, CPR guidelines broadly categorized feedback devices, including those that provide general guidance but not correction of the skill: "The use of feedback devices or prompts, such as metronomes,..." [17]. The guidelines published in 2015 clearly distinguished the devices providing corrective feedback from the other type of guiding devices: “In conducting this analysis, we separated CPR feedback devices that provide corrective feedback to the learner from prompt devices that provide only a tone or rate for the rescuer to follow (with no feedback on how the learner is actually performing).” [18]. Our focus is on studies using corrective feedback devices for skills acquisition and retention.

CPR training feedback devices represent a transformative step forward in teaching life-saving skills. By providing real-time, objective feedback, these devices enhance learning outcomes, build confidence, and ensure high-quality CPR training. As technology continues to evolve, feedback devices are likely to become even more accessible and sophisticated, further improving the effectiveness of CPR training programs.

<u>CPR Quality</u>

Apart from skills acquisition and retention, several factors can impact the quality of CPR, ranging from individual rescuer characteristics to environmental and situational variables. These factors are relevant to provide a comprehensive understanding of CPR performance and allow the rescuer to recognize them and be aware of their impact.

- Rescuer fatigue: Performing effective CPR is physically demanding. Fatigue can lead to shallower compressions and inconsistent technique. Switching rescuers every two minutes can help maintain quality [19,20].
- Environmental challenges: The location of a cardiac arrest can affect CPR quality. Limited space, uneven surfaces, or the presence of crowds may hinder proper positioning and movement [21,22].
- Stress: Rescuers often face intense stress during emergencies, which can impair decision-making and motor skills [23].
- Rescuer Characteristics: Aspects such as body mass index (BMI) and exercise habits are significant predictors of high-quality CPR [24].
- Rescuer Posture: The position of the rescuer, its posture (i.e. standing vs kneeling) and the arm’s angle can affect the quality of CPR [11,25].

Feedback devices should not only monitor technical aspects like compression depth and rate but also detect signs of declining quality that may indicate fatigue, such as a gradual decrease in force or rhythm. By alerting rescuers when performance wanes, these devices can prompt timely interventions, such as switching providers, ensuring that CPR quality is maintained throughout the resuscitation effort.

The quality of CPR is a decisive factor in the survival and recovery of cardiac arrest victims. By adhering to established guidelines, using tools to measure performance, and addressing factors that influence quality, rescuers can maximize the effectiveness of their efforts. Regular training, combined with advancements in technology, ensures that individuals are better equipped to deliver high-quality CPR when it matters most.

Objectives

This thesis seeks to investigate the factors influencing CPR training and performance, addressing the following research questions:

- What is the impact of corrective feedback devices on CPR skill acquisition and retention?
- How do position and arm angle influence the quality of CPR?

Feedback devices have become a standard component of contemporary CPR training programs. Given the wide variety of available brands and technologies, it is crucial to evaluate their effectiveness in facilitating skills acquisition and retention. Additionally, the ability of these devices to provide detailed CPR metrics makes them valuable research tools, facilitating the investigation of adjacent factors - such as the rescuer's posture or ergonomic variables - that influence CPR quality.

Therefore, this thesis has two main objectives:

1. To assess the impact of corrective feedback devices on CPR skill acquisition and retention, in comparison with instructor-led feedback;
2. To study the influence of rescuer position and arm angle on chest compression quality, using feedback devices for assessment of CPR quality.

References

1. Sá-Couto, C., & Nicolau, A. (2019). General public's knowledge regarding basic life support: A pilot study with a Portuguese sample. Acta Médica Portuguesa, 32(2), 111-118.
2. Nicolau, A. F. S. (2018). Development and validation of a low-cost tool for CPR self-training (Master's thesis, Universidade do Porto (Portugal)).
3. Sá-Couto, C., Ferreira, A. M., Almeida, D., Nicolau, A., & Vieira-Marques, P. (2018). Evaluation of skills acquisition using a new low-cost tool for CPR self-training. Porto Biomedical Journal, 3(1), e8.
4. Myat, A., Song, K. J., & Rea, T. (2018). Out-of-hospital cardiac arrest: current concepts. The Lancet, 391(10124), 970-979.
5. Gonzalez, D., Dahiya, G., Mutirangura, P., Ergando, T., Mello, G., Singh, R., ... & Elliott, A. M. (2024). Post Cardiac Arrest Care in the Cardiac Intensive Care Unit. Current Cardiology Reports, 26(2), 35-49.
6. Gräsner, J. T., Wnent, J., Herlitz, J., Perkins, G. D., Lefering, R., Tjelmeland, I., ... & Bossaert, L. (2020). Survival after out-of-hospital cardiac arrest in Europe-Results of the EuReCa TWO study. Resuscitation, 148, 218-226.
7. Barros, A. J., & Enfield, K. B. (2023). In-Hospital Cardiac Arrest. *Emergency Medicine Clinics*, *41*(3), 455-464.
8. Andersen, L. W., Holmberg, M. J., Berg, K. M., Donnino, M. W., & Granfeldt, A. (2019). In-hospital cardiac arrest: a review. *Jama*, *321*(12), 1200-1210.
9. Panchal, A. R., Bartos, J. A., Cabañas, J. G., Donnino, M. W., Drennan, I. R., Hirsch, K. G., ... & Berg, K. M. (2020). Part 3: adult basic and advanced life support: 2020 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation, 142(16_Suppl_2), S366-S468.
10. Cheng, A., Magid, D. J., Auerbach, M., Bhanji, F., Bigham, B. L., Blewer, A. L., ... & Donoghue, A. (2020). Part 6: resuscitation education science: 2020 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation, 142(16_Suppl_2), S551-S579.
11. Mayrand, K. P., Fischer, E. J., & Ten Eyck, R. P. (2015). A simulation-based randomized controlled study of factors influencing chest compression depth. Western Journal of Emergency Medicine, 16(7), 1135.
12. Yeung, J., Meeks, R., Edelson, D., Gao, F., Soar, J., & Perkins, G. D. (2009). The use of CPR feedback/prompt devices during training and CPR performance: a systematic review. Resuscitation, 80(7), 743-751.
13. Anderson, R., Sebaldt, A., Lin, Y., & Cheng, A. (2019). Optimal training frequency for acquisition and retention of high-quality CPR skills: a randomized trial. Resuscitation, 135, 153-161.

14. Brennan, E. E., McGraw, R. C., & Brooks, S. C. (2016). Accuracy of instructor assessment of chest compression quality during simulated resuscitation. Canadian Journal of Emergency Medicine, 18(4), 276-282.
15. Nagafuchi, K., Hifumi, T., Nishimoto, N., Kondo, Y., Yoshikawa, K., Iwami, T., & Kuroda, Y. (2019). Chest Compression Depth and Rate—Effect on Instructor Visual Assessment of Chest Compression Quality—. Circulation Journal, 83(2), 418-423.
16. Gugelmin-Almeida, D., Tobase, L., Polastri, T. F., Peres, H. H. C., & Timerman, S. (2021). Do automated real-time feedback devices improve CPR quality? A systematic review of literature. Resuscitation plus, 6, 100108.
17. Bhanji, F., Mancini, M. E., Sinz, E., Rodgers, D. L., McNeil, M. A., Hoadley, T. A., ... & Hazinski, M. F. (2010). Part 16: education, implementation, and teams: 2010 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation, 122(18_suppl_3), S920-S933.
18. Bhanji, F., Donoghue, A. J., Wolff, M. S., Flores, G. E., Halamek, L. P., Berman, J. M., ... & Cheng, A. (2015). Part 14: education: 2015 American Heart Association guidelines update for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation, 132(18_suppl_2), S561-S573.
19. Abelairas-Gómez, C., Rey, E., González-Salvado, V., Mecías-Calvo, M., Rodríguez-Ruiz, E., & Rodríguez-Núñez, A. (2018). Acute muscle fatigue and CPR quality assisted by visual feedback devices: a randomized-crossover simulation trial. PLoS One, 13(9), e0203576.
20. Ho, C. S., Hsu, Y. J., Li, F., Tang, C. C., Yang, C. P., Huang, C. C., ... & Chang, C. H. (2021). Effect of Ambulance Stretcher Bed Height Adjustment on CPR Quality and Rescuer Fatigue in a Laboratory Environment. International Journal of Medical Sciences, 18(13), 2783.
21. Holt, J., Ward, A., Mohamed, T. Y., Chukowry, P., Grolmusova, N., Couper, K., ... & Perkins, G. D. (2020). The optimal surface for delivery of CPR: a systematic review and meta-analysis. Resuscitation, 155, 159-164.
22. Choi, S., Kim, T. H., Hong, K. J., Lee, S. G. W., Park, J. H., Ro, Y. S., ... & Do Shin, S. (2023). Comparison of prehospital resuscitation quality during scene evacuation and early ambulance transport in out-of-hospital cardiac arrest between residential location and non-residential location. *Resuscitation*, *182*, 109680.
23. Vincent, A., Semmer, N. K., Becker, C., Beck, K., Tschan, F., Bobst, C., ... & Hunziker, S. (2021). Does stress influence the performance of cardiopulmonary resuscitation? A narrative review of the literature. *Journal of critical care*, *63*, 223-230.
24. Lin, C. C., Kuo, C. W., Ng, C. J., Li, W. C., Weng, Y. M., & Chen, J. C. (2016). Rescuer factors predict high-quality CPR—a manikin-based study of health care providers. The American journal of emergency medicine, 34(1), 20-24.
25. Foo, N. P., Chang, J. H., Lin, H. J., & Guo, H. R. (2010). Rescuer fatigue and cardiopulmonary resuscitation positions: a randomized controlled crossover trial. Resuscitation, 81(5), 579-584.

Chapter 2

Influence of Training With Corrective Feedback Devices on Cardiopulmonary Resuscitation Skills Acquisition and Retention: Systematic Review and Meta-Analysis

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JMIR Medical Education, 10, e59720

Introduction

Sudden cardiac arrest (SCA) is a global leading cause of death [1], resulting from the interruption of cardiac mechanical activity and confirmed by the absence of signs of circulation [2]. In 2021, the estimated incidence of out-of-hospital cardiac arrests (OHCAs) in the United States was 92.3 cases per 100,000 individuals, with an adult rate of survival to hospital discharge following OHCA of 9.1% [2]. In Europe, the most recent estimation of the incidence of OHCA was 89 cases per 100,000 individuals, with an average survival rate of 8% [1,3,4]. Regarding in-hospital cardiac arrest, based on the latest data from the United Kingdom and the United States, there are around 1.6 to 2.85 cases of in-hospital cardiac arrest per 1000 hospital admissions, with a survival rate from 18.4% to 25.6% [5]. Globally, the incidence of SCA keeps increasing, representing a significant public health problem [1].

Early and high-quality cardiopulmonary resuscitation (CPR) can double or triple the survival rate from SCA [6,7]. CPR is an emergency lifesaving intervention for SCA that can be provided by both laypeople and health care professionals. It consists of applying chest compressions and rescue breaths to the victim. For adults, a 30:2 compressions-to-breaths ratio is recommended [7,8]. Chest compression is the most important component of CPR, as it provides organ perfusion and oxygenation during SCA [7,8]. Chest compression–only approach is acceptable if lay rescuers are untrained or are reluctant to provide rescue breaths [7]. The American Heart Association and the European Resuscitation Council have established detailed guidelines [7,8] for performing high-quality chest compressions during CPR. Key recommendations include placing hands on the lower half of the sternum, ensuring a compression depth of at least 5 cm (2 inches) but not exceeding 6 cm (2.4 inches), maintaining a compression rate of 100 to 120 compressions per minute, with minimal interruptions, and allowing the chest wall to fully recoil after each compression. Additionally, if possible, chest compressions should be performed on a firm surface.

Improving CPR quality by adhering to established guidelines has been shown to positively impact patient outcomes, particularly by increasing the survival rate of SCA victims [9]. To achieve this, training is recommended for both laypeople and health care professionals. Such training aims to improve CPR skills, thereby elevating the quality of the maneuvers performed and increasing patient safety [10]. Studies have shown that the quality of CPR performed by health care professionals and laypeople is usually poor [11-14]. CPR training may improve providers' confidence and performance [15-17]. A typical CPR training session is delivered at a single period of time, with no interruptions, and supervised by certified instructors [18].

During a CPR training session, the feedback provided to the participant is crucial; however, the instructor's assessment of the chest compression quality often tends to be subjective and suboptimal [19,20]. The effectiveness of the training methods of CPR instructors could be significantly enhanced by incorporating supportive devices, which offer quantitative assessments and objective feedback on chest compression quality [14,19,21].

A CPR training device with corrective feedback enhances the learning experience by offering audiovisual feedback based on assessed CPR quality parameters. These devices typically provide real-time feedback, allowing the participant to immediately adjust and improve their technique while performing maneuvers [22-25]. Since 2010, both the American Heart Association and European Resuscitation Council guidelines have endorsed the use of prompts and feedback devices for CPR training, recognizing their role in promoting skills acquisition and retention [26,27]. Initially, these guidelines broadly categorized feedback devices, including those offering general guidance without correcting skills (eg, metronome). However, as of 2015, the guidelines clearly distinguished between devices that provide corrective feedback and those that offer general guidance [28].

In the literature, there are several studies related to the use of both corrective and guiding feedback devices in CPR training, involving different target populations (from laypeople to health care professionals), training methodologies (different durations, formats, and assessment methods), and equipment. This diversity in study design makes it difficult to generalize their results. Furthermore, given the impact of corrective feedback devices in CPR training and the high potential to contribute to better quality in CPR maneuvers, it is of most relevance to study their influence through evidence synthesis studies.

To our knowledge, the existing reviews on this topic [29-32] lack at least 1 key aspect: (1) a focus on corrective feedback devices, as recommended by the recent guidelines [18], excluding studies on guiding devices; (2) an expanded target audience that includes both laypeople and health care professionals, training on both adult and pediatric manikins; (3) the provision of a reliable meta-analysis; and (4) the exclusion of studies focusing on real emergency setting or adjacent aspects to CPR training (eg, testing feedback devices).

Some existing reviews addressing similar topics are based on outdated guidelines [29,30] or have a broader scope, including the analysis of feedback devices in real clinical settings [29-31]. The distinction between studies focusing on specific target groups (eg, laypeople [32] or health care professionals [30,31]), along with varying methodologies and the exclusion of meta-analysis [29,31], highlights the limitations of current research.

This systematic review and meta-analysis aim to comprehensively survey the literature to characterize and assess the impact of corrective feedback devices on CPR skills acquisition and retention for both laypeople and health care professionals compared to the absence of these feedback devices. Training duration was also studied.

Methods

Study Design

This study is a systematic review and meta-analysis following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 guidelines [33], as shown in Appendix 1, and the Cochrane Handbook for Systematic Reviews of Interventions [34]. The study protocol was developed by the research team and registered in PROSPERO (registration CRD42021240953). The protocol can be accessed through the PROSPERO website. No ethics approval was required.

Information Sources and Search Strategy

Searches were conducted in MEDLINE (through PubMed), Web of Science, and Scopus, including publications between January 2015 and December 2023. The search strategy and query were designed to include all relevant publications considering the established eligibility criteria. The search query is presented in Table 2 and Appendix 2 and includes keywords based on three categories: (1) CPR, (2) feedback devices, and (3) outcomes. Each category considered several keywords that were searched in the publications' titles and abstracts. The search strategy was adapted to all included databases. The reference lists of relevant systematic reviews were screened to identify additional studies. Duplicates were removed using Mendeley Reference Manager and, later, verified using CADIMA software (Julius Kühn-Institut) [35].

Table 2 - General Search Strategy.

Publications from January 2015 to December 2023 in MEDLINE, Web of Science, and Scopus
1. Cardiopulmonary resuscitation [tab]
2. CPR [tab]
3. Basic life support [tab]
4. BLS [tab]
5. Resuscitation [tab]
6. 1 OR 2 OR 3 OR 4 OR 5
7. Training [tab]
8. Feedback [tab]
9. Manikin* [tab]
10. Device* [tab]
11. Prompt* [tab]
12. Audiovisual [tab]
13. Technology [tab]
14. Simulat* [tab]
15. 7 OR 8 OR 9 OR 10 OR 11 OR 12 OR 13 OR 14
16. Quality [tab]
17. Performance [tab]
18. Compression* [tab]
19. Acquisition [tab]
20. Retention [tab]
21. 16 OR 17 OR 18 OR 19 OR 20
22. 6 AND 15 AND 21

Eligibility Criteria

The PICOS (participants, intervention, control, outcomes, and studies) framework was used to support the identification of the eligibility criteria.

- The participants or population (P) was either laypeople or health care professionals. No age limitations were included.
- The intervention (I) was the use of CPR training devices with feedback, providing corrective information to the learner during a training program or exercise. These included instrumented manikins, smart devices, and feedback provided by medical devices or other technologies.
- The comparator or control (C) was CPR training without corrective feedback devices, including instructor-led demonstration or feedback using static manikins or autonomous training (without instructor) using static manikins.
- The main outcomes (O) selected were CPR quality parameters, namely, the quality of chest compression–related components.
- The type of studies (S) included was randomized controlled trials (RCTs).

Studies that included participants performing CPR in real patients were excluded. Studies focused on team CPR performance were excluded. Animal studies, case reports, conference abstracts, reviews, trial protocols, and studies with incomplete or missing data were excluded. Publications prior to 2015 were excluded to minimize bias from outdated CPR guidelines and to ensure that the technology in the included studies provides corrective feedback, thus reducing heterogeneity and enhancing the reliability of the findings. No country or language restrictions were considered.

Selection Process

The study selection process was executed using CADIMA software [35], which facilitated effective management and tracking of the selection process as well as analysis of interreviewer agreement.

Initially, a pilot analysis was conducted by 2 reviewers (AN and IJ), who independently assessed 100 abstracts. This preliminary stage aimed to evaluate the strength of agreement between reviewers and to identify and adjust any significant discrepancies in their assessment. The interrater reliability was quantified using the Cohen's κ statistic.

After refining the analysis approach, as informed by the initial pilot analysis, the reviewers transitioned to the screening phase. During this phase, titles and abstracts underwent an independent screening process conducted by the same 2 reviewers (AN and IJ). This step was crucial to ensure a thorough and unbiased selection process, and only relevant studies were considered for full-text review.

The next step was the inclusion phase, where selected papers were subjected to a comprehensive full-text analysis. This phase was expanded to include a third reviewer (CSC) to bring additional perspective and expertise, particularly in cases of initial disagreement. All 3 reviewers (AN, IJ, and CSC) independently analyzed the full texts.

In both the screening and inclusion phases, differences in opinions were resolved through in-depth discussions until a consensus was reached. During the inclusion phase, each reviewer meticulously documented the reasons for excluding papers. This step was critical for ensuring transparency and accountability in the selection process.

Data Extraction and Outcomes

Data extraction was performed by 2 reviewers (IJ and AN) using a standardized data extraction form. CPR quality parameters were considered, namely the overall chest compression quality score. Additional parameters were extracted, including compression depth, compression frequency, chest wall recoil, and hand positioning.

Extracted data included authors, year of publication, country, study design, type of participants (laypeople or health care professionals), type of intervention, type of control, feedback device, number of participants in each group, training duration, CPR quality overall score (%), and quality of each parameter of chest compressions (%).

Risk of Bias Assessment

The quality of the selected studies was assessed using the Cochrane risk-of-bias tool for randomized trials (RoB 2) [36] by 2 independent reviewers (AN and IJ). RoB 2 tool evaluates each study using 5 different criteria: randomization process, deviations from intended interventions, missing outcome data, measurement of the outcome, and selection of the reported result. For each item, the risk was marked as low, some concerns, and high. Uncertainties and disagreements were addressed and resolved through consensus. Studies were not blinded regarding authors, institutions, and journals. Publication bias was assessed through a funnel plot.

Synthesis Methods

A meta-analysis and a narrative synthesis were conducted to identify associations and explore heterogeneity in the selected studies. Data were analyzed using R (version 4.3.2; R Foundation for Statistical Computing). In the meta-analysis, the mean and SD of the data were primarily used. In cases where studies presented median and IQR, these were converted into mean and SD under the assumption of normally distributed data [37]. This assumption is based on the statistical principle that, in a normally distributed sample, the mean is an approximate measure of the median, and the SD can be estimated by dividing the IQR by 1.35 [37,38]. If the mean and SD could not be estimated, those were excluded from the meta-analysis. The effect size was calculated using the mean differences with 95% CIs. The random-effects model was used because of the variation in study characteristics. Heterogeneity was studied using I^2 statistic, with values below 40% representing low heterogeneity [34]. Several studies had a multiple-arm RCT design; in those cases, the relevant groups (intervention and control) were included in the pairwise comparison of intervention groups. Studies with distinct groups of adult and pediatric CPR training were included with multiple intervention groups.

Sensitivity analysis was conducted through subgroup analysis to identify the sources of heterogeneity and measure the effects within each subgroup (eg, acquisition vs retention). This analysis also determined if the performance scores varied across the subgroups. The subgroup analyses explored potential effect modifiers, including skills acquisition (assessed immediately after training), training duration (≤30 vs >30 minutes), and time elapsed after training (3 vs 9-12 months). Other subgroups were considered (eg, target audience—health care professionals vs laypeople) but were not performed due to the limited or absent number of trials available. Subgroups with enough data were used for meta-analysis.

A narrative synthesis was performed for all included studies, including those excluded from meta-analysis, following the SWiM (Synthesis Without Meta-Analysis) reporting guidelines [39]. The studies were grouped by the training-assessment interval, clearly distinguishing between skills acquisition and retention over time. When available, the main outcome selected was chest compression score. The certainty of evidence was evaluated using the GRADE (Grading of Recommendations Assessment, Development and Evaluation) approach [40].

Results

Search Results

The studies' selection process is represented in the PRISMA flow diagram [33] (Figure 2). The initial search retrieved 10,095 results, of which 4427 were duplicates. Of the remaining 5668 unique publications, 5619 were excluded after screening the title and abstract. The remaining 49 publications were screened for a full review, resulting in the 20 studies included. All included studies reported approval by an ethical committee.

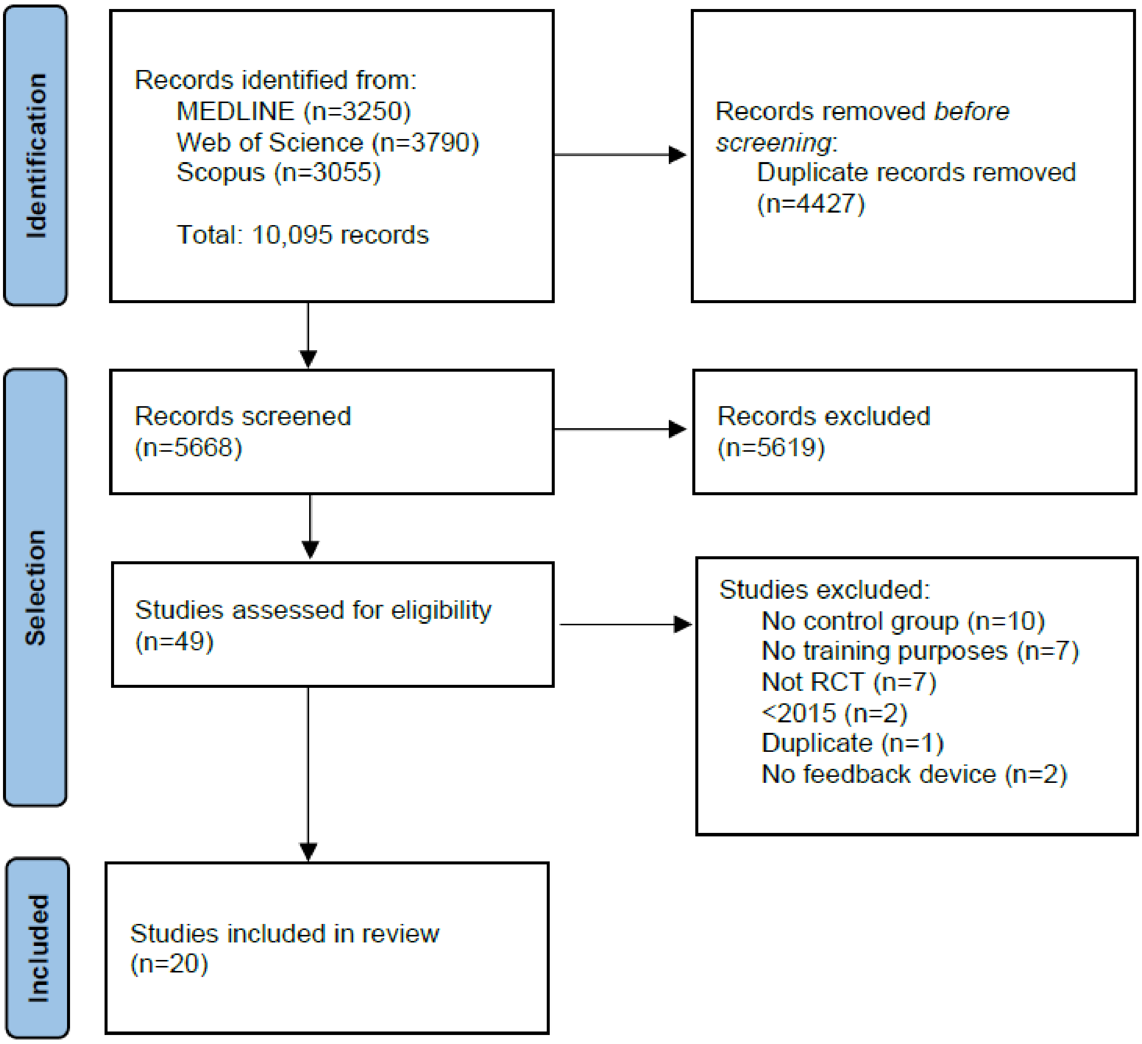

Figure 2 - PRISMA flow diagram of the selection process.

Cohen's κ coefficient of agreement between the reviewers was 0.49 at the pilot screening stage, representing a fair agreement [34]. Throughout the full screening stage, the Cohen's κ coefficient improved to 0.62, representing a good agreement. The overall percentage of agreement was 99%.

Characteristics of Included Studies

Table 3 presents the main characteristics of the 20 included studies. Studies data were collected from 15 distinct countries. The study population is diverse, including laypeople [23,41-43], health care professionals [44-46], and lifeguards [47], among others. The sample size is heterogeneous. Although the majority of the included studies used Laerdal QCPR technology in the intervention group, the training methodologies vary substantially, with considerable differences in training duration, elapsed time to assessment, and assessment format (Table 4).

Table 4 details relevant characteristics regarding study design and outcomes. Training methodologies included short single training sessions [23,41,42,44,46,47,49,50,52,53,55,56,58,59], short recurrent practice over time [45], and long single training sessions [48,51,54,57]. The educational adjuncts in all studies were based on corrective feedback devices, although some also included video-based instructions or allied corrective feedback devices with instructor feedback [42,43,46,48,51,55,58,59]. Regarding training-assessment interval, skills acquisition assessment was not comprised in all studies, and assessment intervals for skills retention span from few weeks to several months. Skills acquisition was assessed by 14 studies [41-44,46,48-53,57-59]. In total, 6 studies presented the assessment of skills retention at 3 months [42,44,45,49,57,59], and 3 studies [45,49,59] included an assessment at 9 to 12 months. Assessment duration also varied among the studies, with most considering 2 minutes of CPR, with only 4 studies using a different assessment duration [41,47,53,55]. Assessment exercises ranged from continuous chest compression [23,41,42,45,49,56-59] to a defined number of CPR cycles [44,55]. The outcomes were mostly presented using mean and SD and median and IQR for chest compression–related parameters and overall score. Additional specifications of the included studies can be found in Appendix 3.

Table 3 - Characteristics of the included studies.

Study	Country	Sample	Previous training	Feedback device or data collection
Baldi et al (2017) [41]	Italy	450 Laypeople	Prior to the study: no previous training Upon entry to the study: 5-hour BLS[a] or AED[b] courses with 1 hour of theory and 4 hours of practice, with different training time with feedback	Training: Laerdal Resusci Anne Assessment: Laerdal Resusci Anne
Chamdawala et al (2021) [42]	United States	220 High school students	Prior to the study: regardless Upon entry to the study: 30-minute standard CPR[c] training with an instructor	Training: Laerdal Resusci Anne Assessment: Laerdal Resusci Anne
Cortegiani et al (2017) [23]	Italy	125 High school students	Prior to the study: unknown Upon entry to the study: 30-minute standard BLS-D[d] training with an instructor; practice until reached the minimum technical skill	Training: Laerdal Resusci Anne Assessment: Laerdal Resusci Anne
Eshel et al (2019) [48]	Israel	145 First-year medical students	Prior to the study: no previous training Upon entry to the study: 1-hour lecture and 10 academic hours of review and hands-on CPR training	Training: Laerdal Resusci Anne Assessment: Laerdal Resusci Anne

González-Santano et al (2020) [47]	Spain	30 Beach lifeguards	Prior to the study: BLS training in the previous 2 years Upon entry to the study: 12-minute session of training with at least 6 minutes of CPR	Training app: Massage cardiaque et DSA app Training device: Laerdal Resusci Anne Assessment: Laerdal Resusci Anne
Jang et al (2020) [49]	South Korea	95 University students	Prior to the study: unknown Upon entry to the study: standard BLS or AED training program	Training: BT-SEEM BT-Inc CPR training manikin Assessment: BT-CPTA BT-Inc CPR training manikin
Katipoglu et al (2021) [50]	Poland	111 First-year medical students	Prior to the study: unknown Upon entry to the study: standard BLS course	Training: Laerdal Resusci Anne Assessment: Laerdal Resusci Anne
Kim et al (2021) [51]	South Korea	64 Junior nursing students	Prior to the study: no previous training Upon entry to the study: 40-minute theoretical online lecture session and an 80-minute noncontact practice session	Training: Laerdal Resusci Anne Assessment: Laerdal Resusci Anne
Labuschagne et al (2022) [52]	South Africa	53 Final-year medical students	Prior to the study: conventional CPR training in the third year of the medical program Upon entry to the study: 1-hour CPR theoretical lesson every 2 weeks	Training: QCPR manikins Assessment: QCPR manikins

Lee et al (2023) [44]	Taiwan	90 Nurses	Prior to the study: recertification CPR program Upon entry to the study: 10-minute standardized CPR lecture and 30-minute practice	Training: Laerdal Little Anne QCPR Assessment: Laerdal Little Anne QCPR
Lin et al (2018) [45]	Canada	87 Health care providers	Prior to the study: PALS[e] or ACLS[f] certification within the past 2 years Upon entry to the study: standard BLS course	Training: Laerdal Resusci Anne Assessment: Laerdal Resusci Anne
Moreno et al (2021) [46]	Spain	212 Primary care staff	Prior to the study: unknown Upon entry to the study: 10-minute standardized CPR lecture and 6-minute practice	Training: Laerdal Little Anne QCPR Assessment: Laerdal Little Anne QCPR
Pavo et al (2016) [53]	Austria	326 Third-year medical students	Prior to the study: basic BLS skills Upon entry to the study: 2 hours of standard BLS (AED-BLS) training; practice until feel sufficient confidence	Training: HeartStart MRx with Q-CPR-Technology on AmbuManC manikin Assessment: AmbuManC manikins with the Ambu CPR software

Sá-Couto et al (2018) [54]	Portugal	39 Medical and engineering students	Prior to the study: no previous training Upon entry to the study: revision of CPR guidelines and algorithm	Training: CPR personal trainer on Simulaids Adult Brad Assessment: video analysis and checklist
Sarac (2017) [55]	Turkey	76 Second-year university students	Prior to the study: no previous training Upon entry to the study: 14-week first aid course with 2 weeks, 2 hours per week CPR section	Training: Laerdal Little Anne Assessment: Laerdal Resusci Anne
Smereka et al (2019) [56]	Poland	94 First-year nursing students	Prior to the study: no previous training Upon entry to the study: standard BLS course+10-minute practical training	Training: TrueCPR on an unknown training manikin Assessment: unknown training manikin
Suet et al (2020) [57]	France	61 Second-year medical students	Prior to the study: unknown Upon entry to the study: 1-day duration course with CPR training representing half of the day	Training app: iPhone app ZOLL PocketCPR on Laerdal Resusci Anne Training QCPR: Laerdal Resusci Anne Assessment: Laerdal Resusci Anne

Tanaka et al (2019) [43]	Japan	497 Laypeople	Prior to the study: regardless Upon entry to the study: instructor-led lecture followed by psychomotor practice focused on chest-compression CPR	Training: Laerdal Little Anne with QCPR Classroom Assessment: Laerdal Little Anne with QCPR Classroom
Wagner et al (2019) [58]	Austria	653 Third-year medical students	Prior to the study: unknown Upon entry to the study: revision of CPR guidelines and demonstration of the CPR algorithm by an instructor	Training: Laerdal Resusci Anne Assessment: Laerdal Resusci Anne
Zhou et al (2020) [59]	China	97 Third-year medical students	Prior to the study: regardless Upon entry to the study: 45-minute CC[g]-only CPR training program with 5 cycles of CC on manikins	Training: Laerdal Resusci Anne Assessment: Laerdal Resusci Anne

[a]BLS: basic life support. [b]AED: automated external defibrillator. [c]CPR: cardiopulmonary resuscitation. [d]BLS-D: basic life support and defibrillation. [e]PALS: pediatric advanced life support. [f]ACLS: advanced cardiovascular life support. [g]CC: chest compression.

Table 4 - General design and outcomes of included studies.

Study	Intervention or control	Assessment	Training-assessment interval	Main outcomes or results
Baldi et al (2017) [41]	Control: BLS[a] or AED[b] course without any feedback. Intervention SF[c]: BLS or AED with a 1-minute training session with a feedback device. Intervention LF[d]: BLS or AED with a 10-minute training session with a feedback device.	1-minute chest compression session without feedback.	Postintervention	The percentage of compressions with correct depth was higher in the LF group compared to the control (75.7% vs 66.6%).
Chamdawala et al (2021) [42]	Control: practice CPR[e] with a schoolteacher. Training duration not available. Intervention: 2-minute training session with feedback device and instructor verbal prompts if needed.	2-minute chest compression session without feedback.	Postintervention 10 weeks 28 weeks 52 weeks	The intervention group had a higher compression score (61%) than the control group (41%).
Cortegiani et al (2017) [23]	Control: 2-minute training session with an instructor. Intervention: 2-minute training session with feedback device.	2-minute chest compression session without feedback.	7 days	The intervention group had a higher compression score (90%) than the control group (67%).

Eshel et al (2019) [48]	Control: academic course with 10 hours of CPR training with an instructor. Intervention: academic course with 10 hours of CPR training with instructor and feedback device.	CPR OSCE[f] evaluation at the end of the course. Assessment duration not available.	Postintervention	The intervention group had a higher chest compression fraction (57%) than the control group (49%).
González-Santano et al (2020) [47]	Control: at least, 6-minute training session with instructor. Intervention—app: at least, a 6-minute training session with the app. Intervention—feedback device: at least, a 6-minute training session with a feedback device.	3-minute CPR session without feedback.	Between 7 and 15 days	The percentage of compressions with correct depth was higher in the intervention group (68.2% vs 30.8%).
Jang et al (2020) [49]	Control: four 2-minute sessions of CPR without feedback. Intervention: four 2-minute sessions of CPR with a feedback device.	2-minute chest compression session without feedback.	Postintervention 3 months 6 months 9 months	The intervention group presented higher percentage of adequate chest compression depth than the control group (51% vs 26.9%).

Katipoglu et al (2021) [50]	Control: 15-minute CPR training session without feedback. Intervention: 15 minutes of CPR training with a feedback device.	2-minute CPR session with feedback for the intervention group on postintervention assessment and without feedback on 1-month follow-up.	Postintervention 1 month	The intervention group presented better depth on chest compressions than the control group (50 vs 39 mm).
Kim et al (2021) [51]	Control: 80-minute practice session with nurse. Intervention: 80-minute practice session with feedback device and feedback from nurse.	Not available.	Postintervention 4 weeks	The intervention group had a slightly higher score in CPR performance (37.23) than the control group (33.06).
Labuschagne et al (2022) [52]	Control: 10-minute standard CPR training without an instructor. Intervention: 10-minute CPR training with a feedback device.	2-minute CPR session without feedback	Postintervention	Similar results in both groups.
Lee et al (2023) [44]	Control: 30-minute standard CPR training with an instructor. Intervention: 30-minute CPR training with a feedback device.	5 cycles of CPR	Postintervention 12 weeks	The intervention group had significantly higher chest compression scores when compared to the control group.

Lin et al (2018) [45]	Control: standardized AH[g] BLS course with an instructor. Training duration not available. Intervention: 2-minute training session with a feedback device, at least once a month.	2-minute chest compression session without feedback.	3 months 6 months 9 months 12 months	The intervention group had a greater proportion of participants with excellent CPR (54.3%) than the control group (14.6%).
Moreno et al (2021) [46]	Control: CPR training with an instructor. Intervention: CPR training with feedback device and instructor.	2-minute CPR session without feedback.	Postintervention 6 months	The main outcome improved with statistical significance in the intervention group with respect to control.
Pavo et al (2016) [53]	Control: CPR training session with feedback provided by a team member. Training duration not available. Intervention: CPR training session with feedback provided by feedback device. Training duration not available.	8-minute, 2-rescuer CPR session without feedback.	Postintervention	The quality of CPR in control and intervention groups was similar.

Sá-Couto et al (2018) [54]	Control: 1-hour training session with an instructor. Intervention: 1-hour training session with a feedback device.	2-minute BLS algorithm session without feedback, rated with a checklist.	1 week	Both groups presented identical mean differences for the total score, with no statistical difference.
Sarac (2017) [55]	Control: first aid course with instructor. Intervention—real time: 10 CPR sets with real-time feedback provided by feedback device and instructor when necessary. Intervention—report: 10 CPR sets with instructor feedback and printed report of CPR skills after training.	10 sets of CPR without feedback.	4 weeks	Both interventions performed better in some compression skills than the control group.
Smereka et al (2019) [56]	Control: 30-minute autonomous training session without a feedback device. Intervention: 30-minute training session with a feedback device.	2-minute chest compression session without feedback.	1 month	The intervention group is associated with better CPR skills 1 month after the training period.

Suet et al (2020) [57]	Control: half-day CPR training session with an instructor. Intervention—app: half-day CPR training session with an instructor and guided iPhone app PocketCPR. Intervention—QCPR: half-day CPR training session with a feedback device.	2-minute chest compression session without feedback.	Postintervention 3 months	QCPR group had a higher median compression score (72%) than the control group (22.5%).
Tanaka et al (2019) [43]	Control: standard CPR training with an instructor. Training duration not available. Intervention: CPR training with instructor and feedback device. Training duration not available.	2-minute CPR session without feedback.	Postintervention	The intervention group improved at 39%, while the control group improved at 20%.
Wagner et al (2019) [58]	Control: 2-minute training session with an instructor. Intervention—only feedback device: 2-minute training session with a feedback device. Intervention—feedback device and instructor: 2-minute training session with feedback from instructor seen on feedback device.	2-minute chest compression session without feedback.	Postintervention	Both interventions were similar for total compression score (DF[h]: 87.2%; IDF[i]: 93.2%) but significantly better than the control group (77.3%).

Zhou et al (2020) [59]	Control: 30-minute training session with an instructor. Intervention: 30-minute training session with feedback device and instructor.	2-minute chest compression session without feedback.	Day 1 (postintervention) Day 3 (postintervention 2) Day 7 (postintervention 3) 3 months 12 months	Similar results in both groups.

[a]BLS: basic life support. [b]AED: automated external defibrillator. [c]SF: short feedback. [d]LF: long feedback. [e]CPR: cardiopulmonary resuscitation. [f]OSCE: Objective Structured Clinical Examination. [g]AHA: American Heart Association. [h]DF: device feedback. [i]IDF: instructor and device feedback.

Risk of Bias in Studies

The risk of bias was assessed in all 20 RCTs. Among the studies included, 40% (n=8) presented a high risk of bias [42,43,46,48,49,52,55,57], and 50% (n=10) presented a low risk of bias [23,41,44,45,50,51,53,56,58,59]. Table 5 illustrates the risk of bias in each domain (D1-D5), based on RoB 2 [36], along with the overall risk of bias.

Across all domains, the randomization process was the primary reason for the risk of bias due to no information or absence of random allocation sequence or no information or absence of allocation sequence concealment. Studies were assessed to have an overall “high risk” of bias if there were at least 1 “high risk” in any of the criteria (D1-D5).

Table 5 - Risk of bias.

Study ID	D1	D2	D3	D4	D5	Overall
Baldi et al (2017) [41]	+[a]	+	+	+	+	+
Chamdawala et al (2021) [42]	+	±[b]	–[c]	+	+	–
Cortegiani et al (2017) [23]	+	+	+	+	+	+
Eshel et al (2019) [48]	–	+	+	+	+	–
González-Santano et al (2020) [47]	+	+	±	+	+	±
Jang et al (2020) [49]	±	+	–	+	+	–
Katipoglu et al (2021) [50]	+	+	+	+	+	+
Kim et al (2021) [51]	+	+	+	+	+	+
Labuschagne et al (2022) [52]	–	+	+	+	–	–
Lee et al (2023) [44]	+	+	+	+	+	+
Lin et al (2018) [45]	+	+	+	+	+	+
Moreno et al (2021) [46]	±	+	–	+	+	–
Pavo et al (2016) [53]	+	+	+	+	+	+
Sá-Couto et al (2018) [54]	±	+	+	+	+	±
Sarac (2017) [55]	–	+	+	+	+	–
Smereka et al (2019) [56]	+	+	+	+	+	+
Suet et al (2020) [57]	+	+	+	–	+	–
Tanaka et al (2019) [43]	±	+	–	+	+	–
Wagner et al (2019) [58]	+	+	+	+	+	+
Zhou et al (2020) [59]	+	+	+	+	+	+

randomization process (D1), deviations from intended interventions (D2), missing outcome data (D3), measurement of the outcome (D4), and selection of the reported result (D5). [a]**+**: low risk. [b]**±**: some concerns. [c]**–**: high risk.

<u>Synthesis of CPR Quality</u>

The skills acquisition subgroup included 8 studies [41,46,48,51-53,57,58] involving 1477 participants. Meta-analysis results revealed high heterogeneity (I^2>75%, as illustrated in Figure 3). All studies presented a positive mean difference for chest compression score, with an average of 17.37%, favoring the use of corrective feedback devices.

Study	Experimental Total	Experimental Mean	Experimental SD	Control Total	Control Mean	Control SD	MD	95%-CI	Weight (random)
Labuschagne, 2022	25	83.00	14.8148	28	75.00	6.6667	8.00	[1.69; 14.31]	11.6%
Kim, 2021	31	92.65	7.6600	33	75.61	11.3100	17.04	[12.33; 21.75]	11.7%
Moreno, 2021	121	66.00	25.0000	91	58.00	26.0000	8.00	[1.04; 14.96]	11.5%
Suet, 2020	23	72.00	34.0741	20	22.50	36.8148	49.50	[28.19; 70.81]	8.6%
Eshel, 2019	67	61.00	32.0370	78	8.00	19.2593	53.00	[44.22; 61.78]	11.2%
Wagner, 2019	109	87.50	21.6000	108	79.60	30.6000	7.90	[0.85; 14.95]	11.5%
Baldi, 2017	150	92.50	47.0000	150	79.40	41.6000	13.10	[3.06; 23.14]	11.0%
Pavo, 2016	102	43.00	22.9630	110	41.00	32.5926	2.00	[-5.55; 9.55]	11.4%
Wagner, 2019 (*)	114	89.00	18.5000	117	82.30	23.3000	6.70	[1.28; 12.12]	11.7%
Random effects model	**742**			**735**			**17.37**	**[5.64; 29.11]**	**100.0%**

Heterogeneity: I^2 = 93%, τ^2 = 300.0644, p < 0.01

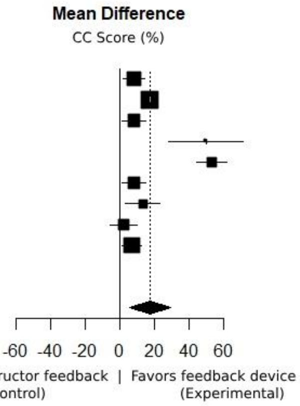

*Figure 3 - Forest plot presenting a mean difference of overall chest compression (CC) score (%) between the intervention (with feedback device) and control groups (instructor feedback). Positive values favor the use of feedback devices. Data collected immediately after training (skills acquisition assessment) [41,46,48,51-53,57,58]. * represents pediatric cardiopulmonary resuscitation training.*

Within the skills acquisition subgroup, further analysis was conducted to examine the duration of training. Five studies, involving a total of 1225 participants, focused on training sessions shorter than 30 minutes [41,46,52,53,58]. These studies uniformly reported a favorable mean difference in chest compression score, with an average improvement of 7.21%, attributed to the use of corrective feedback devices (as shown in Figure 4A). These studies exhibited low heterogeneity (I^2=0%), underscoring the consistency of the positive effects observed. Three studies, involving 252 participants, reported on training sessions with more than 30 minutes [48,51,57] with high heterogeneity (I^2>75%). Despite the observed variability, all studies consistently presented a substantial mean improvement in chest compression score, averaging 38.91% (as shown in Figure 4B), underscoring the impact of using corrective feedback devices in longer training sessions.

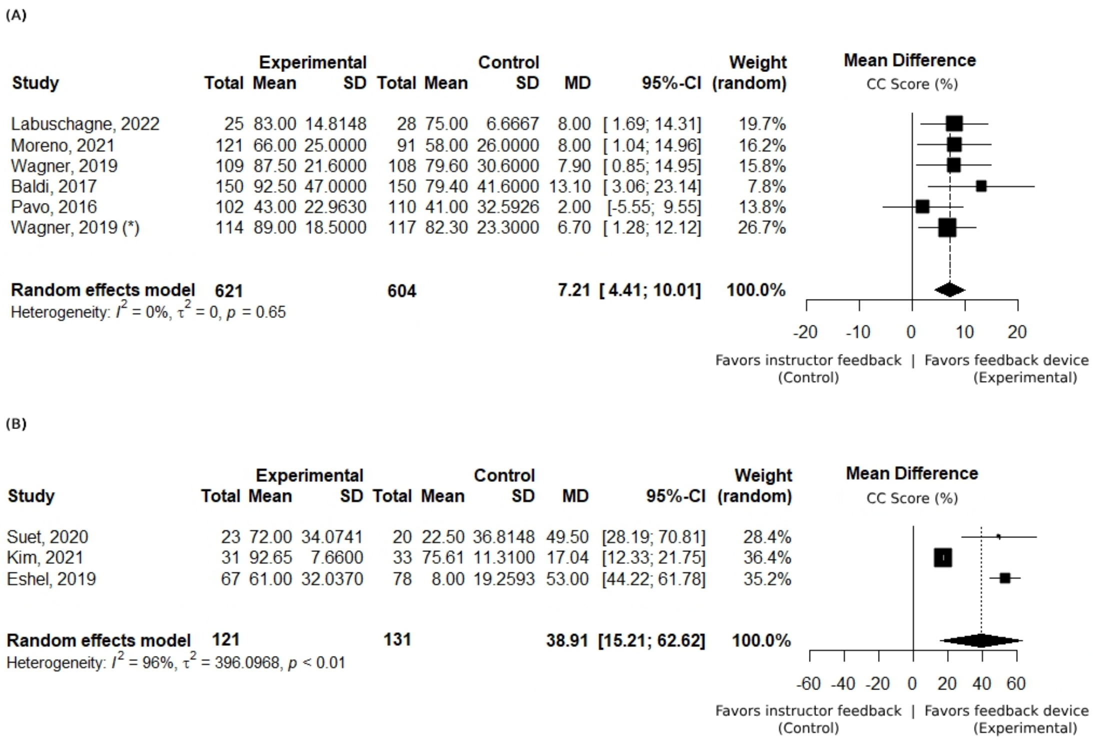

*Figure 4 - Overall chest compression (CC) score: subgroup analysis based on the duration of training. Set of forest plots presenting a mean difference of overall CC score (%) between the intervention (with feedback device) and control groups(instructor feedback). Positive values favor the use of feedback devices. Data collected immediately after training (skills acquisition assessment). Subgroup analysis: (A) studies with less than 30 minutes of training time [41,46,52,53,58] and (B) studies with more than 30 minutes of training time [48,51,57]. * represents pediatric cardiopulmonary resuscitation training.*

Skills retention at 3 months was examined in 3 studies [45,49,59], involving 366 participants, with low heterogeneity (I^2=35%). These studies collectively showed a positive mean difference in depth scores, averaging 17.99%, favoring the use of corrective feedback devices (as illustrated in Figure 5A). For skills retention between 9 and 12 months, 3 studies [45,49,59] were analyzed, revealing low heterogeneity (I^2=33%). All studies reported a positive mean difference in depth score, with an average improvement of 7.84%, favoring the use of corrective feedback devices (as shown in Figure 5B).

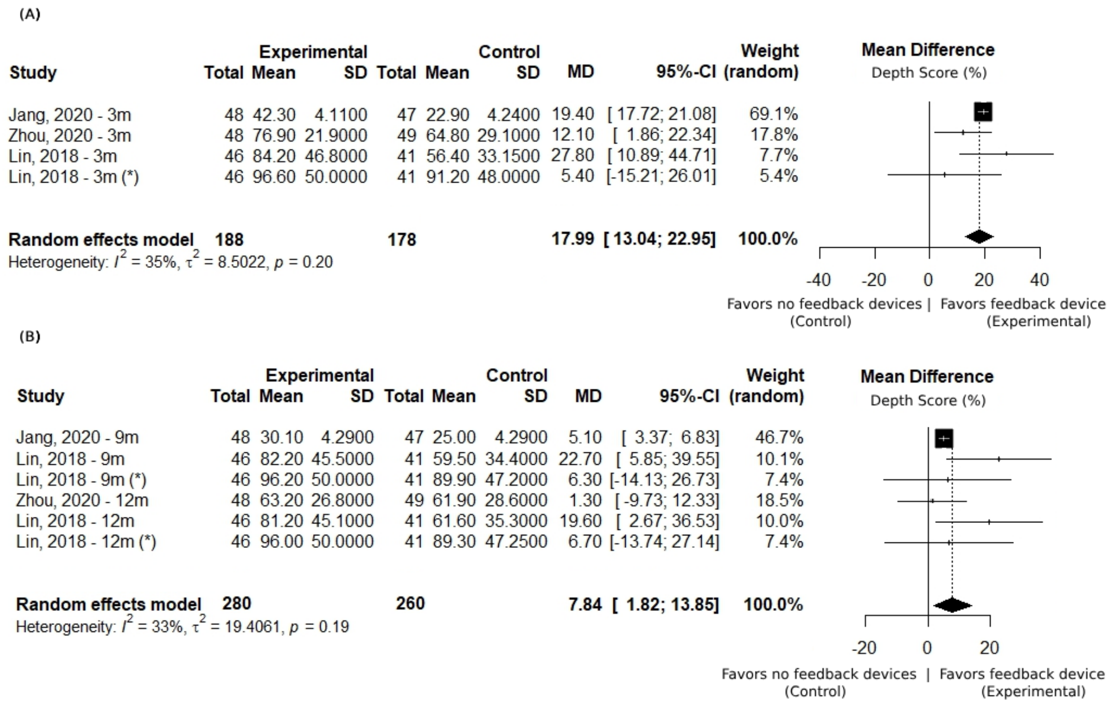

*Figure 5 - Chest compression depth: subgroup analysis based on elapsed time after training. Set of forest plots presenting a mean difference of depth score (%) between the intervention (with feedback device) and control groups (instructor feedback). Positive values favor the use of feedback devices. Subgroup analysis for different periods of retention: (A) 3 months and (B) 9 to 12 months [45,49,59]. * represents pediatric cardiopulmonary resuscitation training.*

Other meta-analyses were conducted to investigate potential sources of heterogeneity, including a subgroup analysis based on risk of bias and study population; however, no significant results were observed. This meta-analysis did not assess the quality of chest recoil, hand positioning, and compression frequency due to insufficient data or challenges in extracting mean and SD values. Certainty of evidence was assessed using the Grading of Recommendations Assessment, Development and Evaluation approach, revealing a very low to low certainty (as shown in Table 6). Publication bias was not detected through the analysis of funnel plots (Appendix 4).

Table 6 - Certainty of evidence (GRADE approach).

	Studies, n	Study design	Risk of bias	Inconsistency	Indirectness	Imprecision	Certainty
CPR[a] skills acquisition: chest compressions score (%)	8	RCT[b]	Serious	Serious[c]	Not serious[d]	Serious[e]	Very low
CPR skills retention: compressions depth score (%)	3	RCT	Serious	Not serious	Not serious	Serious[e]	Low

[a]CPR: cardiopulmonary resuscitation. [b]RCT: randomized controlled trial. [c]High heterogeneity was identified between studies leading to inconsistency. [d]Outcome measures were directly associated with the research question. The majority of the corrective feedback devices provided the required outcomes. [e]High SDs in most studies.

Discussion

Principal Findings

This paper critically evaluates the effectiveness of corrective feedback devices in CPR training for both laypeople and health care professionals. While several reviews support the use of feedback devices for CPR training [29-32], some studies report inaccuracies related to the use of these devices, namely an overestimation of chest compression depth [60,61]. To the best of our knowledge, there is no recent and thorough systematic review and meta-analysis specifically evaluating the effects of CPR training with corrective feedback devices on the skills acquisition and retention among both laypeople and health care professionals. Existing reviews often rely on outdated guidelines [29,30], or encompassed a broader scope, such as the use of feedback devices in real clinical settings [29-31].

Notably, reviews prior to 2015 often did not differentiate between devices providing guidance and those offering corrective feedback, a distinction introduced in 2015 CPR guidelines [28]. One of the earliest systematic reviews showed evidence favoring the use of CPR feedback devices [29]; however, it included studies based on outdated guidelines and “prompt” devices.

A more recent review also reported that feedback devices promote better chest compressions [30]. However, this review included nonrandomized trials, studies based on outdated guidelines, and studies performed in real settings (human studies), increasing the heterogeneity and potentially reducing the quality of the review. Subsequent reviews [31,32] recommended the use of feedback devices but did not include a meta-analysis [31] and focused on specific groups—health care professionals [31] and laypeople [32]. Additionally, these reviews included studies using devices that lacked corrective feedback.

This systematic review and meta-analysis aim to bridge the identified gaps by examining the impact of corrective feedback devices on the quality of chest compressions during CPR training across diverse groups. This review exclusively focuses on studies using corrective feedback devices for skills acquisition and retention, within simulated or training environments, targeting both laypeople and health care professionals. The rigorous search strategy and selection process ensured a comprehensive and inclusive examination, capturing all pertinent studies within the scope of this review.

The risk of bias assessment revealed a general trend of overestimated effects due to methodological flaws, with few studies adhering to CONSORT (Consolidated Standards of Reporting Trials) reporting guidelines [62]. Poorly designed studies may yield larger effect estimates when compared to those with rigorous methodologies, potentially compromising the robustness and reliability of the findings. Several studies included in the meta-analysis were noted to have some concerns or high risk of bias, which may influence the overall findings. These were not excluded to maintain an adequate number of studies under analysis, considering that all of those are RCT, which, per se, represent a superior level of evidence [63].

The majority of studies included in this review featured intervention groups that conducted training autonomously or through self-training without direct instructor involvement. However, some studies did incorporate a degree of instructor mediation within the intervention groups. In these cases, the corrective feedback device remained the central component of the intervention, with the instructors' roles primarily confined to presenting the metrics generated by these devices.

The presence or absence of an instructor in the intervention groups was not considered a criterion for inclusion in this review, which may have introduced a degree of heterogeneity. The varied outcomes and measurement approaches revealed a notable absence of standardized research protocols in this field. Specifically, for identical chest compression parameters, multiple approaches for measuring outcomes were identified. Adoption of standardized protocols and assessments in future research could greatly contribute to accurately extract intervention effects, allowing a more reliable and precise comparison of results.

The conducted meta-analysis revealed significant heterogeneity. Several factors may have contributed to this variability: the quality of the studies included; the variable protocol designs and methodologies used across these studies, including variations in training methods and assessment procedures; the diversity of the outcomes measured; the presence of nonreporting bias, where studies showing nonsignificant or minimal effect sizes might be underreported; and intrinsic heterogeneity due to a wide range of variables identified as relevant to the analysis.

Despite significant heterogeneity among some study results, this meta-analysis provides insights into the positive impact of corrective feedback devices on CPR training. As illustrated in Figure 3, there is an overall positive mean difference between the control and intervention groups, suggesting a positive impact of corrective feedback devices in enhancing skills acquisition and improving the quality of chest compressions. Notably, the duration of training plays a critical role in this improvement. Shorter training sessions show a reduced mean difference in chest compression scores between groups, indicating that extended exposure to corrective feedback devices yields better training outcomes. This observation is further supported by the consistency of results across studies with training durations of less than 30 minutes, which exhibit low heterogeneity.

In the analysis of skills retention over time, the depth of chest compressions emerged as the only parameter suitable for inclusion in the meta-analysis. Examining this specific parameter revels that the difference between the control group and the intervention group considerably decreases, when comparing data from the 3-month and 9- to 12-month subgroups, accompanied by an increase in heterogeneity (as illustrated in Figure 5). This trend suggests that, while the immediate benefits of using corrective feedback devices to enhance the quality of chest compression depth are clear, these benefits tend to converge over time, leading to less pronounced differences between groups and greater variability in study findings.

The maximum follow-up time analyzed in this review was 12 months due to the lack of reliable studies with longer follow-up periods. More robust studies with extended follow-up times are needed, especially considering that the recommended interval for recertification is 24 months. The studies with health care professionals [44-46] were too few to allow a comparison with studies focusing on laypeople; however, the results suggest a similar impact of corrective feedback devices in both groups. Future work could focus on exploring the differences in CPR skills acquisition and retention between these groups.

Regarding the corrective feedback devices used, the majority were Laerdal products, including full-body simulators or torsos. It was unclear whether these devices provided real-time feedback or presented a summary of the CPR quality at the end of each training session. While real-time feedback could enable immediate correction of maneuvers, it might also serve as a distraction during training sessions. This analysis, to our knowledge, has not been studied and could be an important topic for future research.

The majority of the studies included in this review revealed that the use of corrective feedback devices during CPR training led to significant enhancements in 1 or more key chest compression parameters. Although the improvements across all parameters were not uniform, the evidence strongly supports that corrective feedback devices contribute to an overall improvement in CPR skills acquisition among both laypeople and health care professionals, especially when exposed to longer training sessions. Longitudinal analysis of skills retention indicates that the long-term benefits become less distinct, especially after 3 months. These results are consistent with the findings from a previous systematic review [32].

The contribution of corrective feedback devices is significant not only for more objective and standardized training but also for enabling more frequent practice, without being dependent on the presence of an instructor. This facilitates continuous improvement and broader preparation for performing CPR.

Limitations

This review is not without limitations. The high heterogeneity, variations in the study designs, and generally low quality of the included studies challenge the validity and generalization of conclusions. Additionally, this review only included RCTs, which may hinder relevant conclusions resulting from other designs. The exclusion of studies published before 2015 may have also omitted relevant data. Moreover, the use of different tools across studies to evaluate training outcomes introduces further variability, potentially affecting the judgment of findings.

Conclusions

This review supports the use of corrective feedback devices in CPR training as a beneficial complement or surrogate to traditional training methods (instructor-based feedback). Corrective feedback devices offer objective insights that can enhance immediate skills acquisition and may contribute to long-term retention. However, these findings must be interpreted with caution due to the significant variation in study designs and outcomes, along with the overall low quality of existent studies, highlighting the urgent need for well-designed, high-quality studies with standardized protocols.

Acknowledgments

The research team acknowledges the contribution of Luís Filipe Ribeiro de Azevedo on providing methodological clarifications as an expert in research synthesis. This paper was supported by institutional funds through the PhD Program in Clinical and Health Services Research from the Faculty of Medicine of the University of Porto.

Data Availability

The search strategy is provided in Appendix 2. The datasets generated and analyzed during this study are available from the author on reasonable request.

References

1. Vazquez AR, Sudhir A. Cardiac arrest as a public health issue. Emerg Med Clin North Am. 2023;41(3):405-411.
2. Tsao CW, Aday AW, Almarzooq ZI, Anderson CAM, Arora P, Avery CL, et al. Heart disease and stroke statistics-2023 update: a report from the American Heart Association. Circulation. 2023;147(8):e93-e621.
3. Gräsner JT, Wnent J, Herlitz J, Perkins GD, Lefering R, Tjelmeland I, et al. Survival after out-of-hospital cardiac arrest in Europe—results of the EuReCa TWO study. Resuscitation. 2020;148:218-226.
4. Perkins GD, Graesner JT, Semeraro F, Olasveengen T, Soar J, Lott C, et al. European Resuscitation Council Guidelines 2021: executive summary. Resuscitation. 2021;161:1-60.
5. Wu L, Narasimhan B, Bhatia K, Ho KS, Krittanawong C, Aronow WS, et al. Temporal trends in characteristics and outcomes associated with in-hospital cardiac arrest: a 20-year analysis (1999-2018). J Am Heart Assoc. 2021;10(23):e021572.
6. Semeraro F, Greif R, Böttiger BW, Burkart R, Cimpoesu D, Georgiou M, et al. European Resuscitation Council Guidelines 2021: systems saving lives. Resuscitation. 2021;161:80-97.
7. Panchal AR, Bartos JA, Cabañas JG, Donnino MW, Drennan IR, Hirsch KG, et al. Part 3: adult basic and advanced life support: 2020 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation. 2020;142(16_suppl_2):S366-S468.
8. Olasveengen TM, Semeraro F, Ristagno G, Castren M, Handley A, Kuzovlev A, et al. European Resuscitation Council guidelines 2021: basic life support. Resuscitation. 2021;161:98-114.
9. Harris AW, Kudenchuk PJ. Cardiopulmonary resuscitation: the science behind the hands. Heart. 2018;104(13):1056-1061.
10. Wyckoff MH, Greif R, Morley PT, Ng KC, Olasveengen TM, Singletary EM, et al. 2022 International consensus on cardiopulmonary resuscitation and emergency cardiovascular care science with treatment recommendations: summary from the basic life support; advanced life support; pediatric life support; neonatal life support; education, implementation, and teams; and first aid task forces. Circulation. Dec 20, 2022;146(25):e483-e557.
11. Semark B, Årestedt K, Israelsson J, von Wangenheim B, Carlsson J, Schildmeijer K. Quality of chest compressions by healthcare professionals using real-time audiovisual feedback during in-hospital cardiopulmonary resuscitation. Eur J Cardiovasc Nurs. Jun 2017;16(5):453-457.
12. Vadeboncoeur T, Stolz U, Panchal A, Silver A, Venuti M, Tobin J, et al. Chest compression depth and survival in out-of-hospital cardiac arrest. Resuscitation. 2014;85(2):182-188.

13. Odegaard S, Saether E, Steen PA, Wik L. Quality of lay person CPR performance with compression: ventilation ratios 15:2, 30:2 or continuous chest compressions without ventilations on manikins. Resuscitation. 2006;71(3):335-340.
14. Ong EHM. Improving the quality of CPR in the community. Singapore Med J. 2011;52(8):586-591.
15. Källestedt MLS, Berglund A, Herlitz J, Leppert J, Enlund M. The impact of CPR and AED training on healthcare professionals' self-perceived attitudes to performing resuscitation. Scand J Trauma Resusc Emerg Med. 2012;20:26.
16. Villalobos F, Del Pozo A, Rey-Reñones C, Granado-Font E, Sabaté-Lissner D, Poblet-Calaf C, et al. Lay people training in CPR and in the use of an automated external defibrillator, and its social impact: a community health study. Int J Environ Res Public Health. 2019;16(16):2870.
17. Oermann MH, Krusmark MA, Kardong-Edgren S, Jastrzembski TS, Gluck KA. Training interval in cardiopulmonary resuscitation. PLoS One. 2020;15(1):e0226786.
18. Greif R, Lockey A, Breckwoldt J, Carmona F, Conaghan P, Kuzovlev A, et al. European Resuscitation Council guidelines 2021: education for resuscitation. Resuscitation. 2021;161:388-407.
19. Brennan EE, McGraw RC, Brooks SC. Accuracy of instructor assessment of chest compression quality during simulated resuscitation. CJEM. 2016;18(4):276-282.
20. Nagafuchi K, Hifumi T, Nishimoto N, Kondo Y, Yoshikawa K, Iwami T, et al. Chest compression depth and rate—effect on instructor visual assessment of chest compression quality. Circ J. 2019;83(2):418-423.
21. Anderson R, Sebaldt A, Lin Y, Cheng A. Optimal training frequency for acquisition and retention of high-quality CPR skills: a randomized trial. Resuscitation. 2019;135:153-161.
22. Cheng A, Magid DJ, Auerbach M, Bhanji F, Bigham BL, Blewer AL, et al. Part 6: resuscitation education science: 2020 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation. 2020;142(16_Suppl_2):S551-S579.
23. Cortegiani A, Russotto V, Montalto F, Iozzo P, Meschis R, Pugliesi M, et al. Use of a real-time training software (Laerdal QCPR®) compared to instructor-based feedback for high-quality chest compressions acquisition in secondary school students: a randomized trial. PLoS One. 2017;12(1):e0169591.
24. Zapletal B, Greif R, Stumpf D, Nierscher FJ, Frantal S, Haugk M, et al. Comparing three CPR feedback devices and standard BLS in a single rescuer scenario: a randomised simulation study. Resuscitation. 2014;85(4):560-566.
25. Truszewski Z, Szarpak L, Kurowski A, Evrin T, Zasko P, Bogdanski L, et al. Randomized trial of the chest compressions effectiveness comparing 3 feedback CPR devices and standard basic life support by nurses. Am J Emerg Med. 2016;34(3):381-385.

26. Bhanji F, Mancini ME, Sinz E, Rodgers DL, McNeil MA, Hoadley TA, et al. Part 16: education, implementation, and teams: 2010 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation. 2010;122(18 Suppl 3):S920-S933.
27. Nolan JP, Soar J, Zideman DA, Biarent D, Bossaert LL, Deakin C, et al. European Resuscitation Council guidelines for resuscitation 2010 section 1. Executive summary. Resuscitation. 2010;81(10):1219-1276.
28. Bhanji F, Donoghue AJ, Wolff MS, Flores GE, Halamek LP, Berman JM, et al. Part 14: education: 2015 American Heart Association guidelines update for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation. 2015;132(18 Suppl 2):S561-S573.
29. Yeung J, Meeks R, Edelson D, Gao F, Soar J, Perkins GD. The use of CPR feedback/prompt devices during training and CPR performance: a systematic review. Resuscitation. 2009;80(7):743-751.
30. 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. 2014;85(4):460-471.
31. Gugelmin-Almeida D, Tobase L, Polastri TF, Peres HHC, Timerman S. Do automated real-time feedback devices improve CPR quality? A systematic review of literature. Resusc Plus. 2021;6:100108.
32. Kahsay DT, Peltonen LM, Rosio R, Tommila M, Salanterä S. The effect of standalone audio-visual feedback devices on the quality of chest compressions during laypersons' cardiopulmonary resuscitation training: a systematic review and meta-analysis. Eur J Cardiovasc Nurs. 2024;23(1):11-20.
33. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021;372:n71.
34. Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page M, et al. Cochrane Handbook for Systematic Reviews of Interventions Version 6.3. London, England. The Cochrane Collaboration; 2019.
35. Kohl C, McIntosh EJ, Unger S, Haddaway NR, Kecke S, Schiemann J, et al. Online tools supporting the conduct and reporting of systematic reviews and systematic maps: a case study on CADIMA and review of existing tools. Environ Evid. 2018;7(1):1-17.
36. Sterne JAC, Savović J, Page MJ, Elbers RG, Blencowe NS, Boutron I, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. BMJ. 2019;366:l4898.
37. Wan X, Wang W, Liu J, Tong T. Estimating the sample mean and standard deviation from the sample size, median, range and/or interquartile range. BMC Med Res Methodol. 2014;14(1):135.

38. Greco T, Biondi-Zoccai G, Gemma M, Guérin C, Zangrillo A, Landoni G. How to impute study-specific standard deviations in meta-analyses of skewed continuous endpoints? WJMA. 2015;3(5):215.
39. Campbell M, McKenzie JE, Sowden A, Katikireddi SV, Brennan SE, Ellis S, et al. Synthesis without meta-analysis (SWiM) in systematic reviews: reporting guideline. BMJ. 2020;368:l6890.
40. Guyatt GH, Oxman AD, Vist GE, Kunz R, Falck-Ytter Y, Alonso-Coello P, et al. GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. BMJ. 2008;336(7650):924-926.
41. Baldi E, Cornara S, Contri E, Epis F, Fina D, Zelaschi B, et al. Real-time visual feedback during training improves laypersons' CPR quality: a randomized controlled manikin study. CJEM. 2017;19(6):480-487.
42. Chamdawala H, Meltzer JA, Shankar V, Elachi D, Jarzynka SM, Nixon AF. Cardiopulmonary resuscitation skill training and retention in teens (CPR START): a randomized control trial in high school students. Resusc Plus. 2021;5:100079.
43. Tanaka S, Tsukigase K, Hara T, Sagisaka R, Myklebust H, Birkenes TS, et al. Effect of real-time visual feedback device 'Quality Cardiopulmonary Resuscitation (QCPR) Classroom' with a metronome sound on layperson CPR training in Japan: a cluster randomized control trial. BMJ Open. 2019;9(6):e026140.
44. Lee PH, Lai HY, Hsieh TC, Wu WR. Using real-time device-based visual feedback in CPR recertification programs: a prospective randomised controlled study. Nurse Educ Today. 2023;124:105755.
45. Lin Y, Cheng A, Grant VJ, Currie GR, Hecker KG. Improving CPR quality with distributed practice and real-time feedback in pediatric healthcare providers—a randomized controlled trial. Resuscitation. 2018;130:6-12.
46. Moreno S, Sisó-Almirall A, Kostov B, Expósito M, Moreno JR, de Pablo B, et al. Cardiopulmonary resuscitation skill maintenance for primary care staff: brief training sessions with feedback. Emergencias. 2021;33(3):203-210.
47. González-Santano D, Fernández-García D, Silvestre-Medina E, Remuiñán-Rodríguez B, Rosell-Ortiz F, Gómez-Salgado J, et al. Evaluation of three methods for CPR training to lifeguards: a randomised trial using traditional procedures and new technologies. Medicina (Kaunas). 2020;56(11):577.
48. Eshel R, Wacht O, Schwartz D. Real-time audiovisual feedback training improves cardiopulmonary resuscitation performance: a controlled study. Simul Healthc. 2019;14(6):359-365.
49. Jang TC, Ryoo HW, Moon S, Ahn JY, Lee DE, Lee WK, et al. Long-term benefits of chest compression-only cardiopulmonary resuscitation training using real-time visual feedback manikins: a randomized simulation study. Clin Exp Emerg Med. 2020;7(3):206-212.

50. Katipoglu B, Madziala MA, Evrin T, Gawlowski P, Szarpak A, Dabrowska A, et al. How should we teach cardiopulmonary resuscitation? Randomized multi-center study. Cardiol J. 2021;28(3):439-445.
51. Kim Y, Han H, Lee S, Lee J. Effects of the non-contact cardiopulmonary resuscitation training using smart technology. Eur J Cardiovasc Nurs. 2021;20(8):760-766.
52. Labuschagne MJ, Arbee A, de Klerk C, de Vries E, de Waal T, Jhetam T, et al. A comparison of the effectiveness of QCPR and conventional CPR training in final-year medical students at a South African university. Afr J Emerg Med. 2022;12(2):106-111.
53. Pavo N, Goliasch G, Nierscher FJ, Stumpf D, Haugk M, Breckwoldt J, et al. Short structured feedback training is equivalent to a mechanical feedback device in two-rescuer BLS: a randomised simulation study. Scand J Trauma Resusc Emerg Med. 2016;24:70.
54. Sá-Couto C, Ferreira AM, Almeida D, Nicolau A, Vieira-Marques P. Evaluation of skills acquisition using a new low-cost tool for CPR self-training. Porto Biomed J. 2018;3(1):e8.
55. Sarac L. Effects of augmented feedback on cardiopulmonary resuscitation skill acquisition: concurrent versus terminal. Eurasian J Educ Res. 2017;17(72):83.
56. Smereka J, Szarpak L, Czekajlo M, Abelson A, Zwolinski P, Plusa T, et al. The TrueCPR device in the process of teaching cardiopulmonary resuscitation: a randomized simulation trial. Medicine (Baltimore). 2019;98(27):e15995.
57. Suet G, Blanie A, de Montblanc J, Roulleau P, Benhamou D. External cardiac massage training of medical students: a randomized comparison of two feedback methods to standard training. J Emerg Med. 2020;59(2):270-277.
58. Wagner M, Bibl K, Hrdliczka E, Steinbauer P, Stiller M, Gröpel P, et al. Effects of feedback on chest compression quality: a randomized simulation study. Pediatrics. 2019;143(2):e20182441.
59. Zhou XL, Wang J, Jin XQ, Zhao Y, Liu RL, Jiang C. Quality retention of chest compression after repetitive practices with or without feedback devices: a randomized manikin study. Am J Emerg Med. 2020;38(1):73-78.
60. Perkins GD, Kocierz L, Smith SC, McCulloch RA, Davies RP. Compression feedback devices over estimate chest compression depth when performed on a bed. Resuscitation. 2009;80(1):79-82.
61. Segal N, Laurent F, Maman L, Plaisance P, Augustin P. Accuracy of a feedback device for cardiopulmonary resuscitation on a dental chair. Emerg Med J. 2012;29(11):890-893.
62. Schulz KF, Altman DG, Moher D, CONSORT Group. CONSORT 2010 statement: updated guidelines for reporting parallel group randomized trials. Ann Intern Med. 2010;152(11):726-732.
63. Melnyk BM, Fineout-Overholt E. Evidence-Based Practice in Nursing & Healthcare: A Guide to Best Practice. Philadelphia, PA. Lippincott Williams & Wilkins; 2022.

Chapter 3

Influence of rescuer position and arm angle on chest compression quality: An international multicentric randomized crossover simulation trial

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Resuscitation plus, 20, 100815

Introduction

Cardiopulmonary resuscitation (CPR) is a crucial intervention for managing cardiac arrest, a major public health issue with persistently low survival rates despite significant advancements in resuscitation science [1, 2]. High-quality chest compressions (CC) during CPR are crucial for improving patient survival and neurological outcomes [3]. Effective CC can increase survival rates by 2 to 4 times and enhance subsequent interventions in the chain of survival [4].

The success of resuscitation depends on both the timeliness and quality of CC [3, 4]. Effective CC require correct hand placement on the lower sternum with arms extended at a 90° angle to the chest, a rate of 100 to 120 compressions per minute, a depth of 5 to 6 cm, while allowing complete chest recoil [3, 5]. Training is essential for improving and maintaining CPR quality, impacting skill acquisition and retention [6]. Technology-enhanced training tools that provide directive feedback on compression parameters have been shown to enhance training outcomes, for both laypeople and healthcare professionals [6].

Despite evidence that technology-enhanced training improves CPR quality, it has not been consistently translated to better patient outcomes in clinical settings [2, 6]. This disconnect highlights the need for ongoing research into CPR quality and the factors influencing rescuer performance.

Factors such as rescuer fatigue and the physical setting can significantly impact compressions quality [3, 7, 8]. The rescuer's position relative to the patient, often dictated by the surrounding environment (e.g., patient on the floor or bed), can affect compression depth and chest recoil [8, 9], especially if the patient is on a soft surface or the rescuer is in an unstable or uncomfortable position [10].

Rescuers must adapt their position according to the environment, with common positions including kneeling on the floor, standing beside the bed, standing on a step stool, or kneeling on the bed. The choice of position depends on the environment (pre-hospital vs. in-hospital) [3], the ergonomics of the space (e.g., bed height) [11, 12], and the rescuer's comfort (e.g., difficulties associated with kneeling) [13], among other factors. The goal is to optimize a 90° arm angle perpendicular to the patient's chest [8], allowing the rescuer to use body weight to achieve effective CC. Inadequate arm angles, often exceeding 90°, can result from insufficient knowledge or experience, fatigue, or suboptimal settings [8, 14].

Adjusting the bed height or using a step stool can help bring the rescuer closer to the ideal 90° angle and potentially improving CC quality [8, 14, 15]. CPR seems to be most effective when the rescuer kneels on the ground beside the patient's chest in pre-hospital settings or stands beside the bed in hospital settings, with the patient placed on a firm surface [3]. While some studies have found similar outcomes in both positions [16, 17, 18], others have reported conflicting results, with better effectiveness noted when kneeling on the ground [19] or standing beside the bed [20]. Additionally, the use of a step stool is not consensual, with some studies favoring its use [9, 14], and others suggesting alternative positioning [13]. The variability in findings across different studies underscores the need for this research.

This study explores the influence of rescuer position and arm angle on the quality of CC in healthcare professionals experienced in CPR, in a simulated setting. By studying the impact of these variables on CPR performance, this research aims to develop recommendations that enhance rescuer efficiency and effectiveness. The ultimate goal is to improve patient outcomes by providing insights that could lead to improved training protocols and more effective CPR delivery.

Methods

This study is an international, multicentric, randomized crossover manikin trial, with an independent group design, conducted in Portugal, Germany, and Finland.

The study protocol was developed collaboratively, through online meetings and a site visit to standardize data collection across all locations. The protocol was registered in ClinicalTrials.gov (NCT05405569) and received ethical approval from the respective institutional committees: Portugal (58/CEFMUP/2022), Germany (23–0215), and Finland (21/2022). Written informed consent was obtained from all participants, and data were anonymized with unique IDs. The Data Protection Committee of the University of Porto also approved the study (A-3/2023).

<u>Participants and sample size</u>

Recruitment and data collection took place at the Simulation Center of the Faculty of Medicine of the University of Porto (Portugal), the Human Simulation Center at the Institute for Emergency Medicine and Management in Medicine, Ludwig-Maximilians University Munich (Germany), and the Arcada Patient Safety and Learning Center at Arcada University of Applied Sciences (Finland).

A convenience sample strategy was used to recruit healthcare professionals—nurses, physicians, and paramedics. Inclusion criteria required participants to be aged 18 to 65, in good health, physically fit, and experienced in CPR. Pregnant women and those self-reporting physical fatigue or muscle pain were excluded.

The sample size was calculated considering the four independent groups, corresponding to the different rescuer positions, and two paired variables, reflecting the arm angles. An ANOVA test for repeated measures with within-between interactions was used, with a significance level (α) of 0.05 and a power ($1-\beta$) of 0.80, and an effect size of 0.25. This resulted in a minimum sample size of 48 participants, calculated using G*Power software.

Study design

Each site adhered to the defined protocol and utilized identical equipment for data collection. A comprehensive guideline document, including equipment setup and a flow diagram of the process, was distributed to all institutions prior to data collection. This process was overseen by a local expert to ensure consistency. Data collection occurred from May to October 2023.

Participants were allocated into four independent groups using a stratified randomization process, based on rescuer positioning and gender: (1) Manikin laying on the ground and rescuer kneeling on the floor; (2) Manikin laying on a bed and rescuer standing (without a step stool); (3) Manikin laying on a bed and rescuer standing on a step stool; and (4) Manikin laying on a bed and rescuer kneeling on the bed. No mattress was used, to prevent chest compression damping, and the bed was adjusted to the rescuer's patella level to ensure consistent conditions.

A randomized crossover design was implemented within each group, with participants assigned by coin flip to start with either a standard arm angle of 90° or an altered angle of 105°. The latter angle was chosen as it represents a significant, yet common, deviation from the optimal 90°. This difference is substantial enough to potentially elicit a measurable effect while still being within a practical range of motion. Each participant performed CC twice, with a 10-minute rest period between trials to minimize fatigue effects. Each CC trial consisted of 3 min of uninterrupted CC, aligned with the durations used in other similar studies [21]. Participants received no performance feedback or elapsed time updates during the trials, except corrections for arm angle deviations. Fig. 6 illustrates the study flow diagram.

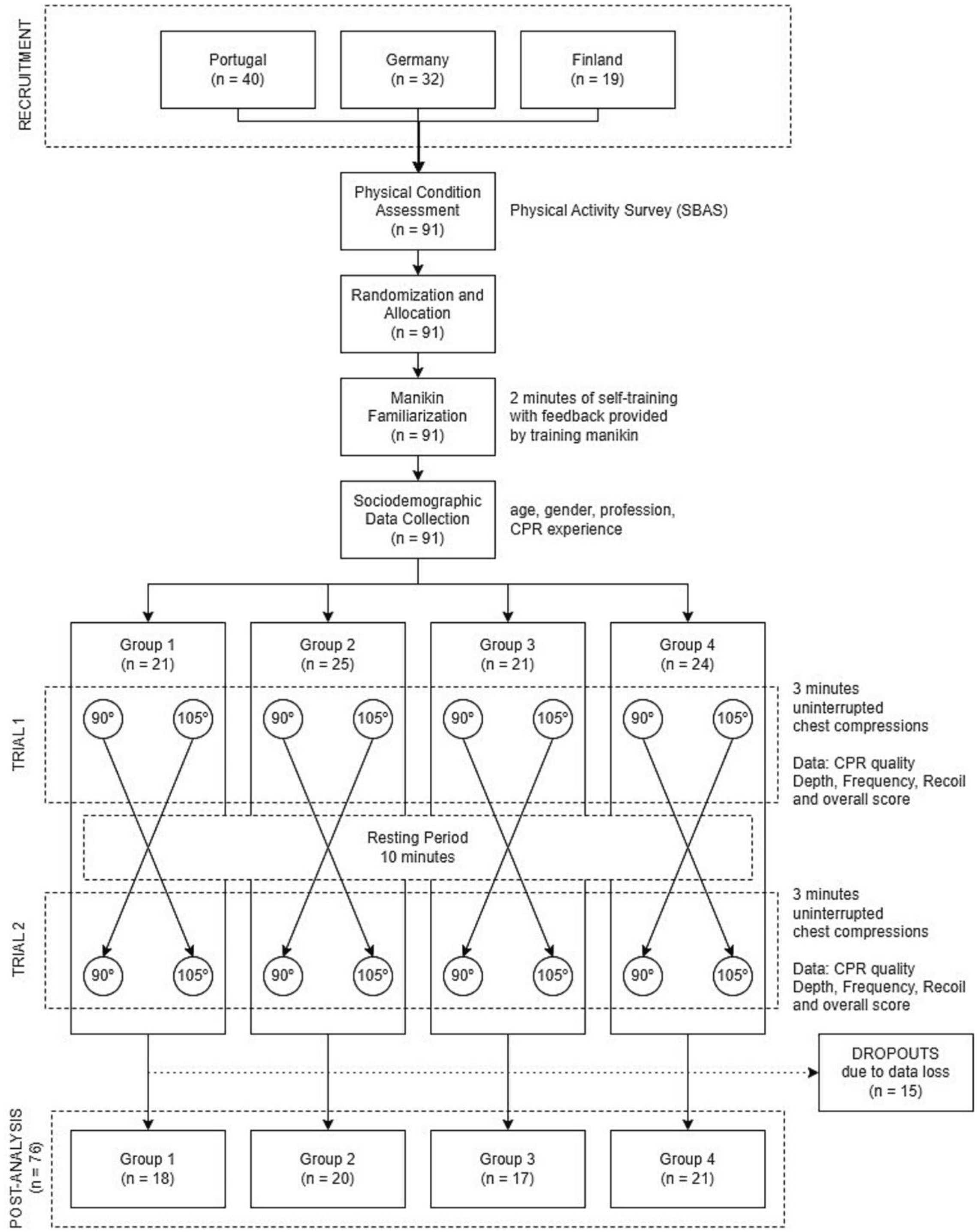

Figure 6 - Participant flow diagram. Group 1: Manikin laying on the ground and rescuer with knees on the floor; Group 2: Manikin laying on the bed and rescuer standing (no step stool); Group 3: Manikin laying on the bed and rescuer with step stool; Group 4: Manikin laying on the bed and rescuer with knees on the bed.

The Laerdal Resusci Anne Simulator equipped with Laerdal SimPad was used for all trials. Before the study trials, participants underwent a 2-minute manikin familiarization session, receiving real-time feedback to calibrate their performance.

Each trial simulated a standard asystole scenario, with CC waveform data captured by the Laerdal system. Data was processed and analyzed using MATLAB R2023b, employing a validated script [22, 23] to extract and calculate relevant CPR parameters, including rate, depth, and recoil. From these metrics, an overall CC quality score was derived.

Before each trial, participants were briefed, and demographic data were collected through an electronic questionnaire. Physical activity was assessed using the Stanford Brief Activity Survey (SBAS) [24], which categorizes physical activity levels based on job-related and leisure-time activities. Depending on the participant self-assessment, the SBAS tool will classify the physical activity as inactive, light, moderate, hard, and very hard.

Arm angles during CPR were monitored through real-time video analysis with Kinovea software [8], as depicted in Fig. 7. During the trials, participants were promptly informed if their arm angles deviated from the predefined settings and were guided to correct their positioning through voice commands (e.g., shift slightly forward).

Due to the nature of the study design, blinding of participants and researchers to the protocol and study aims was not possible.

Figure 7 - Example of participant position for 105° arm angle, in Group 1 (Manikin laying on the ground and rescuer with knees on the floor). The angle is assessed through video recording and Kinovea software.

<u>Primary outcomes and covariates</u>

The primary outcomes of this study were CPR quality parameters, including (1) CC overall score (%), (2) CC depth (cm), (3) CC rate (compressions per minute − cpm), and (4) chest recoil (cm). A MATLAB algorithm [22, 23] was used to process and analyze the continuous raw data from chest compressions in each CPR trial. The algorithm detected each compression peak and calculated quality parameters every 15-seconds using a 4-second window. These parameters were then converted into percentage score (%) using a piecewise linear function [22, 23]. The overall score (%) was the average of these individual parameter scores. Across each 3-minute trial, this approach generated 13 epochs where the parameters were calculated.

Covariates included gender, age (years), nationality, profession, and elapsed time since last CPR training dichotomized into < 24 months and ≥ 24 months. The two-year timeframe is representative of CPR courses validity [2]. Physical activity was categorized using SBAS, and dichotomized into two groups: “active”, which includes moderate-intensity activity, hard-intensity activity and very hard-intensity activity, and “sedentary”, which includes light-intensity activity and inactive. This approach is consistent with other studies [24, 25] and reflects the World Health Organization (WHO) definition of physical activity and sedentary behavior [26]. Additional rescuer characteristics, such body mass index (BMI), were collected but found to be non-significant covariates and therefore were not included in the final analysis.

Statistical analysis

Differences between groups were explored using a Kruskal-Wallis test for continuous data and a chi-square test for categorical data.

Linear mixed-effect models were used to analyse outcomes, incorporating both fixed and random effects. The fixed effects included three independent variables: group as a between-subject factor with four levels, arm angle as a within-subject factor with two levels, and time as a within-subject covariate across 13 measurements. The model also accounted for second-order interactions among these variables, specifically group-by-angle, group-by-time, and arm angle-by-time. Each data point in the analysis was classified according to time, participant, and arm angle. Participant and arm angle were treated as nested classification factors to effectively capture their interactions. The random effects were modelled to include the participant and the arm angle nested within the participant, to adequately represent the within-subject correlation. A general positive-definite Log-Cholesky parametrization was used for the covariance matrix. The model was adjusted for covariates, including gender, SBAS, and the time since the last CPR training, to account for potential confounding factors that might influence the outcomes. Assumptions of normality and homogeneity were assessed by visually inspecting the qq-plots and scatter plots of standardized residuals versus fitted values.

Statistical analysis was conducted using IBM SPSS Statistics software (version 29.0) for the Kruskal-Wallis and chi-squared tests, and software R (version 4.2.2) for linear mixed models. A significance level of 5 % was used.

Results

Participants' characteristics

The study initially included 91 participants across the three participating countries. Throughout the data collection process, there were no losses, however, 15 participants were excluded due to data recording issues, resulting in a final sample of 76 participants: 30 (39.5 %) from Portugal, 28 (36.8 %) from Germany, and 18 (23.7 %) from Finland (Fig. 6).

Participants were allocated into the 4 study groups with a balanced distribution based on demographic characteristics. Subsequent analysis revealed no significant associations between any demographic variable and the study groups (Table 7).

The mean age of the participants was 35.8 ± 8.9 years old, with 38 (50 %) identifying as female. The professional background of the sample consisted of 34 (45 %) nurses, 22 (29 %) physicians, and 20 (26 %) paramedics. Approximately 63 % of the participants were classified as active. Notably, nearly 33 % of the participants had not received formal CPR training in the past 2 years.

Table 7 - Demographics of the participants.

		Group 1 (n = 18)	Group 2 (n = 20)	Group 3 (n = 17)	Group 4 (n = 21)	p-value*
Age (mean ± SD) Overall: 35.8 ± 8.9 years		35.3 ± 10.2	35.7 ± 10.3	35.1 ± 7.7	37.0 ± 7.8	0.900
Gender	Male (n = 38)	10	10	8	10	0.955
	Female (n = 38)	8	10	9	11	
Profession	Physician (n = 22)	4	7	5	6	0.866
	Nurse (n = 34)	8	9	9	8	
	Paramedic (n = 20)	6	4	3	7	
Location	Portugal (n = 30)	8	9	5	8	0.696
	Germany (n = 28)	7	6	8	7	
	Finland (n = 18)	3	5	4	6	
SBAS	Active (n = 48)	11	10	13	14	0.403
	Sedentary (n = 28)	7	10	4	7	
Last CPR training	< 24 months (n = 51)	13	14	13	11	0.387
	>= 24 months (n = 25)	5	6	4	10	

*Pearson's chi-squared test for categorical data. For the variable Age it was used a non-parametric test: Kruskal–Wallis. p-value < 0.05 is statistically significant.

Quality of compressions with different rescuer positions and arm angle

Table 8 and Fig. 8 present the CC scores for each study group and both arm angles. Fig. 8 details the compression parameters throughout the 3-minute trials, sampled every 15 s (13 epochs), providing a comprehensive view of performance over time. For simplicity and ease of reading, Table 8 presents these values at 60-second intervals (4 epochs), offering a summarized view of the data. The shadowed areas in Fig. 8 represent the correct or acceptable range, with overall scores above 75 % considered indicative of effective compressions [27]. Adequate recoil was defined as chest depression less than 5 mm, with 0 mm representing full chest decompression.

Table 8 - Cardiopulmonary resuscitation (CPR) quality based on rescuer position and arm angle.

Variable	Group	Arm angle	Time (s)			
			0	60	120	180
Overall Compression Score, % (mean ± SD)	1 (n = 18)	90°	83.0 ± 18.4	78.4 ± 19.0	76.9 ± 19.4	69.8 ± 19.1
		105°	80.9 ± 19.9	75.4 ± 22.6	74.0 ± 20.9	68.9 ± 21.0
	2 (n = 20)	90°	87.5 ± 17.1	82.1 ± 19.0	80.3 ± 21.1	74.8 ± 21.9
		105°	84.8 ± 15.1	77.3 ± 16.8	73.8 ± 18.7	71.2 ± 20.0
	3 (n = 17)	90°	85.8 ± 15.6	83.7 ± 15.1	80.8 ± 19.7	78.8 ± 20.2
		105°	83.9 ± 15.8	80.7 ± 18.0	73.9 ± 22.4	70.1 ± 24.1
	4 (n = 21)	90°	72.9 ± 25.9	69.4 ± 25.9	69.7 ± 26.2	68.8 ± 25.5
		105°	67.8 ± 21.8	68.6 ± 18.7	67.0 ± 19.5	65.9 ± 17.8
	All (n = 76)	90°	82.0 ± 20.4	78.1 ± 20.8	76.7 ± 22.0	72.9 ± 21.9
		105°	79.0 ± 19.4	75.2 ± 19.2	72.0 ± 20.1	68.9 ± 20.3
Compression Depth, cm (mean ± SD)	1 (n = 18)	90°	5.6 ± 0.6	5.2 ± 0.7	5.0 ± 0.9	4.8 ± 1.0
		105°	5.0 ± 0.8	4.7 ± 0.9	4.6 ± 1.0	4.4 ± 1.1
	2 (n = 20)	90°	5.7 ± 0.5	5.4 ± 0.6	5.0 ± 1.1	4.8 ± 1.0
		105°	5.0 ± 0.6	4.5 ± 0.8	4.2 ± 0.9	4.0 ± 1.1
	3 (n = 17)	90°	5.7 ± 0.5	5.4 ± 0.7	5.1 ± 1.0	5.0 ± 1.0
		105°	5.1 ± 0.9	4.7 ± 1.1	4.5 ± 1.3	4.2 ± 1.4
	4 (n = 21)	90°	5.2 ± 1.0	5.0 ± 1.2	4.8 ± 1.2	4.6 ± 1.2
		105°	4.4 ± 0.9	4.1 ± 1.1	3.9 ± 1.1	3.8 ± 1.1
	All (n = 76)	90°	5.5 ± 0.7	5.2 ± 0.8	5.0 ± 1.0	4.8 ± 1.1
		105°	4.8 ± 0.8	4.5 ± 1.0	4.3 ± 1.1	4.1 ± 1.2
Compression Rate, cpm (mean ± SD)	1 (n = 18)	90°	114.4 ± 13.0	112.3 ± 11.2	111.7 ± 12.2	112.5 ± 13.2
		105°	112.1 ± 13.2	113.8 ± 15.1	112.6 ± 16.4	113.1 ± 17.0
	2 (n = 20)	90°	113.1 ± 10.1	111.2 ± 12.2	110.8 ± 12.9	111.2 ± 13.9
		105°	112.5 ± 10.0	111.5 ± 12.1	111.9 ± 12.0	111.8 ± 14.4
	3 (n = 17)	90°	116.1 ± 12.2	114.6 ± 12.4	115.0 ± 14.5	115.3 ± 16.0
		105°	114.4 ± 10.5	112.6 ± 11.9	113.2 ± 14.6	112.9 ± 16.3
	4 (n = 21)	90°	117.9 ± 13.1	117.0 ± 15.4	115.9 ± 15.0	116.6 ± 16.6
		105°	117.7 ± 17.6	116.7 ± 14.3	116.9 ± 16.1	113.8 ± 16.4
	All (n = 76)	90°	115.4 ± 12.1	113.8 ± 13.0	113.4 ± 13.6	113.9 ± 14.9
		105°	114.3 ± 13.3	113.7 ± 13.3	113.7 ± 14.7	112.9 ± 15.7
Compression Recoil, cm (mean ± SD)	1 (n = 18)	90°	0.38 ± 0.31	0.35 ± 0.33	0.32 ± 0.30	0.33 ± 0.31
		105°	0.30 ± 0.31	0.22 ± 0.29	0.21 ± 0.23	0.22 ± 0.25
	2 (n = 20)	90°	0.44 ± 0.32	0.51 ± 0.40	0.49 ± 0.39	0.48 ± 0.40
		105°	0.24 ± 0.31	0.31 ± 0.30	0.28 ± 0.26	0.27 ± 0.30
	3 (n = 17)	90°	0.45 ± 0.33	0.41 ± 0.28	0.36 ± 0.28	0.36 ± 0.27
		105°	0.29 ± 0.34	0.23 ± 0.26	0.25 ± 0.29	0.23 ± 0.31
	4 (n = 21)	90°	0.48 ± 0.32	0.45 ± 0.28	0.46 ± 0.27	0.45 ± 0.28
		105°	0.20 ± 0.27	0.19 ± 0.24	0.15 ± 0.21	0.17 ± 0.24
	All (n = 76)	90°	0.44 ± 0.31	0.43 ± 0.32	0.41 ± 0.32	0.41 ± 0.32
		105°	0.25 ± 0.30	0.24 ± 0.27	0.22 ± 0.25	0.22 ± 0.27

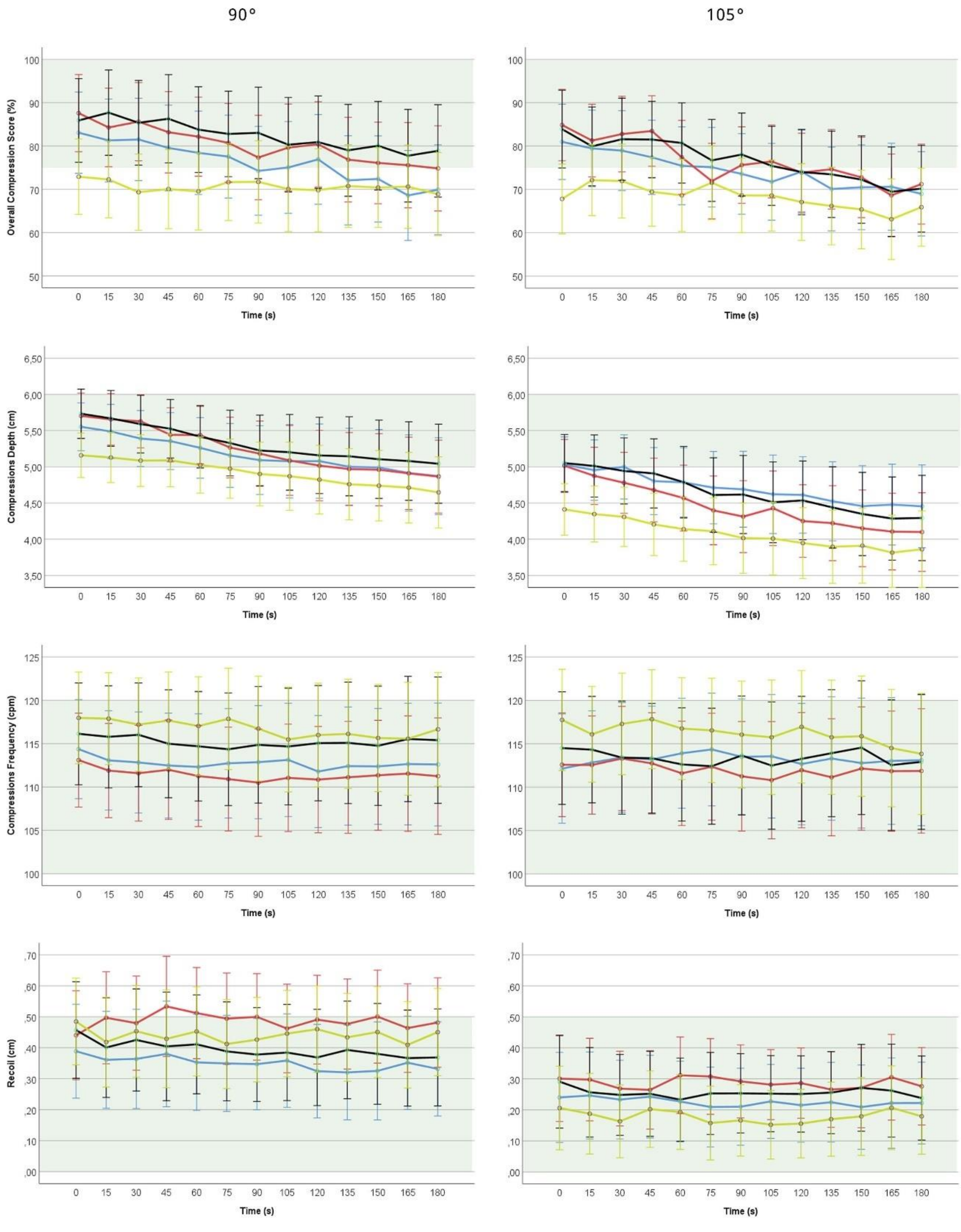

Figure 8 - CPR Quality based on rescuer position and arm angle (overall compression score (%), rate (cpm), depth values (cm) and recoil (cm)). Green areas represent guidelines recommendations. Error bars represent 95% confidence interval.

Overall compression score

The overall compression score (OCS) declined over time across all groups, regardless of the arm angle. Groups using a 90° arm angle generally exhibited higher initial compression scores compared to those using a 105° angle. This pattern was consistent across all groups. Group 3 (rescuers standing on a step stool beside the bed) maintained relatively higher scores over time, particularly in the 90° angle. In contrast, Group 4 (rescuers kneeling on the bed) consistently scored below 75 % throughout the trial, especially with the 105° arm angle. The mixed-effects model analysis (Table 9) corroborates these observations, showing a significant decrease in OCS with the 105° arm angle (Coeff = -2.58, SE = 3.59) and a negative coefficient for time, indicating a general decline as the trial progressed. Furthermore, Group 4 had a significant negative effect on the score compared to the reference group (Group 2).

Other covariates also significantly influenced the OCS. Active participants had significantly higher scores (Coeff = 12.46, SE = 3.58), highlighting the impact of physical fitness on CPR performance. Additionally, participants who had received CPR training within the last two years had better scores (Coeff = -7.35 for training ≥ 24 months, SE = 3.67), underscoring the importance of regular training to maintain or improve CPR skills.

Compression depth

Similarly to the overall score, the compression depth decreased throughout the 3-minute trial for all groups. The 90° arm angle consistently allowed for deeper compressions than the 105° angle. Participants with the 90° arm angle maintained adequate depth (5–6 cm) up to 2 −minutes, except for Group 4, which fell below this threshold after 75 s. In contrast, those using the 105° arm angle exhibited a decline from nearly the beginning of the trial, with Group 4 starting with a mean depth of 4.4 cm (Fig. 8, Table 8). The mixed-effects model (Table 9) showed that the 105° arm angle significantly reduced compression depth (Coeff = -0.77, SE = 0.16).

Compression rate and recoil

Compression rate remained stable across all groups and time points, suggesting that rescuers maintained the recommended rate despite the observed decline in other metrics. Moreover, recoil values remained below 5 mm, across all groups and both arm angles, demonstrating effective chest recoil across all settings. Notably, the 105° angle was associated with significantly better recoil (Coeff = -0.208, SE = 0.073).

Table 9 - Assessment of statistical significance based on the coefficients of linear mixed models, adjusted for gender, SBAS and last CPR training. The group G2 and the arm angle at 90° were considered the reference group.

	OCS	Depth	Rate	Recoil
Fixed effects model[1]	**Coeff (SE)**	**Coeff (SE)**	**Coeff (SE)**	**Coeff (SE)**
Intercept	81.59(4.65)***	5.52(0.21)***	115.14(3.51)***	0.535(0.078)***
Groups				
G1	−5.92(5.49)	−0.24(0.25)	1.71(4.03)	−0.118(0.096)
G3	−2.31(5.64)	−0.01(0.25)	4.87(4.15)	−0.056(0.098)
G4	−14.91(5.34)**	−0.44(0.24)	6.43(3.94)	−0.003(0.093)
Arm angle				
105°	−2.58(3.59)	−0.77(0.16)***	0.56(1.81)	−0.208(0.073)**
Time	−0.06(0.02)***	−0.004(0.001)***	−0.006(0.011)	−0.000(0.001)
Position:Arm angle				
G1:105°	1.98(5.15)	0.31(0.23)	−0.12(2.61)	0.075(0.105)
G3:105°	−1.94(5.23)	0.10(0.24)	−2.39(2.65)	0.061(0.107)
G4:105°	1.36(4.96)	−0.05(0.23)	−1.12(2.51)	−0.061(0.101)
Position:Time				
G1:Time	0.00(0.03)	0.001(0.001)	0.003(0.01)	−0.000(0.001)
G3:Time	0.01(0.03)	0.000(0.001)	0.002(0.01)	−0.000(0.001)
G4:Time	0.05(0.02)*	0.002(0.001)	−0.007(0.01)	−0.000(0.001)
Arm angle:Time				
105°:Time	−0.01(0.01)*	−0.000(0.001)	0.000(0.001)	0.000(0.001)
Gender				
Male	1.24(3.38)	0.43(0.15)	−2.61(2.68)	0.096(0.053)
SBAS				
Active	12.46(3.58)***	0.08(0.16)	−4.90(2.85)	−0.100(0.056)
Last Training				
>= 24 *m*	−7.35(3.67)*	−0.32(0.17)	2.07(2.92)	−0.127(0.058)
Random effects model	**SD (95 %CI)**	**SD (95 %CI)**	**SD (95 %CI)**	**SD (95 %CI)**
Participant (Time)				
Intercept	12.33 (9.59–15.85)	0.57 (0.44–0.73)	10.96(9.05–13.28)	0.18 (0.13–0.25)
Slope	0.07 (0.06–0.09)	0.004(0.003–0.005)	0.05 (0.04–0.06)	0.0005(0.0004–0.0006)
Arm angle within participant				
Intercept	11.02 (9.3–13.0)	0.51 (0.43–0.60)	5.62 (4.76–6.64)	0.22 (0.19–0.26)
Residuals	7.55 (7.30–7.80)	0.24 (0.23–0.25)	2.90 (2.80–2.99)	0.08 (0.08–0.09)

Statistical significance: *p < 0.05; **p < 0.01; ***p < 0.001. Coeff: Coefficient; SE: Standard error; SD: standard deviation; CI: Confidence interval. [1]The main effects and 2nd order interaction are presented. The 3rd order interaction was non-significant and therefore was not included in the models.

Discussion

This study provides a comprehensive analysis of how rescuer position and arm angle influence the quality of CC among experienced healthcare professionals. Conducted across three European countries, this international multicentric study, was grounded in a robust protocol to ensure data standardization and mitigate confounding variables. The international scope of the study introduces a diverse participant pool, enhancing the generalizability of the findings across different settings, professional backgrounds, and cultural characteristics.

The results demonstrate that both rescuer position and arm angle significantly impact the quality of CC during cardiopulmonary resuscitation, among healthcare professionals. Groups using a 90° arm angle consistently achieved higher overall compression scores compared to those using a 105° angle. However, scores declined over time in all groups, indicating that rescuers are susceptible to fatigue even with optimal arm positioning.

Compression depth mirrored overall scores, with deeper and more effective compressions achieved at a 90° angle, reinforcing the ergonomic advantage of arms perpendicular to the patients' chest [3, 4]. However, achieving full recoil was more challenging at this angle, though still within acceptable limits (chest depression < 5 mm).

The compression rate remained stable across all conditions, suggesting that maintaining the recommended rate is an intrinsic mechanism, not affected by fatigue or arm angle.

Notably, rescuers standing on a step stool (Group 3) maintained higher scores over time. This suggests that elevated position, combined with 90° arm angle, optimize the effectiveness of compressions by allowing more efficient use of body weight and reducing arm fatigue.

Conversely, rescuers kneeling on the bed (Group 4) showed consistently lower scores, highlighting the potential physical discomfort and poor biomechanical support associated with this position, which increases fatigue and diminishes the quality of CC [19]. This finding suggests the need for alternative setups, such as equipping hospital rooms with step stools, to improve rescuer ergonomics and compression effectiveness.

The study also highlights the role of physical fitness and recent CPR training in performance. Participants who were physically active or had received recent training performed better, underscoring the importance of regular physical conditioning and continuous professional development to maintain CPR proficiency.

Recent studies [28, 29, 30] have explored several factors influencing CPR quality, including rescuer fatigue, rotation timing, anthropometric characteristics, and innovative positioning techniques, highlighting that this area of research remains complex and requires further investigation. Anthropometric characteristics, such as BMI and height, have been associated with deeper compressions in settings using a fixed bed height [7, 28]. In the present study, BMI was not found a significant covariate as the bed height was adjusted to the rescuers' patella. This finding is supported by Charungwatthana et al. [30], who tested various rescuer positions and concluded that high-quality CPR could be achieved in any position, provided the bed was adjusted to the rescuer's knee height. These results emphasize the importance of considering ergonomics and dynamically adjusting the environment based on rescuer's physical characteristics.

Rescuer fatigue is associated to CC and tensiomyography data suggest that 2-min cycles of continuous chest compressions may induce to neuromuscular fatigue, compromising CPR quality [7]. Kim et al. [29] examined the effect of rotation timing on CC quality, finding that rescuers who rotated every minute achieved significantly better CC depth. These findings align with the results of this study, where CC depth was consistently lower, across all groups, at 120 s, compared to 60 s (Table 8). Rotation intervals recommendations may need to be adjusted to maintain high-quality CPR.

This study demonstrated that, several factors contribute to the quality of CC, including rescuer position, arm angle, rescuing duration, physical fitness, and recent training. Maximizing the quality of CC requires understanding these factors and deliberately adapting the ergonomics of the resuscitation environment.

Training programs should integrate these findings into their curricula, moving beyond traditional kneeling positions. Training should be context-aware and customizable, addressing the ergonomic realities of different environments. The technology could play a pivotal role in providing real-time feedback on arm angles and body positioning to optimize training effectiveness. Training should move beyond technical skills to enhance awareness of the factors influencing CPR quality, offering personalized experiences that allow practitioners to identify and mitigate potential performance challenges. These findings advocate for a shift in CPR training paradigms, ensuring that different settings are considered, leading to training that is adaptive and responsive to the ergonomic realities faced by healthcare professionals in critical care situations.

Limitations

This study has some limitations. The study design did not allow for blinding, which may have introduced bias in the performance and quality of compressions. Having carried out a multicentric, international and multiprofessional study, introduced some heterogeneity in participant profiles, however efforts were made to minimize this when allocating participants to groups. Additionally, 15 participants were excluded due to data collection issues, potentially introducing selection bias. The stiffness of the manikin was reported to be unrealistic, causing increased fatigue and potentially affecting compression quality, despite participants having a familiarization session before the trials. Similar equipment was used across all 3 sites, ensuring that the results remained comparable. Lastly, the results of this study were obtained in a simulated setting, which may not fully reflect the real clinical environment. Factors such as the adrenaline surge experienced during a real emergency were not considered.

Conclusions

This study highlights the significant influence of rescuer position and arm angle on CPR quality. The 90° arm angle and elevated positions, such as standing on a step stool, were found to optimize compression depth and effectiveness, while kneeling on the bed was detrimental to performance. Additionally, physical fitness and recent training are key factors in improving CPR performance.

Acknowledgments

This work was supported by national funds of the FCT – Fundação para a Ciência e a Tecnologia, I.P., under the project “QualityCPR, ref. 2022.03731.PTDC”.

The authors would like to acknowledge the collaboration of the fellow researchers and colleagues at the Institute for Emergency Medicine and Medical Management, LMU University Hospital, the fellow lecturers and colleagues at Arcada Patient Safety and Learning Center, and the professionals at the intensive care and post anesthesia care units from São João University Hospital Center. Special thanks are also extended to all participants who volunteered for this study.

References

1. Merchant, R. M., Topjian, A. A., Panchal, A. R., Cheng, A., Aziz, K., Berg, K. M., ... & Adult Basic and Advanced Life Support, Pediatric Basic and Advanced Life Support, Neonatal Life Support, Resuscitation Education Science, and Systems of Care Writing Groups. (2020). Part 1: executive summary: 2020 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation, 142(16_Suppl_2), S337-S357.
2. Cheng, A., Magid, D. J., Auerbach, M., Bhanji, F., Bigham, B. L., Blewer, A. L., ... & Donoghue, A. (2020). Part 6: resuscitation education science: 2020 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation, 142(16_Suppl_2), S551-S579.
3. Panchal, A. R., Bartos, J. A., Cabañas, J. G., Donnino, M. W., Drennan, I. R., Hirsch, K. G., ... & Berg, K. M. (2020). Part 3: adult basic and advanced life support: 2020 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation, 142(16_Suppl_2), S366-S468.
4. Perkins, G. D., Handley, A. J., Koster, R. W., Castrén, M., Smyth, M. A., Olasveengen, T., ... & Greif, R. (2015). European Resuscitation Council Guidelines for Resuscitation 2015: Section 2. Adult basic life support and automated external defibrillation. Resuscitation, 95, 81-99.
5. Olasveengen, T. M., Semeraro, F., Ristagno, G., Castren, M., Handley, A., Kuzovlev, A., ... & Perkins, G. D. (2021). European resuscitation council guidelines 2021: basic life support. Resuscitation, 161, 98-114.
6. Greif, R., Lockey, A., Breckwoldt, J., Carmona, F., Conaghan, P., Kuzovlev, A., ... & Monsieurs, K. G. (2021). European resuscitation council guidelines 2021: education for resuscitation. Resuscitation, 161, 388-407.
7. Abelairas-Gómez, C., Rey, E., González-Salvado, V., Mecías-Calvo, M., Rodríguez-Ruiz, E., & Rodríguez-Núñez, A. (2018). Acute muscle fatigue and CPR quality assisted by visual feedback devices: a randomized-crossover simulation trial. PLoS One, 13(9), e0203576.
8. Mayrand, K. P., Fischer, E. J., & Ten Eyck, R. P. (2015). A simulation-based randomized controlled study of factors influencing chest compression depth. Western Journal of Emergency Medicine, 16(7), 1135.
9. Hong, C. K., Park, S. O., Jeong, H. H., Kim, J. H., Lee, N. K., Lee, K. Y., ... & Hwang, S. Y. (2014). The most effective rescuer's position for cardiopulmonary resuscitation provided to patients on beds: a randomized, controlled, crossover mannequin study. The Journal of emergency medicine, 46(5), 643-649.
10. Holt, J., Ward, A., Mohamed, T. Y., Chukowry, P., Grolmusova, N., Couper, K., ... & Perkins, G. D. (2020). The optimal surface for delivery of CPR: a systematic review and meta-analysis. Resuscitation, 155, 159-164.

11. Ho, C. S., Hsu, Y. J., Li, F., Tang, C. C., Yang, C. P., Huang, C. C., ... & Chang, C. H. (2021). Effect of Ambulance Stretcher Bed Height Adjustment on CPR Quality and Rescuer Fatigue in a Laboratory Environment. International Journal of Medical Sciences, 18(13), 2783.
12. Cho, J., Oh, J. H., Park, Y. S., Park, I. C., & Chung, S. P. (2009). Effects of bed height on the performance of chest compressions. Emergency Medicine Journal, 26(11), 807-810.
13. Foo, N. P., Chang, J. H., Lin, H. J., & Guo, H. R. (2010). Rescuer fatigue and cardiopulmonary resuscitation positions: a randomized controlled crossover trial. Resuscitation, 81(5), 579-584.
14. Lee, D. H., Kim, C. W., Kim, S. E., & Lee, S. J. (2012). Use of step stool during resuscitation improved the quality of chest compression in simulated resuscitation. Emergency Medicine Australasia, 24(4), 369-373.
15. Yun, S. W., Lee, B. K., Jeung, K. W., Park, S. W., Choi, S. S., Lee, C. H., & Ryu, S. Y. (2014). The effect of inclined step stool on the quality of chest compression during in-hospital cardiopulmonary resuscitation. The American Journal of Emergency Medicine, 32(8), 851-855.
16. Chi, C. H., Tsou, J. Y., & Su, F. C. (2008). Effects of rescuer position on the kinematics of cardiopulmonary resuscitation (CPR) and the force of delivered compressions. Resuscitation, 76(1), 69-75.
17. Jäntti, H., Silfvast, T., Turpeinen, A., Kiviniemi, V., & Uusaro, A. (2009). Quality of cardiopulmonary resuscitation on manikins: on the floor and in the bed. Acta anaesthesiologica scandinavica, 53(9), 1131-1137.
18. Oh, J. H., Kim, C. W., Kim, S. E., Lee, S. J., & Lee, D. H. (2014). Comparison of chest compressions in the standing position beside a bed at knee level and the kneeling position: a non-randomised, single-blind, cross-over trial. Emergency Medicine Journal, 31(7), 533-535.
19. Hasegawa, T., Okane, R., Ichikawa, Y., Inukai, S., & Saito, S. (2020). Effect of chest compression with kneeling on the bed in clinical situations. Japan Journal of Nursing Science, 17(2), e12314.
20. Jones, A. Y., & Lee, R. Y. (2008). Rescuer’s position and energy consumption, spinal kinetics, and effectiveness of simulated cardiac compression. American Journal of Critical Care, 17(5), 417-425.
21. Ashton, A., McCluskey, A., Gwinnutt, C. L., & Keenan, A. M. (2002). Effect of rescuer fatigue on performance of continuous external chest compressions over 3 min. Resuscitation, 55(2), 151-155.
22. Nicolau, A. F. S. (2018). Development and validation of a low-cost tool for CPR self-training (Master's thesis, Universidade do Porto (Portugal)).
23. Jorge, I., Sá-Couto, C., & Nicolau, A. (2022, June). Development of an Objective Measurement System for Quality Assessment of Chest Compressions. In 2022 17th Iberian Conference on Information Systems and Technologies (CISTI) (pp. 1-6). IEEE.

24. F. Taylor-Piliae, R. E., Norton, L. C., Haskell, W. L., Mahbouda, M. H., Fair, J. M., Iribarren, C., ... & Fortmann, S. P. (2006). Validation of a new brief physical activity survey among men and women aged 60–69 years. American journal of epidemiology, 164(6), 598-606.
25. Joseph, R. P., Keller, C., Adams, M. A., & Ainsworth, B. E. (2016). Validity of two brief physical activity questionnaires with accelerometers among African-American women. Primary health care research & development, 17(3), 265-276.
26. World Health Organization. (2020). WHO guidelines on physical activity and sedentary behaviour. World Health Organization.
27. Catalisano, G., Milazzo, M., Simone, B., Campanella, S., Catalanotto, F. R., Ippolito, M., ... & Cortegiani, A. (2024). Intentional interruptions during compression only CPR: A scoping review. Resuscitation Plus, 18, 100623.
28. Zhang, N., Wang, J., Li, Y., Liu, J., & Zhu, H. (2024). How Does Rescuer's Position Setting Impact Quality of Chest Compression: A Randomized Crossover Simulation Study on Unexperienced Clinicians. Emergency Medicine International, 2024(1), 9950885.
29. Kim, D. H., Seo, Y. W., & Jang, T. C. (2023). CPR quality with rotation of every 1 versus 2 minutes as characteristics of rescuers: A randomized crossover simulation study. Medicine, 102(10), e33066.
30. Charungwatthana, N., Laohakul, P., Tangsuwanaruk, T., & Wittayachamnankul, B. (2024). Effectiveness of innovative chest compression on the emergency department stretcher by an alternative method: a randomized controlled crossover trial. Scientific Reports, 14(1), 12284.

Chapter 4

Discussion

This thesis provided valuable insights into various aspects of cardiopulmonary resuscitation and the role of feedback devices in training and performance. Specifically, the research conducted offered novel findings on how corrective feedback devices influence the acquisition and retention of CPR skills. It also examined the critical impact of rescuer positioning and arm angle on the quality of chest compressions, answering the research questions: What is the impact of corrective feedback devices on CPR skill acquisition and retention? How do position and arm angle influence the quality of CPR?

The findings of this thesis contributed to understanding the beneficial role of corrective feedback devices in enhancing the quality of CPR training, especially by demonstrating that extended exposure to corrective feedback yields better training outcomes. Additionally, this thesis contributed to understanding different factors that influence the quality of CPR while emphasizing that a 90° arm angle consistently leads to higher overall compression scores and deeper, more effective compressions compared to a 105° angle. Finally, the results from both research papers can promote continuous development of feedback technology, namely by incorporating guidance on the rescuer posture to improve efficiency and reduce fatigue.

Enhancing the quality of CPR requires a multifaceted approach involving the integration of corrective feedback technologies, the refinement of training methodologies, the incorporation of personalized educational strategies, and the optimization of clinical environments. Feedback devices should be designed to deliver real-time data on key metrics such as chest compression depth, rate, and recoil, ensuring adherence to resuscitation guidelines. Moreover, these devices should incorporate features that guide ergonomic optimization, such as adjustments to arm angles and body posture, to improve the efficiency and sustainability of compressions. The durability, portability, and affordability of such devices are critical to their widespread implementation.

In terms of training methodologies, evidence supports the need for extended practice sessions, as longer durations facilitate improved skill acquisition and retention. Periodic refresher courses, conducted every three to six months, are vital to counteract skill decay. Scenario-based learning is indispensable, simulating real-world challenges such as performing compressions on unconventional surfaces or in confined spaces, to prepare practitioners for the varied contexts encountered in clinical and prehospital environments.

Personalized training strategies should highlight the relationship between physical fitness and CPR performance. Trainees should be educated on maintaining physical strength and stamina, with modules addressing how fitness impacts resuscitation efficacy. Feedback devices should be utilized to tailor instruction, focusing on specific areas for improvement, such as achieving full chest recoil or maintaining consistent compression depth. Emphasis on ergonomic techniques, including the effective use of body weight, is essential to reduce fatigue and enhance performance during prolonged resuscitation efforts.

Key topics in training should include achieving complete chest recoil without compromising compression depth, managing fatigue over time, and navigating environmental challenges, such as performing CPR in constrained or unconventional settings. Training programs should also emphasize the importance of team-based dynamics, including role rotation in multi-rescuer scenarios, to ensure sustained high-quality compressions.

In clinical practice, healthcare facilities must adapt to support effective resuscitation efforts. Providing ergonomic equipment, such as step stools and height-adjustable beds, can optimize rescuer positioning and reduce fatigue. Real-time monitoring systems with integrated feedback capabilities should be installed in critical care units to guide ongoing adjustments and maintain CPR quality during clinical interventions.

For laypeople, community-based training initiatives focusing on basic CPR skills are crucial. Accessible feedback devices should be employed to reinforce correct techniques and build confidence.

Future Research

Future research should prioritize investigating the direct impact of CPR training on patient outcomes. While numerous studies have evaluated the efficacy of training methods and feedback devices on skill acquisition, a significant gap exists in understanding how these improvements translate to survival rates and neurological outcomes in real-world cardiac arrest scenarios. Large-scale, longitudinal studies linking training interventions to patient-centered outcomes will provide critical evidence to refine CPR protocols and training programs.

The role of muscle fatigue in influencing chest compression quality remains an underexplored area that needs further investigation. Prolonged resuscitation efforts, especially in emergency settings, often result in rescuer fatigue, compromising compression depth and rate over time. Future studies should evaluate the physiological thresholds of fatigue, its onset under varying ergonomic conditions, and the effectiveness of strategies, such as role rotation and fitness training, in mitigating its impact. Understanding these factors can inform the development of targeted interventions to sustain high-quality CPR during extended resuscitation efforts.

Mass training initiatives for laypeople represent another critical avenue for improving community response to cardiac arrest. Research is needed to identify the most effective delivery methods for large-scale education, including the use of technology, public campaigns, and community partnerships. These initiatives should focus on increasing accessibility, ensuring skill retention, and fostering confidence among participants in acting during emergencies. Similarly, healthcare professionals would benefit from structured refresher courses, conducted at regular intervals, to address skill degradation and integrate the latest evidence-based practices into routine resuscitation efforts.

Finally, future work should examine the factors influencing CPR quality and foster greater self-awareness among rescuers regarding their performance. Studies could explore the impact of ergonomic adjustments, cognitive load, and psychological stressors on CPR delivery. Promoting self-awareness through feedback, training, and debriefing sessions can empower rescuers to identify and address performance gaps, ensuring consistent and effective resuscitation efforts. These research directions collectively aim to enhance CPR training and practice, ultimately improving survival and quality-of-life outcomes for cardiac arrest patients.

Appendices

Appendix 1 – PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	Title
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	Abstract Checklist
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	Introduction, 4^{th} and 5^{th} par.
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	Introduction, last (6^{th}) par.
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	Methods, Eligibility Criteria
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	Methods, Information Sources and Search Strategy, 1^{st} par. and Appendix Search Strategy
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	Methods, Information Sources and Search Strategy, 2^{nd} and 3^{rd} par. and Appendix Search Strategy
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	Methods, Selection Process
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	Methods, Data extraction and Outcomes, 1^{st} sent.
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	Methods, Data extraction and Outcomes.

Section and Topic	Item #	Checklist item	Location where item is reported
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	Methods, Data extraction and Outcomes.
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	Methods, Risk of Bias Assessment
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	Methods, Data extraction and Outcomes.
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	Methods, Synthesis Methods, 1st and 4th par.
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	Methods, Synthesis Methods, 2nd and 3rd par
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	Methods, Synthesis Methods, 2nd and 3rd par
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	Methods, Synthesis Methods, 2nd and 3rd par
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	Methods, Synthesis Methods, 2nd and 3rd par
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	Methods, Synthesis Methods, 4th par
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	Methods, Risk of Bias Assessment
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	×
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	Results, Search Results. Figure 1
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	Results, Search Results. Figure 1
Study characteristics	17	Cite each included study and present its characteristics.	Results, Characteristics of included studies + Table 1 and Table 2

Section and Topic	Item #	Checklist item	Location where item is reported
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	Results, Risk of Bias in Studies + Table 3
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	Results, Characteristics of included studies + Table 1 and Table 2
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	Results, Risk of Bias in Studies
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	Results, Synthesis of CPR Quality
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	Results, Synthesis of CPR Quality
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	Results, Synthesis of CPR Quality
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	Discussion, 5th par.
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	x
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	Discussion, 1st and 2nd par.
	23b	Discuss any limitations of the evidence included in the review.	Limitations
	23c	Discuss any limitations of the review processes used.	Discussion, 5th par.
	23d	Discuss implications of the results for practice, policy, and future research.	Discussion, 4th to 9th par.
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	Methods, 2nd par.
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	Methods, 2nd par.
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	Prospero
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	Acknowledgements

Section and Topic	Item #	Checklist item	Location where item is reported
Competing interests	26	Declare any competing interests of review authors.	Conflicts of Interest
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	Data Availability, Appendix Search Strategy, Appendix Studies Characteristics

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71

Appendix 2 – PRISMA 2020 Checklist

General Strategy

Publications from January 2015 to December 2023. MEDLINE, Web of Science and Scopus.
1. Cardiopulmonary resuscitation [tab] **2.** CPR [tab] **3.** Basic life support [tab] **4.** BLS [tab] **5.** Resuscitation [tab] **6.** 1 OR 2 OR 3 OR 4 OR 5 **7.** Training [tab] **8.** Feedback [tab] **9.** Manikin* [tab] **10.** Device* [tab] **11.** Prompt* [tab] **12.** Audiovisual [tab] **13.** Technology [tab] **14.** Simulat* [tab] **15.** 7 OR 8 OR 9 OR 10 OR 11 OR 12 OR 13 OR 14 **16.** Quality [tab] **17.** Performance [tab] **18.** Compression* [tab] **19.** Acquisition [tab] **20.** Retention [tab] **21.** 16 OR 17 OR 18 OR 19 OR 20 **22.** 6 AND 15 AND 21

MEDLINE – PubMed

Search	Query
#23	Search: #22 AND 2015:2023[dp]
#22	Search: #6 AND #15 AND #21
#21	Search: #16 OR #17 OR #18 OR #19 OR #20
#20	Search: Retention[Title/Abstract]
#19	Search: Acquisition[Title/Abstract]
#18	Search: Compression*[Title/Abstract]
#17	Search: Performance[Title/Abstract]
#16	Search: Quality[Title/Abstract]
#15	Search: #7 OR #8 OR #9 OR #10 OR #11 OR #12 OR #13 OR #14
#14	Search: Simulat*[Title/Abstract]
#13	Search: Technology[Title/Abstract]
#12	Search: Audiovisual[Title/Abstract]
#11	Search: Prompt*[Title/Abstract]
#10	Search: Device*[Title/Abstract]
#9	Search: Manikin*[Title/Abstract]
#8	Search: Feedback[Title/Abstract]
#7	Search: Training[Title/Abstract]
#6	Search: #1 OR #2 OR #3 OR #4 OR #5
#5	Search: Resuscitation[Title/Abstract]
#4	Search: BLS[Title/Abstract]
#3	Search: Basic life support[Title/Abstract]
#2	Search: CPR[Title/Abstract]
#1	Search: Cardiopulmonary resuscitation[Title/Abstract]

Web of Science

Query: ((TS=(Cardiopulmonary resuscitation) OR TS=(CPR) OR TS=(Basic life support) OR TS=(BLS) OR TS=(Resuscitation)) AND (TS=(Training) OR TS=(Feedback) OR TS=(Manikin*) OR TS=(Device*) OR TS=(Prompt*) OR TS=(Audiovisual) OR TS=(Technology) OR TS=(Simulat*)) AND (TS=(Quality) OR TS=(Performance) OR TS=(Compression*) OR TS=(Acquisition) OR TS=(Retention))) AND DOP=(2015/2023)

Scopus

Query: ((TITLE-ABS(Cardiopulmonary resuscitation) OR TITLE-ABS(CPR) OR TITLE-ABS(Basic life support) OR TITLE-ABS(BLS) OR TITLE-ABS(Resuscitation)) AND (TITLE-ABS(Training) OR TITLE-ABS(Feedback) OR TITLE-ABS(Manikin*) OR TITLE-ABS(Device*) OR TITLE-ABS(Prompt*) OR TITLE-ABS(Audiovisual) OR TITLE-ABS(Technology) OR TITLE-ABS(Simulat*)) AND (TITLE-ABS(Quality) OR TITLE-ABS(Performance) OR TITLE-ABS(Compression*) OR TITLE-ABS(Acquisition) OR TITLE-ABS(Retention))) AND PUBYEAR > 2014

Appendix 3 – Study Characteristics

The printed version cannot display the following table clearly due to the large amount of data. Please refer to the complete table here: JMIR Med Educ 2024;10:e59720 (Multimedia Appendix 3).

Author	Year Published	Country	Study Design	Population		Previous Training	Intervention Description	Feedback Device		Outcomes	
				N	Participants			Training	Assessment	Assessment-Training Interval	Data
Cortegiani et al [1]	2017	Italy	Randomized Trial	125	Secondary School Students	**Previous:** unknown **Upon study:** a trained instructor performed a 30-minute interactive frontal lesson about cardiac arrest and BLS-D. students of both groups started to practice until they reached a minimum sufficient technical skill to perform a 2-minute training session according to the instructor in charge.	**Standard Feedback from instructor group:** received feedback on their practice during the 2-minute training session according to instructor's opinion. At the end of the session, all participants received a feedback on their performance based on the instructor's judgment. **QCPR group:** training by the instructor on chest compressions using a mannequin connected to a personal computer running specific software proving real-time electronic feedback about CPR quality. Practice until they reached a minimum sufficient technical skill to perform a 2-minute training session according to the instructor in charge. Performed a 2-minute training session taking into account the real-time data of the software trying to correct themselves to reach the high-quality targets. At the end of the session, all participants received a feedback on their performance: in the QCPR group the feedback was based on results from the software. **Assessment:** 2-minute chest compression session without feedback neither from the software nor from the instructor.	**Standard Feedback from instructor group:** Laerdal Resusci Anne **QCPR Group:** Laerdal Resuscie Anne QCPR with Wireless SkillReporter	Laerdal Resuscie Anne QCPR with Wireless SkillReporter for data collection	7 days	**Primary:** compression score calculated by Laerdal QCPR **Secondary:** 1) compression rate 2) compression depth 3) percentage of compressions with complete chest release 4) percentage of compressions with correct hand position. **Other:** 5) overall dichotomous judgment from the instructor who judged students' performance (adequate/not adequate); 6) proportion of students reaching a compression score of 75% (minimum score for an "Advanced CPR Performer" according to manufacturer's indications and confirmed by consensus among authors) and 90%; 7) proportion of students reaching a compression score of 90%; 8) 1–5 Likert-scale score from participants investigating the degree of their comfort and how they enjoyed the overall experience
Lin et al [2]	2018	Canada	Randomized Controlled Trial	87	Healthcare Providers working in the Emergency Department	**Previous:** Pediatric healthcare providers (nurses, residents, respiratory therapists) and Pediatric Advanced Life Support (PALS), or Advanced Cardiac Life Support (ACLS) certification within the past 2 years. **Upon study:** each participant had taken an initial BLS course to ensure equal opportunity for CPR skill acquisition upon entry into the study.	**Control Group:** Standardized AHA BLS course only. Participants in the control group received the standardized AHA BLS course only, led by certified BLS instructors 12 months after taking the initial BLS course. During the course, participants practiced without real-time feedback and the course instructor evaluated the CPR quality with visual assessment for chest compression (CC) depth and recoil and a stop-watch for CC rate. **Intervention Group:** access to a CPR training unit and received just-in-time CPR training in a longitudinal fashion in the ED. The training unit also provided feedback on all CPR metrics during compressions. At the end of each CPR practice event, the feedback device provided terminal feedback for the learner on the quality of CPR. Healthcare providers in the intervention group practiced continuous CCs for 2 min on both adult and infant-sized mannequins with real-time feedback. All participants in the intervention group were required to practice at least once a month with no maximum for the number of times they were permitted to practice. **Assessment:** Assessment sessions were run in the same setting as the practice sessions. All participants were assessed at baseline and every 3 months during the study.	**Control Group:** Laerdal Resusci Anne, Laerdal Resusci Baby **Intervention group:** Laerdal Resusci Anne with SimPad SkillReporter, Laerdal Resusci Baby with SimPad SkillReporter	Laerdal Resusci Anne with SimPad SkillReporter for data collection Laerdal Resusci Baby with SimPad SkillReporter for data collection	Baseline 3 months 6 months 9 months 12 months	**Primary:** "excellent CPR", defined as achieving at least 90% of all AHA standards for CC depth, rate and recoil for each individual criterion. **Secondary:** (i) Percentage of compression depth > 50 mm for adult/child and compression depth > 40 mm for infant, (ii) Percentage of CC with rate of 100–120/min, and (iii) Percentage of CC with complete recoil.
Chamdawala et al [3]	2021	USA	Randomized Controlled Trial	**220**	High school Students	**Previous:** All students were eligible to participate in our study, regardless of their prior experience ortraining in CPR. **Upon study:** The next day, all study participants received standard CPR training, which consisted of a school teacher-facilitated 30-minute theoretical and practical group training session, using 'The CPR in Schools Training Kit' endorsed by the AHA.	**Standard Group:** practice CPR on the inflatable manikin under the supervision of the school teacher. **Feedback Group:** FG performed two minutes of compression-only CPR training on the Resusci Anne QCPR manikin. The research assistant (RA) provided verbal prompts if the student had difficulty interpreting the feedback device. **Assessment:** Within the two to three days following the intervention, we tested students from both groups by having them complete the same questionnaire and perform two minutes of compression-only CPR on the feedback manikin;	**Standard Group:** none. Inflatable manikin. **Feedback Group:** Resusci Anne QCPR (Laerdal Medical Corporation, USA) with SimPad with SkillReporter	Resusci Anne QCPR (Laerdal Medical Corporation, USA) with SimPad with SkillReporter	0 weeks 10 weeks 28 weeks 52 weeks	**Primary:** compression score **Secondary:** (1) participants achieving "Advanced CPR Performer" status, defined as an overall CS of 75% according to the manufacturer's guidelines; (2) individual component CPR metrics such as mean compression depth and rate, and percentage of the time the student used correct hand position and allowed for full chest recoil; (3) theoretical knowledge and self-perceived comfort in performing CPR in real-life, collected via the questionnaire during each follow-up testing session.
Moreno et al [4]	2021	Spain	Randomized Controlled Trial	**212**	Primary care staff	**Previous:** unknown **Upon study:** a session was held joint 10-minute theory on quality CPR, by an accredited life support instructor basic (SVB), to all participants. Subsequently, All of them followed the 6-minute individualized and isolated practical training with an instructor and an Annie QCPR® manikin (Laerdal).	**Group 1:** the participant received corrections from the instructor while both the instructor and the participant visualized in the laptop monitor the quality of the compressions thoracic and ventilation; **Group 2:** the participant received corrections from the instructor while the instructor viewed the quality of chest compressions and ventilations on the laptop monitor, but not the participant; **Control Group:** the participant received corrections from the instructor, but neither the instructor nor the participant saw the quality of chest compressions and ventilations on the laptop monitor. **Training:** a session was held joint 10-minute theory on quality CPR, by an accredited life support instructor basic (SVB), to all participants. Subsequently, All of them followed the 6-minute individualized and isolated practical training with an instructor and an Annie QCPR® manikin (Laerdal). 1) participants initially performed 2 minutes of CPR during which the quality of the maneuvers was recorded; 2) 2 minutes of CPR were subsequently performed with a training intervention by the instructor; and 3) finally the participants were able to perform another 2 minutes of CPR recorded by the program, without the intervention of the instructor **Assessment:** 2 minutes of CPR recorded by the program, individually and isolated, without receiving corrections from the instructor or viewing the feedback.	**Group 1:** Little Anne QCPR system equipped with Skill Reporter wireless software (Laerdal) **Group 2:** Little Anne QCPR system equipped with Skill Reporter wireless software (Laerdal) **Control Group:** Little Anne QCPR system	Little Anne QCPR system equipped with Skill Reporter wireless software (Laerdal)	Post Intervention 6 months	Primary: compression score Secondary: all measurements of compression quality, ventilation and chest expansion fraction, measured directly by the Skillreporter® program (Laerdal) - Compression score, Ventilation score, Compression fraction score, Number of compressions with correct decompression, Average compression depth, Number of compressions with adequate depth, Compression number with appropriate rhythm, Medium compression rhythm Ventilation score, Number of ventilations with adequate volume, Average ventilation volume, Medium ventilation rate
Suet et al [5]	2020	France	Randomized Trial	**61/55**	Second-year medical students on basic emergency procedures	**Previous:** unknown **Upon study:** For each student involved, the training session had a 1-day duration and CPR training represented half of the day.	**Control group:** traditional ECM training method. The trainer interacted with students by performing initially the task then providing continuous feedback and immediately correcting errors made by students performing the tasks themselves. **Group 2:** training was done in the presence of the trainer but was guided by a feedback method, namely the iPhone App PocketCPR (ZOLL Medical, Chelmsford, MA). **Group 3:** used the Resusci Anne QCPR system equipped with Skill Reporter wireless software (Laerdal). **Training:** For each student involved, the training session had a 1-day duration and CPR training represented half of the day. The ECM part of the training session was nearly 90 min, and each student performed the procedural task several times for a total of 5–8 min. The manikin used was a Resusci Anne. **Assessment:** perform a 2-min ECM without interruption.	**Control Group:** none. Resusci Anne manikin **Group 2:** iPhone App PocketCPR (ZOLL Medical, Chelmsford, MA) on Resusci Anne manikin **Group 3:** Resusci Anne QCPR system equipped with Skill Reporter wireless software (Laerdal)	Resusci Anne QCPR system equipped with Skill Reporter wireless software (Laerdal) for data collection	0 days (post-intervention) 3 months	**Primary:** overall quality of ECM (compression score) at 3 months after initial training. **Secondary:** 5 different components of compression score analyzed separately, evaluation of satisfaction by a Kirkpa-trick level 1 questionnaire distributed at the end of the initial session.
Kim et al [6]	2021	South Korea	Randomized Controlled Trial	64	Junior nursing students	**Previous:** Exclusion criteria were (i) students with basic life support (BLS) certifications and (ii) students completed or taking any BLS trainings using any real-time feedback devices. **Upon study:** The training consisted of a 40-min theoretical online lecture session and an 80-min non-contact practice session.	**Control group:** 40-min theoretical online lecture session and the 80-min face-to-face practice session with a training nurse but without real-time feedback from the smart devices. A training nurse observed and guided students' performance and provided feedback through face-to-face education. After completing each CPR performance, the students reviewed the details of their overall performance from the records of cameras in the debriefing session. **Experimental group:** 40-min theoretical online lecture session and an 80-min non-contact practice session which used the real-time on-screen feedback devices (SkillGuide from Laerdal Medical) displaying the detailed degrees of compression depth, complete or incomplete release, compression rate, time, and hand placement continuously during the CPR performance. A training nurse can observe the student directly through a glass window, grasp facial expressions and detailed movements through two cameras, identify the accuracy of a student's CPR practice in real time through a monitor linked to a smart device, and educate the student on the CPR process and give feedback through a microphone. After completing each CPR performance, the debriefing session allowed students to recognize their overall performance and the degrees of performance accuracy from the visual records of proximity and distance cameras as well as the debrief mode records of the real-time devices. **Assessment:** Posttest was conducted by two measurement researchers at right after the training and 4 weeks later to identify the continuity of the training effects.	**Control Group:** none. Resusci Anne manikin **Experimental Group:** Resusci Anne	Resusci Anne	0 days (post-intervention) 4 weeks	**General:** Chest compression accuracy (calculated from compression depth, rate, release, and hand position), Mouth-to-mouth ventilation accuracy (assessed with the mouth-to-mouth ventilation scores), Cardiopulmonary resuscitation performance ability (measured using the 20-item CPR performance ability scale based on the 2015 Korean guideline for CPR).

Wagner et al [7]	2018	Austria	Randomized Simulation Study	653	Third-year medical students	**Previous**: Third-year medical students from the Medical University of Vienna who were required to do their mandatory pediatric CPR training were included. **Upon study:** Before the training, participants reviewed the current pediatric CPR guidelines and watched a demonstration of the CPR algorithm by an instructor.	**2 manikin groups:** **Group 1:** performed CPR training using a quality of cardiopulmonary resuscitation (QCPR) infant manikin **Group 2:** performed QCPR training using a QCPR Resusci Anne (LaerdalMedical GmbH) **3 feedback groups:** **(1) instructor feedback (IF) group:** participants completed the CPR training with feedback from their instructor without the assistance of a feedback device **(2) device feedback (DF) group**: participants received direct visual feedback from a feedback device during CPR training but did not received any feedback from an instructor; **(3) instructor and device feedback (IDF) group**: participants received direct verbal feedback from an instructor who continuously observed the participants' actual CC quality on the feedback device. **Training**: In the training phase, participants practiced CPR with feedback for 2 minutes. **Assessment:** 2-minute CPR on the same manikin after 45 minute rest.	**Group 1:** Resusci Baby QCPR (Laerdal Medical GmbH, Stavanger, Norway) the SimPad touchscreen with the SkillReporter software (Laerdal); **Group 2:** QCPR Resusci Anne (LaerdalMedical GmbH) the SimPad touchscreen with the SkillReporter software (Laerdal) **DF group**: SimPad visible to the participant **IDF group**: SimPad visible to the instructor only **IF group**: SimPad masked to both	**Group 1:** Resusci Baby QCPR (Laerdal Medical GmbH, Stavanger, Norway) the SimPad touchscreen with the SkillReporter software (Laerdal) for data collection **Group 2:** QCPR Resusci Anne (LaerdalMedical GmbH) the SimPad touchscreen with the SkillReporter software (Laerdal) for data collection	0 days (post-intervention)	**Primary:** total compression score **Secondary:** all subcomponents of the total compression score, including correct hand position, mean CC depth, CC depth compliance, mean CC rate, CC rate compliance, and the proportion of complete release.
Smereka et al [8]	2019	Poland	Randomized Simulation Trial	94	First year nursing students	**Previous**: no previous participation in a CPR training. **Uppon study:** Prior to the survey, all participants attended a standard training course in basic life support (BLS) based on the American Heart Association (AHA) 2015 guidelines, conducted by accredited AHA instructors. After a successful completion of the theoretical training, the participants underwent a 10-minute practical training during which they performed unassisted chest compressions.	**Training:** theoretical and 10-minute practical training during which performed unassisted chest compressions. **Control group:** next day, practiced chest compressions without the use of any device for half an hour **Experimental group:** next day, practiced with the use of TrueCPR for half an hour. **Assessment:** Further measurement of chest compressions was performed after a month, when the participants were asked to perform a 2-minute unassisted (instrument-free) resuscitation cycle.	**Control group:** none **Experimental Group:** TrueCPR on unknown manikin	unknown makinin	1 month	**General:** Frequency and depth of chest compressions, and the degree of full chest relaxation. **Others:** self-assessed confidence of chest compression quality of the subjects was measured with a 100-point scale
Sá-Couto et al [9]	2018	Portugal	Randomized Control Study	39	Pregraduated students of Medicine and Biomedical Engineering	**Previous**: The recruitment of medical students was restricted to basic years in order to avoid students with CPR training. **Upon study**: On Day 1, students also received the 2015 CPR guidelines1 and algorithm and were advised to review them.	**Control group:** trained with a standard torso and received instructions and feedback from an experienced Basic Life Support (BLS) instructor. The training time was equivalent for both groups and lasted approximately 1 hour for each subgroup of students. **Intervention group:** trained with the prototype, receiving feedback on CPR relevant parameters: hands position, rate, and recoil, from the CPR Personal Trainer interface (without instructor). The training time was equivalent for both groups and lasted approximately 1 hour for each subgroup of students. **Assessment:** Theoretical tests. Practical consisting in executing 2 minutes of the BLS algorithm. All performances were video recorded. The evaluation of the correct application of the BLS algorithm and correct CPR performance of each student was made through visualization of each video by an independent expert, blinded to the study, with the use of a checklist.	**Control Group:** none. Adult Brad (Simulaids) manikin **Intervention Group:** CPR Personal Trainer on Adult Brad (Simulaids)	Video analysis and checklist	1 week	**Checklist:** call for help, check normal breathing, compressions-to-ventilations ratio of 30:2, compression rate, hands position, chest recoil, compressions depth, 2 deep breaths, pause for breaths of <10 seconds, and head extension. Each item was rated as 0-incorrect/not applied, 1—insufficient/incomplete, and 2—correct. The total score of the practical test was calculated as the mean of the 10 items with a maximum value of 2. **Others:** SUS questionnaire
González-Santano et al [10]	2020	Spain	Randomized Trial	30	Beach Lifeguards	**Previous**: All lifeguards had been trained in BLS in the previous 2 years. **Upon study**: 12-min session of training and practised at least 6 min of CPR.	**Traditional training (TT)**: training with a manikin without feedback system guided by the instructor; **App training (AP):** training using an app (Massage cardiaque et DSA) **Feedback training (FT)**: training with a manikin with feedback **Training**: The lifeguards received the same training; a 12-min session of training and practised at least 6 min of CPR. **Assessment:** Between 7 and 15 days after the training, each lifeguard performed an evaluation of a 3-min CPR simulation scenario.	**Traditional training (TT)**: Resusci Anne manikin without feedback system **App training (AP):** Massage cardiaque et DAS app **Feedback training (FT):** Resusci Anne QCPR Skillreporter	Resusci Anne QCPR Skillreporter (Laerdal, Norway) for data collection	Between 7 and 15 days	**General:** Total number of compressions, % hands positioning, mm of depth achieved, % compressions at correct depth, % correct chest recoil, mean rate, % correct rate compressions, total number of ventilations, mean volume, % correct ventilations, and QCPR, QCC (quality of compressions = [(% compressions at correct depth + % correct chest recoil + % correct rate compressions)/3].)
Pavo et al [11]	2016	Austria	Randomised simulation study	326	Undergraduate third year medical students	**Previous:** Students with basic BLS skills were recruited from the second unit of a compulsory BLS training course of the curriculum. **Upon study**: Upon inclusion in the study, all students had received 2 h of basic BLS training on a manikin following a standardised teaching protocol of the Medical University of Vienna according to the ILCOR guidelines for adult automated external defibrillator BLS (AED-BLS). Prior to study measurements, all participants received initial training using a modified 4-stage approach: following a standardised video according to their group, students were allowed to practice their basic life support (BLS) scenario under supervision until they felt sufficiently confident with the method. The duration of the training videos and the free practice differed between the different groups.	**Training:** standardised video according to each group, students were allowed to practice their basic life support (BLS) scenario under supervision until they felt sufficiently confident with the method. The duration of the training videos and the free practice differed between the different groups. **Standard BLS (sCPR) group:** performed resuscitation with a compression to ventilation ratio of 30:2 with a change of rescuer position after 2 min as recommended by the ERC 2010 guidelines **human feedback (hfCPR) group:** The study participant performing ventilation was instructed to give verbal feedback about the aforementioned CPR parameters to the rescuer performing chest compressions at the beginning of each new cycle and to correct in any case of deviation from the trained criteria. **QCPR feedback device (mfCPR) group:** performed BLS using the HeartStart MRx with Q-CPR-TechnologyTM (Philips, Netherlands) feedback device. Real time visual feedback is provided using graphs and numbers on the display of the MRxTM defibrillator placed next to the manikin. Furthermore, automated audio feedback advises the rescuer about necessary corrections if values diverge from the programmed range. **Assessment:** After completion of training, participants performed 8 min of two-rescuer BLS with bag-valve mask ventilation according to ERC 2015 guidelines.	**standard BLS (sCPR) group:** none **human feedback (hfCPR) group:** none **QCPR feedback device (mfCPR) group:** HeartStart MRx with Q-CPR-TechnologyTM (Philips, Netherlands)	Ambu®ManC manikins (Ambu, Ballerup, Denmark) with the Ambu® CPR Software (version 2.3.9, Ambu®, Ballerup, Denmark) for data collection	0 days (post-intervention)	**Primary:** Effective compression ratio (ECR), a parameter combining correct hand position, chest compression depth, and complete decompression multiplied by flow-time fraction -> effective compressions in % (EC: correct hand position, depth (50–60 mm) and complete decompression) multiplied by flow-time fraction (FTF) in %. **Secondary:** EC, compression rate (CR), compression depth, complete decompressions and incorrect pressure point were assessed. Additionally, time related parameters such as FTF (flow time fraction of chest compressions), absolute hands-off time (time fraction without compressions or ventilation) and time until first chest compression as well as ventilation parameters such as ventilation volume, ventilation minute volume, ventilation time and the number of gastric inflations Subjective assessment by study participants
Baldi et al [12]	2017	Italy	Randomized controlled manikin study	450	Laypersons over 18 years old with no previous training in CPR	**Previous**: Laypersons over 18 years old with no previous training in CPR were eligible for randomization. **Upon study**: Each group attended one of three different types of 5-hour BLS/AED courses. Every course consisted of 1 hour of theory and 4 hours of practice. The only difference among the courses was the amount of time spent training with feedback.	**Training:** Each group attended one of three different types of 5-hour BLS/AED courses. Every course consisted of 1 hour of theory and 4 hours of practice. The only difference among the courses was the amount of time spent training with feedback. **Course NF**: simple BLS/AED course without any feedback **Course SF**: BLS/AED course with 1 minute of training with real-time visual feedback manikin **Course LF:** BLS/AED course with 10 minutes of training with real-time visual feedback manikin **Assessment:** At the end of each course, we recorded 1 minute of compression-only CPR using the same software and the same manikin, without visual feedback for the attendee.	**Course NF:** none. Laerdal Little Anne manikin. **Couse SF & LF:** Laerdal Little Anne (Laerdal Medical, Inc., AS, Norway) with Resusci Anne Wireless SkillReporter software, version 1.1.0.20 (Laerdal Medical, Inc., AS, Norway)	Laerdal Little Anne (Laerdal Medical, Inc., AS, Norway) with Resusci Anne Wireless SkillReporter software, version 1.1.0.20 (Laerdal Medical, Inc., AS, Norway) for data collection	0 days (post-intervention)	**General:** Percentage of compressions with correct depth (50 mm–60 mm), the percentage of correctly released compressions, the percentage of compressions with the correct hand position, the number of compressions, and the Total CPR Score **Primary:** difference in the percentage of compressions with correct depth (50 mm–60 mm) among the groups. **Secondary:** differences in the percentage of correctly released compressions, in the percentage of compressions with correct hand position, in the compression rate, and in the Total CPR Score among the groups.
Sarac [13]	2017	**Turkey**		76	Second-year university students of different academic disciplines enrolled in "First Aid " elective course	**Previous**: All were enrolled in "First Aid (FA)," an elective course provided by the School of Physical Education and Sports. One of the students was excluded from the study for having previous training in FA and CPR. **Upon entry the study:** The FA course was a one semester (14 weeks) instructor-led course involving two hours of class time per week. Although the course covered topics, such as circulatory emergencies, respiratory emergencies, soft tissue injuries, and burns, this study only included the topic of CPR. The CPR section of the FA course lasted for two weeks (two hours a week).	**Training**: The FA course was a one semester (14 weeks) instructor-led course involving two hours of class time per week. Each group had four hours (two hours a week) of theoretical training and hands-on practice on a Resusci Anne Basic Torso CPR Manikin During hands-on practice, students were observed and were provided feedback by the instructor when necessary. **Control group:** no feedback **AC (augmented concurrent) group:** realtime feedback from the device. Before administering the post-test, each student in the AC group did ten sets of CPR trials on a Laerdal Resusci Anne Manikin by using its real-time visual feedback features. At the end of this five-minute recovery period, students in the AC group were required to perform ten sets of CPR as a post-test. **AT-KR (augmented terminal knowledge of results) group:** printed report of their CPR skills after the training. Students in AT-KR group were also given ten sets of CPR trial and a five-minute recovery period within the post-test. However, the real-time visual feedback features were not provided to students in the AT-KR group. They were given a printed report of their CPR ventilation and compression skill performance during the ten sets of CPR trial. **Assessment:** Four weeks after the pre-test, all students in the three groups were required to perform ten sets of CPR for a post-test, which was administered in the same manner.	**Control group:** No information **AC & ATKR Groups:** Resusci Anne Basic Torso CPR Manikin	Resusci Anne Basic Torso CPR Manikin with Laerdal Resusci Anne SkillReporter for data collection	4 weeks	**Ventilation skills:** average ventilation volume, average number of ventilations per minute, minute ventilation volume, total number of ventilations, number of correct ventilations, percent of correct ventilations, number of too many ventilations, number of too few ventilations, and number of too fast ventilations **Compression skills:** average compression depth, average number of compressions per minute, average compression rate, total number of compressions, number of correct compressions, percent of correct compressions, number of too deep compressions, number of too shallow compressions, number of wrong hand positions, number of too low hand positions and number of incomplete releases
Jang et al [14]	2020	**South Korea**	Randomized simulation study	**95**	General university students	**Previous**: The inclusion criteria were age 19 years and university students. There were no exclusion criteria. **Upon study**: All participants attended basic life support (BLS) and AED training program. The official BLS and AED training programs from the Korean Association of Cardiopulmonary Resuscitation were employed to train both groups for 1 hour each. The CPR course comprised theory and practice classes that included performing a 2-minute COCPR, four times.	**Training:** The official BLS and AED training programs from the Korean Association of Cardiopulmonary Resuscitation were employed to train both groups for 1 hour each. The CPR course comprised theory and practice classes that included performing a 2-minute COCPR, four times. **Real-time feed-back group (RTFG):** training with feedback **Non-feedback group (NFG):** training without feedback **Assessment:** 2-minute COCPR skill immediately after the training. To evaluate skill retention, the groups were re-evaluated 3 , 6 , and 9 months after the training. No further feedback was provided after initial training.	**NF group:** no information **RTFG group:** CPR training manikin (BT-SEEM; BT Inc., Goyang, Korea)	BT-CPTA (BT Inc.).	0 days (post intervention) 3 months 6 months 9 months	**General:** chest compression rate, the average depth of chest compression, the percentage of adequate chest compression depth, correct hand position (%), and chest recoil (%)

Zhou et al [15]	2020	China	Randomized controlled study	97	Third-year medical students	**Previous**: The characteristics of participants, including age, sex, height, weight, number of previous CPR trainings, and the experience of actual CPR, were recorded. **Upon study**: 45-minute CC-only CPR training program that included the following: (1) instruction and practice ofcardiac arrest recognition and calling 1-2-0 (emergency call in China) for help, (2) instruction and practice of CC, and (3) use of an automated external defibrillator (AED). During training, instructors were asked to ensure each participant perform 5 cycles (2 min/cycle) of CC on manikins.	**Training:** 45-minute CC-only CPR training program. In each session, participants first practiced CC under the supervision of instructors for a total of 30 min. **RP group:** performed repetitive sessions of CC-only CPR under the guidance of the instructor **RP + AVF group:** performed repetitive sessions of CC-only CPR under the guidance of them instructor and the real-time AVF devices **Assessment:** One hour after each session each participant performed a 2-min CC, and the quality of compressions was determined (short- time retention). long-time CC quality retention were performed at 3 months and 12 months after training.	**Both:** Laerdal Resusci Anne QCPR torso manikin (Laerdal China Ltd., Hangzhou, China) with SimPad Plus	Laerdal Resusci Anne QCPR torso manikin (Laerdal China Ltd., Hangzhou, China) with SimPad Plus for data collection	day 1 (post-intervention 1) day 3 (post-intervention 2) day 7 (post-intervention 3) 3 months 12 months	**General:** CC rate, depth, correct hand position, and complete chest recoil
Eshel et al [16]	2019	**Israel**	Randomized controlled study	145	First-year medical students	**Previous**: The study included 201 first-year medical students, from 2 consecutive classes, participating in a semestrial mandatory "First Aid and Emergency Medicine" course. Students with advanced medical experience and training were exempt from the course and were not included in the study groups. **Upon study:** The CPR module curriculum, based on the 2015 AHA guidelines, included a 1-hour lecture and 10 academic hours of review and hands-on CPR training in small groups, as well as additional none-mandatory training time before the final examination. The final examination of the course, performed at the end of academic semester, included a written segment and a standardized OSCE.	**Training**: 1-hour lecture and 10 academic hours of review and hands-on CPR training in small groups, as well as additional none-mandatory training time before the final examination. The only major difference between the groups was the use of real-time audiovisual feedback teaching aids in the intervention group. **Control group:** taught CPR on manikins without feedback capabilities **Intervention group:** CPR training with an added real-time feedback audiovisual device **Assessment:** No information	**Control Group**: Laerdal Resusci Anne **Intervention group**: Laerdal Resusci Anne QCPR manikin accompanied by the handheld Simpad Skillreporter apparatus (Laerdal Medical AS, Stavanger, Norway).	Laerdal Resusci Anne QCPR manikin accompanied by the handheld Simpad Skillreporter apparatus (Laerdal Medical AS, Stavanger, Norway) for data collection	**post intervention**	**Primary:** Total CPR Score, Chest Compression Fraction (CCF), Compressions with Adequate Depth (percentage of compressions with a measured depth of ≥50 mm) **Secondary:** "Other inclusive parameters calculated by the manikin"
Katipoglu et al [17]	2021	**Poland**	Randomized simulation study	111	First year students of medicine	**Previous:** unknown. **Upon study:** In both groups a 5 minutes standardized training on how to perform CPR of an adult was performed prior to the study. Both groups then underwent a basic life support (BLS) course based on the AHA guidelines, with the first group (experimental group) performed chest compressions to observe, in real-time, chest compressions parameters indicated by software included in the simulator, and the second group (control group) performed compressions without the possibility of observing simulator indications. After a 10-minute resuscitation, the participants had a 30-minute break and then a 2-minute cycle of CPR based on a scheme of 30 compressions: 2 rescue breaths. The first group performed compressions on the basis of simulator indications, while the second group did not.	**Training:** In both groups a 5 minutes standardized training on how to perform CPR of an adult was performed prior to the study and a 10-minute resuscitation. **Experimental group:** performed chest compressions to observe, in real-time, chest compressions parameters indicated by software included in the simulator. **Control group:** performed compressions without the possibility of observing simulator indications. **Assessment:** The participants had a 30-minute break and then a 2-minute cycle of CPR. Experimental group was able to observe real-time measurements Repeated assessment 1 month after training. Both experimental and control groups were not able to observe real-time measurements regarding quality of chest compression.	**Control group:** no information **Experimental group**: Resusci Anne® QCPR (Laerdal, Stavanger, Norway)	Resusci Anne® QCPR (Laerdal, Stavanger, Norway) for data collection	**post intervention** 1 month	**General:** total compression score, compression depth, compression depth compliance, compression rate per minute (CPM), compression rate compliance, full release, correctness of chest position
Tanaka et al [18]	2019	Japan	Cluster randomized control trial	497	CPR layperson trainees	**Previous**: . The exclusion criteria were working as a healthcare professional regularly involved in resuscitation, such as Emergency Medical Technicians, paramedics and emergency room physicians or nurses. Previous CPR training status and quantity and timing of previous trainings were not used as inclusion or exclusion criteria. **Upon study**: The training started with a PowerPoint presentation-based instructor-led lecture followed by psychomotor practice. Psychomotor practice focused on chest-compression CPR.	**Control group:** standard CPR training with instructor's subjective feedback based on the instructor's experience **QCPR Classroom group:** subjective and objective feedback from the instructor based on real-time feedback through the manikin, and were able to correct themselves based on feedback displayed on the screen of the device. **Assessment:** 1min of chest compression was measured after the training as a post-test.	**QCPR group**: Laerdal QCPR Classroom manikin system (Laerdal Medical, Stavanger, Norway) **Control group**: Laerdal Little Anne manikins. However, we did not use a screen to show students objective feedback.	Laerdal QCPR Classroom manikin system (Laerdal Medical, Stavanger, Norway) for data collection	0 days (post intervention)	**Primary:** compression depth (mm), compression rate (cpm), adequate depth (%) and adequate recoil (%). **Secondary:** scores from a survey conducted after the training
Labuschagne et al [19]	2022	South Africa	**Experimental Study**	53	Final-year (fifth year of study) undergraduate medical students	**Previous**: all participants in the study had previously received the same CPR training (via the con- ventional CPR training method) in their third year of the medical under- graduate programme. **Upon study**: In their fifth year, students receive CPR training in the Anaesthesiology rotation and in the Family Medicine rotation. The fifth-year undergraduate medical students rotating at Anaesthesi- ology attended scheduled BLS lectures as part of their Anaesthesiology curriculum. A different group of fifth-year students (consisting of 6–8 students) attended the lecture every two weeks. This study was con- ducted during the Anaesthesiology CPR training session	**Training:** All the participants received the same one-hour theoretical lecture on CPR, presented by the same anaesthesiologist with more than 30 years' experience as an educator. Thereafter, the participants were divided into two groups for practical training. **Control Group (CPR)**: The CPR group, in a different room, were given the opportunity to practice using conventional CPR manikins.Students in both groups were allowed to practice (in separate rooms) for approximately 10 minutes. **QCPR Group:** The QCPR group was put into a room and given access to the QCPR manikins and tablets with the programme. Students in both groups were allowed to practice (in separate rooms) for approximately 10 minutes. **Assessment**: After the 10-minute practical training session, both groups were tested using the QCPR manikin and programme. The practical test was done for two minutes per person as this is one typical cycle in practical CPR before the medical practitioner switches with another to avoid exhaustion and to maintain effectiveness.	**Control Group (CPR):** Conventional CPR manikins **QCPR Group:** electronic-feedback QCPR manikins	QCPR manikins	Post intervention	**General**: Flow fraction, Average compression rate per minute, Compressions of adequate depth, Compressions of adequate rate, Total effectiveness percentages
Lee et al [20]	2023	Taiwan	Randomised Controlled Study	90	Nurses	**Previous**: A recertification program for the CG participants was arranged in the same week, whereas that for the EG participants was conducted in the following week. **Upon study**: Participants received a 10-min standardized lecture that provided up-to-date information on high-quality CPR. Subsequently, all participants practiced CPR skills for 30 min in a kneeling position on a Little Anne QCPR manikin.	**Training**: Participants received a 10-min standardized lecture that provided up-to-date information on high-quality CPR. Subsequently, all participants practiced CPR skills for 30 min in a kneeling position on a Little Anne QCPR manikin. **Control**: Participants in the CG were judged on the basis of instructors' visual perception; instructors advised participants for improving their skills. **Intervention**: Participants in the EG adjusted their skills according to the real-time visual feedback data displayed on an iPad in front of them. **Assessment**: The postintervention test, consisting of 5 cycles of CPR and the selfefficacy questionnaire, was administered to both groups immediately after the recertification program (T1) and 12 weeks later (T2).	**Control group:** Little Anne QCPR, Laerdal Medical **Experimental group**: Little Anne QCPR, Laerdal Medical	Little Anne QCPR, Laerdal Medical	Post intervention 12 months	**Primary:** group differences noted in performance parameters after 5 cycles of CPR: (a) appropriate rate: percentage of chest compression counts between 100 and 120 per min, (b) appropriate depth: percentage of chest compression depth between 5 and 6 cm, (c) appropriate chest recoil: percentage of fully recoiled chest after each compression, (d) chest compression factor (CCF): percentage of time spent on providing chest compressions, and (e) the total score of chest compression quality: a summed score of appropriate rate, depth, and chest recoil. **Secondary:** group differences noted in self-efficacy measured using a questionnaire developed by modifying the Basic Resuscitation Skills Self-Efficacy Scale

REFERENCES

1 Cortegiani A, Russotto V, Montalto F, Iozzo P, Meschis R, Pugliesi M, et al. Use of a real-time training software (Laerdal QCPR®) compared to instructor-based feedback for high-quality chest compressions acquisition in secondary school students: a randomized trial. PLoS One. 2017;12(1):e0169591.
2 Lin Y, Cheng A, Grant VJ, Currie GR, Hecker KG. Improving CPR quality with distributed practice and real-time feedback in pediatric healthcare providers—a randomized controlled trial. Resuscitation. 2018;130:6-12.
3 Chamdawala H, Meltzer JA, Shankar V, Elachi D, Jarzynka SM, Nixon AF. Cardiopulmonary resuscitation skill training and retention in teens (CPR START): a randomized control trial in high school students. Resusc Plus. 2021;5:100079.
4 Moreno S, Sisó-Almirall A, Kostov B, Expósito M, Moreno JR, de Pablo B, et al. Cardiopulmonary resuscitation skill maintenance for primary care staff: brief training sessions with feedback. Emergencias. 2021;33(3):203-210.
5 Suet G, Blanie A, de Montblanc J, Roulleau P, Benhamou D. External cardiac massage training of medical students: a randomized comparison of two feedback methods to standard training. J Emerg Med. 2020;59(2):270-277.
6 Kim Y, Han H, Lee S, Lee J. Effects of the non-contact cardiopulmonary resuscitation training using smart technology. Eur J Cardiovasc Nurs. 2021;20(8):760-766.
7 Wagner M, Bibl K, Hrdliczka E, Steinbauer P, Stiller M, Gröpel P, et al. Effects of feedback on chest compression quality: a randomized simulation study. Pediatrics. 2019;143(2):e20182441.
8 Smereka J, Szarpak L, Czekajlo M, Abelson A, Zwolinski P, Plusa T, et al. The TrueCPR device in the process of teaching cardiopulmonary resuscitation: a randomized simulation trial. Medicine (Baltimore). 2019;98(27):e15995.
9 Sá-Couto C, Ferreira AM, Almeida D, Nicolau A, Vieira-Marques P. Evaluation of skills acquisition using a new low-cost tool for CPR self-training. Porto Biomed J. 2018;3(1):e8.
10 González-Santano D, Fernández-García D, Silvestre-Medina E, Remuiñán-Rodriguez B, Rosell-Ortiz F, Gómez-Salgado J, et al. Evaluation of three methods for CPR training to lifeguards: a randomised trial using traditional procedures and new technologies. Medicina (Kaunas). 2020;56(11):577.
11 Pavo N, Goliasch G, Nierscher FJ, Stumpf D, Haugk M, Breckwoldt J, et al. Short structured feedback training is equivalent to a mechanical feedback device in two-rescuer BLS: a randomised simulation study. Scand J Trauma Resusc Emerg Med. 2016;24:70.
12 Baldi E, Cornara S, Contri E, Epis F, Fina D, Zelaschi B, et al. Real-time visual feedback during training improves laypersons' CPR quality: a randomized controlled manikin study. CJEM. 2017;19(6):480-487.
13 Sarac L. Effects of augmented feedback on cardiopulmonary resuscitation skill acquisition: concurrent versus terminal. Eurasian J Educ Res. 2017;17(72):83.
14 Jang TC, Ryoo HW, Moon S, Ahn JY, Lee DE, Lee WK, et al. Long-term benefits of chest compression-only cardiopulmonary resuscitation training using real-time visual feedback manikins: a randomized simulation study. Clin Exp Emerg Med. 2020;7(3):206-212.
15 Zhou XL, Wang J, Jin XQ, Zhao Y, Liu RL, Jiang C. Quality retention of chest compression after repetitive practices with or without feedback devices: a randomized manikin study. Am J Emerg Med. 2020;38(1):73-78.
16 Eshel R, Wacht O, Schwartz D. Real-time audiovisual feedback training improves cardiopulmonary resuscitation performance: a controlled study. Simul Healthc. 2019;14(6):359-365.
17 Katipoglu B, Madziala MA, Evrin T, Gawlowski P, Szarpak A, Dabrowska A, et al. How should we teach cardiopulmonary resuscitation? Randomized multi-center study. Cardiol J. 2021;28(3):439-445.
18 Tanaka S, Tsukigase K, Hara T, Sagisaka R, Myklebust H, Birkenes TS, et al. Effect of real-time visual feedback device 'Quality Cardiopulmonary Resuscitation (QCPR) Classroom' with a metronome sound on layperson CPR training in Japan: a cluster randomized control trial. BMJ Open. 2019;9(6):e026140.
19 Labuschagne MJ, Arbee A, de Klerk C, de Vries E, de Waal T, Jhetam T, et al. A comparison of the effectiveness of QCPR and conventional CPR training in final-year medical students at a South African university. Afr J Emerg Med. 2022;12(2):106-111.
20 Lee PH, Lai HY, Hsieh TC, Wu WR. Using real-time device-based visual feedback in CPR recertification programs: a prospective randomised controlled study. Nurse Educ Today. 2023;124:105755.

Appendix 4 – Publication bias—funnel plot