



**TURUN  
YLIOPISTO**  
UNIVERSITY  
OF TURKU

# Wearable real-time feedback device to monitor chest compression quality during CPR

Early-stage medical device development

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Desale Tewelde Kahsay





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*To my children—Eden, Hiyab, and Rimna—for being my greatest sources of happiness; and to my parents and siblings, for their unconditional love and support.*

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Faculty of Medicine

Department of Clinical Medicine

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## ABSTRACT

High-quality chest compressions are essential for effective cardiopulmonary resuscitation (CPR), yet achieving and maintaining optimal compression depth and rate remains challenging. Most standalone CPR feedback devices focus solely on monitoring compression depth and rate, and many are rigid and inflexible, which can lead to hand discomfort and pain. This study aimed to develop a concept, design a prototype, and test a wearable feedback device (the Resuscitation glove) that monitors chest-compression quality during cardiopulmonary resuscitation.

The research was conducted within the medical device development process framework, which describes three phases of early-stage development: I) Concept, II) Prototype Design, and III) Prototype Testing. Two studies, including a systematic review (Paper I) and a qualitative study (Paper II), were conducted in phase I to identify existing gaps and define user requirements, guiding the development of a new device. The proof-of-concept study (Study III) in phase II summarised the iterative prototype design process. A simulation-based study (Paper IV), followed by a usability questionnaire in phase III, evaluated the effectiveness and usability of the designed prototype.

The systematic review (Paper I) revealed that the standalone feedback device played a crucial role in improving specific chest compression parameters. However, users have reported discomfort and pain in their hands when using rigid feedback devices. The qualitative study (Paper II) identified 10 themes describing users' needs and factors influencing the acceptability of the CPR feedback device. The proof-of-concept study (Paper III) demonstrated that the Resuscitation glove is feasible and can provide feedback on specific chest compression parameters. The fourth Study (Paper IV) was conducted to test the effectiveness and usability of the resuscitation glove. The resuscitation glove improved certain chest compression parameters, but its usability score was at the lower end of the acceptable range.

Based on the preliminary findings, the resuscitation glove may improve certain chest compression parameters and potentially reduce rescuers' hand discomfort associated with rigid feedback devices.

**KEYWORDS:** Cardiac arrest, CPR, feedback devices, medical device, rescuers

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## TIIVISTELMÄ

Laadukas paineluelytyys on olennaista tehokkaan painelu-puhalluselytyksen (PPE) kannalta, mutta optimaalisen painelusyvytyden ja -taajuuden saavuttaminen ja ylläpitäminen on haastavaa. Useimmat itsenäiset PPE-palautelaitteet keskittyvät ainoastaan painelusyvytyden ja -taajuuden seurantaan ja monet näistä ovat jäykkiä ja taipumattomia, mikä voi aiheuttaa käsien epämukavuutta ja kipua. Tutkimuksen tavoitteena oli kehittää konsepti, suunnitella prototyyppi ja testata puettava palautelaite (elvytyshanska), joka seuraa paineluelytyksen laatua PPE:n aikana.

Tutkimus toteutettiin lääkinnällisten laitteiden kehitysprosessin viitekehyksen kolmen vaiheen kautta: I) Konsepti, II) Prototyypin suunnittelu ja III) Prototyypin testaus. Vaiheessa I suoritettiin systemaattinen katsaus (Artikkeli I) ja laadullinen tutkimus (Artikkeli II), joiden tarkoituksena oli tunnistaa nykyiset puutteet ja määrittellä käyttäjävaatimukset uuden laitteen kehittämiseksi. Vaiheessa II (Artikkeli III) kuvattiin prototyypin iteratiivista suunnitteluprosessia. Suunnittelun prototyypin tehokkuutta ja käytettävyyttä arvioitiin simulaatiopohjaisella tutkimuksella (Artikkeli IV) ja käytettävyysskyselyllä vaiheessa III.

Systemaattinen katsaus (Artikkeli I) osoitti, että itsenäisillä PPE-palautelaitteilla on keskeinen rooli paineluparametrien parantamisessa. Käyttäjät ovat raportoineet käsien epämukavuudesta ja kivusta jäykkärakenteisten palautelaitteiden käytön yhteydessä. Laadullisessa tutkimuksessa (Artikkeli II) tunnistettiin 10 teemaa, jotka kuvaavat käyttäjien tarpeita ja PPE-palautelaitteiden hyväksyttävyyteen vaikuttavia tekijöitä. Konseptin todentamistutkimus (Artikkeli III) osoitti, että elvytyksäsin on käyttökelpoinen ja kykenee antamaan palautetta tiettyjen paineluparametrien osalta. Neljännessä tutkimuksessa (Artikkeli IV) testattiin elvytyksäsiin tehokkuutta ja käytettävyyttä. Elvytyksäsin paransi tiettyjä paineluparametreja, mutta sen käytettävyyss pisteet olivat hyväksyttävän alueen alapäässä.

Alustavien tulosten perusteella elvytyksäsin voi parantaa tiettyjä rintakehän paineluparametreja ja mahdollisesti vähentää järkeen palautelaitteisiin liittyvää pelastajien käsien epämukavuutta.

AVAINSANAT: Sydänpysähdys, elvytys, palautelaitteet, lääkinnälliset laitteet, pelastajat

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# Abbreviations

AED	Automated External Defibrillator
AHA	American Heart Association
ALS	Advanced Life Support
AUS-ROC	Australian Resuscitation Outcomes Consortium
AVF	Audio-Visual Feedback
BLS	Basic Life Support
CI	Confidence Interval
CPP	Coronary Perfusion Pressure
CPR	Cardiopulmonary Resuscitation
CVD	Cardiovascular Disease
ECC	Emergency Cardiac Care
ECG	Electrocardiograph
EMS	Emergency Medical Services
ERC	European Resuscitation Council
ETCO <sub>2</sub>	End-Tidal Carbon Dioxide
FDA	Food and Drug Administration
IHCA	In-Hospital Cardiac Arrest
ILCOR	International Liaison Committee on Resuscitation
IMU	Inertial Measurement Unit
IQR	Interquartile Range
MDD	Medical Device Development
OHCA	Out-Of-Hospital Cardiac Arrests
PCA	Principal Component Analysis
PICO	Population, Intervention, Comparator and Outcome
PIMF	Physiological Information Data-Monitoring Feedback
QCPR	Quality Cardiopulmonary Resuscitation
RoB	Risk of Bias
ROSC	Return of Spontaneous Circulation
SAS	Statistical Analysis System
SCA	Sudden Cardiac Arrest
SCD	Sudden Cardiac Death

SUS	System Usability Scale
UCD	User-Centred Design
USA	United States of America
UTAUT	Unified Theory of Acceptance and Use of Technology

# List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

- I Kahsay, D. T., Peltonen, L-M., 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. *European Journal of Cardiovascular Nursing*, 2024; 23(1), 11–20.
- II Kahsay, D. T., Salanterä, S., Tommila, M., Liukas, T., Rosio, R., Diji, A. K.-A., & Peltonen, L-M. User Needs and Factors Associated with the Acceptability of Audiovisual Feedback Devices for Chest Compression Monitoring in Cardiopulmonary Resuscitation. *CIN: Computers, Informatics, Nursing*, 2024; 42(8), 583–592.
- III Guridi, S., Henry, M., Emmi, P., Guna, S., Kahsay, D. T., Clayton, S. L., Rosio, R., Peltonen, L-M., Tommila, M., Salanterä, S., & Yu, X. A Proof-of-Concept Study on Smart Gloves for Real-Time Chest Compression Performance Monitoring. *IEEE Access*, 2024; 12, 22331–22344.
- IV Kahsay, D. T., Tommila, M., Peltonen, L-M., Löyttyniemi, E., Xiao, Y., Mauranen, H., & Salanterä, S. A Comparison Between a Resuscitation Glove and Standard Manual Compressions on the Quality of Cardiovascular Resuscitation: Manikin-Based Randomised Crossover Trial. *Journal of Cardiovascular Nursing*, 2026; 41(1), 65–74.

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# 1 Introduction

The estimated number of deaths due to cardiovascular disease (CVD) increased from 12.1 million in 1990 to 18.6 million in 2019 (Roth et al., 2020), and the cessation of the beating of the heart, with no signs of circulation, called cardiac arrest, is often associated with CVD (Patel & Hipskind, 2025). Cardiopulmonary resuscitation (CPR) is a life-saving technique that partially restores blood circulation to vital organs, such as the heart and brain (Patel & Hipskind, 2025). If high-quality chest compression is not started immediately, the heart and the brain cells are deprived of oxygen and nutrients, which can lead to rapid and irreversible cell death, leading to permanent neurological injury or death (Meaney et al., 2013; Sandroni et al., 2021; D. D. Nguyen et al., 2024). Therefore, effective chest compressions are a critical component of high-quality CPR and are a widely available means of maintaining blood flow to vital organs during cardiac arrest (Olasveengen et al., 2021).

The components of high-quality chest compressions include placing the hand on the lower half of the sternum, compressing the chest to a depth of 5 to 6 cm, delivering chest compressions at a rate of 100 to 120 per minute, allowing the chest to fully recoil between each compression, and minimising interruptions between compressions (Perkins et al., 2021). Immediate and adequate chest compressions are strongly associated with favourable survival rates after cardiac arrest (Hasselqvist-Ax et al., 2015). As a result, the international CPR guidelines recommend regular training for all citizens, including schoolchildren, because layperson-initiated CPR improves patient outcomes in out-of-hospital cardiac arrests (OHCA) (Naim et al., 2017; Dainty et al., 2022). One study documented a twofold rise in the survival rates of cardiac arrest patients when laypersons initiated CPR before emergency medical services (EMS) arrived at the scene (Hasselqvist-Ax et al., 2015).

Modern CPR was first introduced in the 1960s, with guidelines based on consensus and limited scientific evidence (DeBard, 1980; Ristagno et al., 2009). The aim was to deliver manual chest compressions and rescue breathing without guidance and feedback from technology (DeBard, 1980). Later, studies revealed that many rescuers, including skilled healthcare professionals, fail to adhere to CPR guideline recommendations (Abella, Alvarado, et al., 2005). As a result, scientists developed audiovisual feedback (AVF) devices to monitor rescuers' chest

compressions performance during CPR (González-Otero et al., 2017). Accordingly, the 2010 American Heart Association (AHA) and European Resuscitation Council (ERC) guidelines recommended using real-time AVF devices to enhance the quality of CPR training (Field et al., 2010; Koster et al., 2010). Subsequently, the AHA and ERC resuscitation guidelines confirm the benefits of AVF devices in improving CPR quality in patients with cardiac arrest (Merchant et al., 2020; Olasveengen et al., 2021).

The real-time AVF devices that provide feedback on chest compression quality during CPR are broadly classified into two main categories: integrated and standalone real-time AVF devices. Most integrated devices are incorporated into more complex devices, such as defibrillators and high-fidelity simulation manikins (Miller et al., 2020). Generally, they are less portable and tend to be more expensive and complex, making them less convenient for use at the community level (Miller et al., 2020).

In contrast, real-time standalone AVF devices are independent units typically positioned between the victim's chest and the rescuer's hand (Perkins et al., 2005; Smereka et al., 2019). They are generally more affordable, easy to use, and portable, making them a better option in areas where more advanced, complex devices are not readily available (Miller et al., 2020). Nonetheless, many current standalone real-time AVF devices are made from stiff and rigid materials, which may cause discomfort to the rescuer's hands during CPR (Perkins et al., 2005; Smereka et al., 2019; Miller et al., 2020). Possible hand discomfort caused by the rigid standalone AVF devices may negatively affect the quality of chest compressions during CPR, which may compromise the chance of survival.

Smartwatch-based wearable devices have been developed to overcome the limitations posed by the rigid and hard-to-compress devices placed on the chest of patients and manikins (Song et al., 2016; Lu et al., 2018). These devices are worn on the rescuer's wrist, which is distant from the actual point of compression, which may potentially lead to inaccurate feedback (J. Park et al., 2016; S. Lee et al., 2021). Furthermore, most of the current wearable standalone AVF devices focus on monitoring a narrow range of chest compression metrics, particularly compression depth and rate, with insufficient feedback of other chest compression metrics, such as chest recoil, hand positioning, and interruptions (Aase & Myklebust, 2002; Dellimore et al., 2013; Ahn et al., 2021).

The study aimed to develop the concept, design a prototype, and test a lightweight, soft, user-friendly, real-time, standalone AVF device to monitor chest compression quality, suitable for community settings where complex equipment and highly trained healthcare professionals may not be readily available.

## 2 Review of the Literature

### 2.1 Cardiac Arrest

Cardiac arrest is often a sudden and potentially fatal cessation of heart activity, leading to a loss of blood circulation to vital organs (Patel & Hipskind, 2025). Sudden cardiac arrest (SCA) poses a significant health challenge worldwide, and most frequently occurs in community settings (D. S. Zimmerman & Tan, 2021), known as OHCA. This situation complicates the prompt delivery of essential life-saving resuscitation treatment. Moreover, SCA often occurs unexpectedly in individuals not previously identified as at higher risk (D. S. Zimmerman & Tan, 2021). Sudden cardiac death (SCD) is defined as death that is believed to be of cardiac origin, occurring within one hour of the onset of cardiac symptoms or within 24 hours of the last documented instance of being healthy and alive (Yow et al., 2024).

#### 2.1.1 Incidence of Cardiac Arrest

Cardiac arrest death continues to pose a significant health challenge globally, accounting for nearly 20% of all deaths and up to 50% of cardiovascular deaths in Western societies (Paratz et al., 2020; D. S. Zimmerman & Tan, 2021). Evidence indicates that the annual incidence of OHCA in Europe ranged from 67 to 170 per 100,000 inhabitants, while the annual incidence of in-hospital cardiac arrest (IHCA) ranged from 1.5 to 2.8 per 1,000 hospital admissions (Gräsner et al., 2021). Conversely, in the USA, the overall annual average incidence of OHCA treated by EMS was 81.3 per 100,000 inhabitants, and there were 9 to 10 in-hospital cardiac arrests per 1000 admissions (Andersen et al., 2019; McBride et al., 2025). In 2015, a total of 19,722 cases of OHCA were recorded in Aus-ROC Epistry in Australia and New Zealand, with an incidence ranging from 51 to 107.7 per 100,000 population (Beck et al., 2018).

Differences in practices, guidelines, and definitions may lead to discrepancies in reported cardiac arrest outcomes across registries and studies (Grasner et al., 2024). These discrepancies undermine the validity of direct comparisons of datasets and outcomes, which can impede genuine progress in resuscitation science and highlight

the need for standardised definitions and reporting guidelines (Perkins, Jacobs, et al., 2015). As a result, it was essential to provide standardised descriptions of data sources and definitions to ensure accurate comparisons of outcomes across regions (Otto et al., 2021; Grasner et al., 2024). The Utstein Style was introduced in 1991 to standardise the reporting of care processes and outcomes for patients experiencing cardiac arrest (Cummins et al., 1991). Despite using the Utstein template, registries still exhibit significant differences in inclusion criteria, variable definitions, coding practices, and reporting methods (Beck et al., 2018; Grasner et al., 2024). This may partially explain the differences in reported annual incidence rates across regions with similar health systems and technological advancements.

### 2.1.2 Causes of Cardiac Arrest

Identifying the causes of cardiac arrest is essential, as resuscitation guidelines emphasise recognising the potentially reversible causes of cardiac arrest, which are classified as the 4 Hs (hypoxia, hypovolemia, hypo-/hyperkalaemia, hypo/hyperthermia) and 4 Ts (thrombosis, tension pneumothorax, cardiac tamponade, toxins) (Perkins et al., 2021). Additionally, understanding the causes of cardiac arrest is crucial for post-resuscitation treatment of patients who regain spontaneous circulation, as this treatment also targets the underlying causes (Andersen et al., 2019).

The common causes of cardiac arrest significantly differ between different countries and regions (Andersen et al., 2019; Allencherril et al., 2022). Albert et al. (2023) conducted an observational study using the Swedish Inpatient Registry. They reported myocardial ischemia, pulmonary causes, infections, haemorrhage, and other non-cardiac causes as the most prevalent causes of IHCA (Albert et al., 2023). In contrast, in their single-centre study in Florida, Riley et al. documented hypoxia (20.4%), arrhythmia (6.2%), myocardial infarction (4.0%), hypovolemia (4.0%), and pulmonary embolism (2.6%) as the most common causes of IHCA (Riley et al., 2020).

Allencherril et al.(2022), in their systematic review that included individual studies from multiple countries and continents, identified that the most common causes of IHCA were hypoxia (26.46%), acute coronary syndrome (18.23%), arrhythmia (14.9%), hypovolemia (14.8%), infection (14.4%), and heart failure (12.6%) (Allencherril et al., 2022). Other less frequent causes of IHCA include cardiac tamponade, electrolyte disturbances, pulmonary embolism, neurological issues, toxins, and pneumothorax (Allencherril et al., 2022). The review also indicated that 69.83% of cardiac arrests were initially classified as unshockable, while 21.75% were shockable (Allencherril et al., 2022).

Another study identified coronary artery disease, hypertension, ischaemic heart disease, and left ventricular hypertrophy as the most frequent causes of OHCA in Africa (Thibodeau et al., 2022). Gräsner et al. reported medical aetiology as the most common cause of OHCA in Europe, without specifying which medical causes were most prevalent (Gräsner et al., 2020), confirming the inconsistency in reporting the causes of cardiac arrest across different researchers and regions. Overall, these findings highlight that the causes of cardiac arrest differ greatly between countries and regions, influenced by variations in epidemiology, healthcare systems, and data reporting practices.

### 2.1.3 Outcomes of Cardiac Arrest

The outcome of cardiac arrest is a key indicator of the quality of the entire chain of survival, which can differ significantly depending on whether it is IHCA or OHCA (Høybye et al., 2021; Andersson et al., 2022). For instance, one study compared the characteristics and survival rates of patients with IHCA and OHCA in Denmark, and the rates of Return of Spontaneous Circulation (ROSC), 30-day survival, and one-year survival were higher in IHCA cases compared to OHCA cases (Høybye et al., 2021). Specifically, the ROSC rate was 49% for IHCA versus 27% for OHCA, the 30-day survival rate was 24% versus 17%, and the one-year survival rate was 18% versus 17% (Høybye et al., 2021). Another similar study conducted in Sweden reported significantly lower mortality rates 30 days after IHCA than after OHCA (49.8% versus 62.2%) (Andersson et al., 2022). The long-term neurological outcome was also better after IHCA than after OHCA (40.0% vs. 31.6%). In both studies, the difference in outcome between IHCA and OHCA appears to be due to differences in the characteristics of the cardiac arrest, such as witnessed arrest, faster initiation of CPR, and shockable initial rhythm, rather than the location of the cardiac arrest itself (Høybye et al., 2021; Andersson et al., 2022). This finding challenges the assumption that the cardiac arrest environment is the primary determinant of outcomes; instead, an unfavourable arrest profile and systemic delays appear to be more significant drivers of survival.

Notable differences in outcomes also exist across regions in the IHCA and OHCA cases. Variations in access to healthcare systems, training of medical professionals, characteristics of cardiac arrest, patient demographics, and technologies across different countries and regions may explain these differences (Girotra et al., 2016; Beck et al., 2018; Yan et al., 2020). Yan et al. conducted a systematic review and meta-analysis to analyse the global survival rates of OHCA cases that received CPR (Yan et al., 2020). The hospital discharge survival rate was 8.8%, and the 1-year survival rate for those discharged from the hospital was 7.7%. Survival to hospital discharge was higher for patients whose cardiac arrest was

witnessed and those who received bystander CPR (Yan et al., 2020). Similarly, subgroup analysis by cardiac arrest location showed significant differences in survival rates, ranging from 4.4% to 16.2%. When comparing studies from different continents, pooled survival rates were 16.2% in Oceania, 11.7% in Europe, 7.7% in North America, and 4.4% in Asia (Yan et al., 2020).

Disparities in outcomes are not only observed between countries or continents but also within regions of the same country. Differences in cardiac arrest outcomes can occur across regions within the same country, due to treatment delays caused by specific challenges in urban areas (Connolly et al., 2021). A study was conducted in the United States to investigate regional disparities in survival rates for OHCA at the county level (Girotra et al., 2016). The average survival rate to discharge was 9.6%, but significant variation was observed across regions, with rates ranging from 3.4% to 22.0%. The presence of bystander CPR and automated external defibrillator (AED) accounted for 41% of the differences in survival rates (Girotra et al., 2016). Additionally, cardiac arrest characteristics, such as initial rhythm, location of arrest, and witnessed arrest, explained 27.7% of the variation, while patient demographics accounted for 4.8% of the variation (Girotra et al., 2016). These data collectively indicate that differences in survival rates across regions are caused by systemic factors such as prehospital response, bystander participation, and post-resuscitation care, rather than solely by the patient's clinical characteristics.

Despite the evidence-based updates of resuscitation guidelines, post-resuscitation treatment and technological advances, overall cardiac arrest outcomes remain relatively low (Andersen et al., 2019; Yan et al., 2020; Gräsner et al., 2021). This issue is particularly critical in low-income countries, where outcomes are alarmingly poor and necessitate urgent attention (Gowens et al., 2022; Stassen et al., 2021; Yan et al., 2020). In a study conducted in South Africa, for example, EMS attempted resuscitation in only 7.4% of cardiac arrest cases (Stassen et al., 2021). The study found that only 1.3% of these cases achieved ROSC, while 97.8% of the individuals were declared dead at the scene (Stassen et al., 2021). These findings highlight that improving cardiac arrest outcomes requires not only updates to resuscitation guidelines but also strategies to enhance the quality, accessibility, and consistency of CPR delivery across borders and to support contextually appropriate actions in resource-limited settings.

## 2.2 Cardiopulmonary Resuscitation

### 2.2.1 The Physiology of CPR

Understanding the normal physiology of blood circulation and the changes that occur during cardiac arrest is necessary to take informed, appropriate actions to enhance

patient survival during CPR. Two competing theories explain the mechanism of blood flow to vital organs during CPR: the “*Cardiac Pump Theory*” and the “*Thoracic Pump Theory*” (Kühn et al., 1991; Redberg et al., 1993). The “*Cardiac pump theory*” proposes that applying pressure to the sternum compresses the heart between the sternum and spine, pumping blood out of the heart, while decompression allows the heart to refill (Kouwenhoven et al., 1960). Blood flow to the vital organs occurs when the ventricles contract, causing the mitral valve to close and the aortic valve to open as ventricular pressure exceeds the aortic diastolic pressure (Kühn et al., 1991). According to the cardiac pump theory, sternal compression provides some ventilation and supports compression-only CPR when only one person is attending to the cardiac arrest (Kouwenhoven et al., 1960; Ewy, 2018).

The thoracic pump theory states that the pressure generated in the chest (intrathoracic pressure) during chest compression is transmitted to the intrathoracic vasculature, thereby increasing blood flow to the extrathoracic vascular compartment (Rudikoff et al., 1980; Babbs et al., 1984; Ewy, 2018). During decompression, intrathoracic pressure falls below venous pressure, allowing blood to flow from the extrathoracic venous system into the chest (Rudikoff et al., 1980). Nevertheless, a single mechanism may not explain the complex hemodynamic of blood flow in all patients with cardiac arrest. Depending on the patient's characteristics and the specific circumstances of the cardiac arrest, both cardiac and thoracic pumping mechanisms may contribute to the delivery of blood to vital organs during resuscitation (Cipani et al., 2019). The two most important determinants of blood flow to the vital organs during CPR are the compression and decompression phases of chest compression.

## Compression Phase

The forces driving coronary and cerebral perfusion during CPR differ significantly from normal cardiac physiology (Meaney et al., 2013). Even with the best manual compressions performed according to CPR guidelines, cardiac output to the vital organs is 10 to 30% of the pre-arrest value (Meaney et al., 2013). Standard adult CPR involves performing chest compressions with both hands to increase intrathoracic pressure and squeeze the heart between the sternum and spine (Kouwenhoven et al., 1960; Rudikoff et al., 1980; Lurie et al., 2016). The increased intrathoracic pressure (thoracic pump theory) and heart compression between the sternum and spine (cardiac pump theory) result in forward blood flow (Kühn et al., 1991; Redberg et al., 1993). Due to the pressure difference between the intrathoracic and extrathoracic vasculature and the one-way valves in the heart, blood is pumped from the non-beating heart to the vital organs (Lurie et al., 2016). Provided that the

valves function normally, blood flows anterograde during the chest compression phases of CPR (Kouwenhoven et al., 1960; Lurie et al., 2016).

### Decompression Phase

Myocardial blood flow and adequate coronary perfusion pressure (CPP) are essential for successful coronary resuscitation (Chalkias et al., 2019). Previous studies have shown that a CPP of 15 mmHg is required to initiate electrical activity in the myocardium (Kern, 2000; Reynolds et al., 2010). However, the CPP is nearly zero during the compression phase, which can be explained by the fact that the pressures in the aorta and the right atrium increase equally during the compression phase of CPR (Lurie et al., 2016). The decompression phase (CPR-diastole) is arguably more important than the compression phase during CPR (Harris & Kudenchuk, 2018). During this phase, blood flow to the coronary arteries is established, which is essential for maintaining cardiac function; without it, ROSC becomes impossible (Lurie et al., 2016; Harris & Kudenchuk, 2018; Chalkias et al., 2019). Furthermore, intrathoracic pressure decreases during the decompression phases of cardiopulmonary resuscitation, allowing the heart to partially refill with blood that can be pumped during subsequent compression (Kouwenhoven et al., 1960; Ewy, 2018). For these two reasons, incomplete decompression impairs myocardial and cerebral perfusion during CPR (Lurie et al., 2016; Chalkias et al., 2019). The CPR physiological principles of cardiac and thoracic pump mechanisms emphasise that successful circulation during CPR relies primarily on the quality of compression and decompression, underscoring the significance of high-quality chest compression technique, as discussed in the following section.

### 2.2.2 Significance of Chest Compression Quality

The literature does not provide a single universal indicator of CPR quality (Kłosiewicz et al., 2020). Performing resuscitation during cardiac arrest in accordance with international resuscitation guidelines is referred to as quality CPR (Meaney et al., 2013). Many studies were conducted in the 1990s and 2000s to evaluate the effect of high-quality CPR on patient outcomes after cardiac arrest (Wik et al., 1994; Ko et al., 2005). According to a 1994 Norwegian study, patients who received high-quality bystander CPR had better OHCA outcomes (23%) than those who received low-quality CPR (1%) (Wik et al., 1994). Another similar study was conducted in the USA in 2005 to evaluate the quality of prehospital CPR and its impact on the outcomes of witnessed cardiac arrests (Ko et al., 2005). The quality of CPR was adequate in 29% of arrests, while it was rated inadequate in 71% of cases (Ko et al., 2005). In the same study, hospital discharge survival rates were higher

among patients with adequate CPR performance (53%) than among those with inadequate CPR performance (8%). Both studies showed that providing high-quality CPR, as recommended in resuscitation guidelines, was necessary to improve patient outcomes. However, what are the factors that affect the delivery of high-quality CPR?

Previous studies revealed multiple factors affecting CPR quality during actual and simulated cardiac arrest (H. J. Park et al., 2020; Junli et al., 2023; Sumera et al., 2024). Availability of regular training, harmony in the resuscitation team, availability of CPR materials, the number of rescuers, the age and weight of the rescuers, and the quality of team leaders are some factors that affect the quality of CPR during cardiac arrest (Herlitz et al., 2005; Citolino Filho et al., 2015; H. J. Park et al., 2020; Junli et al., 2023; Sumera et al., 2024). Park et al. (2020), for instance, examined the factors influencing the quality of chest compressions administered by laypersons. They identified that the primary factor affecting the quality of chest compressions was the laypersons' ages, with younger adults being much more likely to perform higher-quality chest compressions during CPR (H. J. Park et al., 2020). Junli et al. (2023) conducted a scoping review to identify factors influencing health professionals' retention of the skills necessary for effective CPR. Factors that affected retention and CPR quality included the frequency of training, the location of the facilities, equipment availability, the educational background of healthcare providers, and the CPR experience of professionals (Junli et al., 2023). This suggests that the factors affecting CPR quality may vary with rescuer capabilities, available equipment, and the location of cardiac arrest; therefore, no single prescribed procedure or scenario can guarantee high-quality CPR.

### 2.2.3 Determinants of Chest Compression Quality

The main objective of CPR during cardiac arrest is to provide oxygenated blood to the vital organs. Chest compressions are a key part of effective CPR as the most accessible method of delivering organ perfusion during cardiac arrest (Olasveengen et al., 2021). Therefore, high-quality chest compressions must be delivered to guarantee sufficient blood flow to the vital organs (Meaney et al., 2013). Based on the resuscitation guidelines, chest compression components that determine the quality of CPR include correct hand position, compression depth, compression rate, the degree of chest wall recoil, and interruption between compressions (Meaney et al., 2013; Olasveengen et al., 2021; Wyckoff et al., 2022). Therefore, it is crucial to understand how each component of chest compression affects perfusion, as discussed in detail below.

### 2.2.3.1 Correct Hand Position during Compression

Proper hand placement on the chest is one of the key elements that help optimise CPR during cardiac arrest (Cha et al., 2013). As a result, the 2020 International Liaison Committee on Resuscitation (ILCOR) review evaluated the evidence regarding the best hand positioning techniques during CPR (Olasveengen et al., 2020). The ILCOR review identified three relevant studies that examined the impact of hand positioning on physiological outcomes (Orlowski, 1986; Cha et al., 2013; Qvigstad et al., 2013). One study reported higher systolic blood pressure and end-tidal carbon dioxide when compressions were delivered at the lower third of the sternum compared with the centre of the chest (Cha et al., 2013). The second study, involving 30 adults, observed no significant difference in end-tidal carbon dioxide with changes in hand position during CPR (Qvigstad et al., 2013). The third study, conducted in children, observed higher systolic and mean arterial pressure when the hands were placed on the lower third of the sternum (Orlowski, 1986). Based on the above very low-certainty evidence, the ILCOR recommends chest compressions on the lower half of the sternum in cardiac arrest patients (Olasveengen et al., 2021; Wyckoff et al., 2022). Therefore, the recommendations from the 2015 resuscitation guidelines remained unchanged (Perkins, Travers, et al., 2015; Travers et al., 2015).

### 2.2.3.2 Chest Compression Depth

Chest compression depth was defined as the “posterior depression of the anterior chest wall in millimetres” (Stiell et al., 2012). Several studies reported higher post-cardiac arrest survival rates with a deeper compression (Stiell et al., 2012; Vadeboncoeur et al., 2014; Riyapan et al., 2019). For example, two studies found that survival rates to hospital discharge significantly increased with each 5 mm increase in compression depth (Stiell et al., 2014; Vadeboncoeur et al., 2014), and one study found that the same increase in compression depth was associated with significant, favourable neurological outcomes (Vadeboncoeur et al., 2014). Another study reported twofold shock success rates when cardiac arrest patients received compression depth greater than 50 mm compared to those who received compression depth less than 50 mm (Babbs et al., 2008). In contrast, one observational study reported a higher risk of injuries with chest compression depths exceeding 60 mm (49%) compared to depths of 50 to 60 mm (27%) (Hellevoet al., 2013), which was the main reason for introducing an upper-limit compression depth in the resuscitation guidelines.

The international resuscitation guidelines recommend a chest compression depth of 50 mm, not more than 60 mm, for an average adult (Olasveengen et al., 2021; Perkins et al., 2021; Wyckoff et al., 2022). The recommendation for the lower limit is based on strong recommendations and low-certainty evidence, while the

recommendation for the upper limit is based on weak recommendations and very low-certainty evidence (Olasveengen et al., 2021; Wyckoff et al., 2022). The 2015 resuscitation guideline and the 2020 ILCOR scoping review served as the foundation for the current compression depth recommendation (Perkins, Travers, et al., 2015; Considine et al., 2020). In the 2020 scoping review, 12 studies, including 1 randomised and 11 observational, reported outcomes related to compression depth (Considine et al., 2020). The included studies examined cardiac arrest outcomes, including shock success, ROSC, survival to hospital admission, favourable neurological function, and survival to hospital discharge. The scoping review found no new evidence to justify conducting another systematic review or to reconsider the 2015 resuscitation recommendations (Olasveengen et al., 2020). As a result, the 2015 ILCOR recommendation on the depth of chest compression remains unchanged.

### 2.2.3.3 Chest Compression Rate

Previous scientific and clinical data suggested that a higher compression rate may improve patient survival rates. For instance, in 1992, Kern et al. found that a compression rate of 120 per minute was associated with a higher mean end-tidal carbon dioxide level ( $15.0 \pm 1.8$  mm Hg) compared to 80 compressions per minute ( $13.0 \pm 1.8$  mm Hg), suggesting improved tissue perfusion (Kern et al., 1992). Similarly, another study reported that higher mean compression rates were associated with increased ROSC (Abella, Sandbo, et al., 2005). The mean chest compression rates for survivors versus non-survivors were  $90 \pm 17$  and  $79 \pm 18$  compressions per minute, respectively (Abella, Sandbo, et al., 2005). In 2015, Idris et al. published a study investigating the association between compression rate and survival after OHCA (Idris et al., 2015). After adjusting for cofounders, they found that a compression rate of 100 to 120/min was associated with better survival to hospital discharge than lower or higher compression rates (Idris et al., 2015).

Based on the evidence, the compression rate recommendation has been increased since the start of modern CPR. In 1960, when the first article on closed-chest compression was published, the recommended compression rate was 60 per minute (Kouwenhoven et al., 1960). The compression rate was increased to 80-100 compressions per minute in the 1986 updated resuscitation guideline (Standards for CPR and ECC, 1986). Following revisions to the resuscitation guidelines in 2000, the compression rate was increased to 100 compressions per minute (Cummins & Hazinski, 2000). The 2000 resuscitation guideline was unique in providing the first international resuscitation recommendations in which multiple international resuscitation councils participated (American Heart Association, 2000). Since 2000, the guideline has been updated every 5 years, and the recommended compression rate remained unchanged until 2015. In 2015, the guidelines were revised to

recommend a minimum compression rate of 100 and a maximum of 120 compressions per minute. This recommendation remains in effect in the 2020 resuscitation guideline because a scoping review by the ILCOR did not find evidence to change the 2015 recommendation (Considine et al., 2020).

#### 2.2.3.4 Chest Recoil

The return of the sternum to a neutral position during the decompression phase of CPR is referred to as full chest wall recoil (Kleinman et al., 2015; Considine et al., 2020). Complete chest recoil is necessary between compressions to allow the chest to fully expand and create negative intrathoracic pressure, which draws blood back into the chest and heart (Kouwenhoven et al., 1960; Lurie et al., 2016; Eijk et al., 2024). By drawing blood back into the chest, the heart can accumulate oxygenated blood in the ventricles to be pumped in the subsequent compression (Lurie et al., 2016). The only force that can pull blood back into the right side of the heart during CPR is passive chest wall recoil, making this refilling process incredibly inefficient (Lurie et al., 2016).

Full chest wall recoil is prevented when the rescuer does not fully release pressure on the chest wall between compressions, a condition known as chest wall leaning (Kleinman et al., 2015; Considine et al., 2020). Additionally, the coronary blood flow occurs during diastole; therefore, complete chest recoil during the decompression phases of the compression is necessary to achieve adequate coronary perfusion (Kern, 2000; Souchtchenko et al., 2013; Lurie et al., 2016). As a result, resuscitation guidelines recommend complete chest recoil, as incomplete recoil from leaning can reduce venous return and cardiac output (Olasveengen et al., 2021; Wyckoff et al., 2022).

#### 2.2.3.5 Interruption (Pause) during CPR

Resuscitation guidelines recommend high-quality compressions with minimal interruption (Olasveengen et al., 2020; Panchal et al., 2020; Olasveengen et al., 2021). Chest compression interruptions must be minimised to avoid ischemic injury, as pauses in chest compression interrupt organ perfusion (Olasveengen et al., 2021). When CPR is stopped for any reason, coronary and cerebral perfusion pressures drop to zero, decreasing the likelihood of ROSC, which requires a minimum CPP of 15 mmHg (Paradis, 1990). Several factors, including provider fatigue, compressor switch, ventilation, endotracheal intubation, pulse checks, vascular access placement, and patient transfer to the ambulance, can interrupt chest wall compression (Souchtchenko et al., 2013).

According to the ERC resuscitation guidelines, chest wall compression interruption should be minimised to 5 seconds to reduce ischemia of vital organs (Perkins et al., 2021). However, in one study, 33.3% of chest compression interruptions lasted longer than 10 seconds, and 4.3% lasted longer than 60 seconds (Dewolf et al., 2021). Pulse check was the most common cause of interruptions in chest compressions during CPR (Hanisch et al., 2020; Dewolf et al., 2021). As stated by Hanisch et al., 41.6% of the interruption time was devoted to manual electrocardiography (ECG) rhythm analysis and pulse checks, 13.7% to AED rhythm analysis, and 8.0% to manual rhythm analysis and shock delivery. The findings suggest that medical devices that detect the return of the pulse during ongoing chest compression are required to minimise the need for manual pulse checks.

Many scholars examined the relationship between interruption and resuscitation outcomes after cardiac arrest. Brouwer et al. (2015) investigated the association between compression interruption and patient outcomes after ventricular fibrillation in OHCA. They reported that the length of pause had a significant negative association with survival to hospital discharge (Brouwer et al., 2015). Other researchers examined the relationship between chest compression interruption and survival following paediatric IHCA (Lauridsen et al., 2024). The chances of a favourable ROSC, survival to hospital discharge, and a good neurological outcome decreased with each 5-second increase in chest compression interruption.

The prevalence of interruptions during CPR has improved over time. The duration per individual interruption dropped from 14 seconds in 2007 to 7 seconds in 2016, and the median total interruption duration per case dropped from 115 seconds in 2007 to 72 seconds in 2016 (Hanisch et al., 2020). Several factors may have contributed to the decline of interruptions over time, including programming initiatives to reduce interruptions, real-time feedback from defibrillators, faster endotracheal intubation, and reduced vascular access (Hanisch et al., 2020).

Despite abundant evidence and clear guidelines defining optimal chest compression parameters, achieving consistent, high-quality chest compression performance remains challenging, particularly for laypersons and inexperienced healthcare professionals, underscoring the need for real-time feedback devices to guide rescuers during CPR.

## 2.3 Feedback Devices for CPR

Improvements in outcomes after cardiac arrest have been significantly shaped by innovative medical devices and technologies (Cabrini et al., 2008; Crowley et al., 2020; Gambolò et al., 2024). Novel medical devices and technologies are being designed to assist in cardiopulmonary resuscitation, both in and out of hospital settings (Levitt et al., 2023). These innovations are expected to continue accelerating

in the coming decades, with the widespread adoption of artificial intelligence to address existing limitations in the precision and prediction of CPR quality (Chikatimalla et al., 2025). One major category of these medical device innovations comprises feedback devices that assist rescuers in improving CPR quality, thereby enhancing survival rates after cardiac arrest. The different types of feedback devices used during CPR will be discussed in the following section, with a particular emphasis on standalone audiovisual feedback (AVF) devices, which are the focus of this study.

### 2.3.1 Types of Feedback Devices

Several feedback devices have been developed to guide the quality of CPR during training and actual patient resuscitation (Gruber et al., 2012; Gugelmin-Almeida et al., 2021; Y. Wang et al., 2023) (**Figure 1**). Based on the source of feedback, CPR feedback devices can typically be classified into two groups: physiological information data-monitoring feedback (PIMF) devices and AVF devices (R. Lyngby, 2022; Y. Wang et al., 2023). The *PIMF* devices provide feedback on the patient's response to the rescuer's actions by tracking one or more CPR parameters, such as cardiac output, mean arterial pressure, ECG amplitude, End-Tidal Carbon Dioxide (ETCO<sub>2</sub>), and oxygen saturation waveform (R. Lyngby, 2022; Y. Wang et al., 2023). In contrast, AVF devices provide audio, visual or audiovisual feedback based on the rescuer's performance (Levitt et al., 2023; Y. Wang et al., 2023), denoting what the provider does to the patient (R. Lyngby, 2022).

The PIMF devices are typically used in advanced life support (ALS) scenarios involving resuscitation experts, which is beyond the scope of this study. In contrast, AVF devices can help experienced and inexperienced rescuers perform high-quality chest compressions during Basic Life Support (BLS) and ALS scenarios after cardiac arrest. Therefore, this study focuses on AVF devices that provide performance-based monitoring of chest compression quality.

AVF devices range from simple metronomes that provide regular beats at a preset frequency to more advanced devices that monitor and deliver corrective, real-time AVF to ensure high chest compression quality during CPR (Yeung et al., 2009; Gugelmin-Almeida et al., 2021; Y. Wang et al., 2023). Metronomes produce an audible signal at a regular interval and do not vary with performance (Gruber et al., 2012; Olasveengen et al., 2020). It typically guides rescuers to compress the chest at a preprogrammed 100-120 beats per minute during CPR (Botelho et al., 2016). Therefore, the metronome can only guide on one compression component: the compression rate. In contrast, real-time AVF devices can monitor single or multiple CPR parameters, such as compression depth, compression rate, and chest recoil. They provide rescuers with real-time feedback to help them make necessary

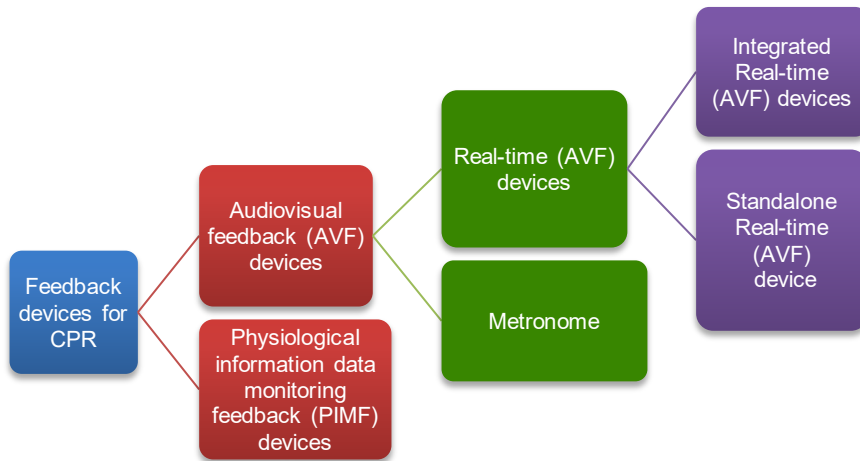
adjustments to their performance (Gruber et al., 2012; Gugelmin-Almeida et al., 2021), guiding them in adhering to resuscitation guidelines.

Real-time AVF devices for chest compression during CPR can be further categorised into integrated and standalone real-time AVF devices (Gruber et al., 2012; Levitt et al., 2023). Integrated real-time AVF devices are typically associated with more complex, multifunctional devices, such as defibrillators and advanced simulation manikins (Gruber et al., 2012; Levitt et al., 2023). Medical devices, such as defibrillators with integrated AVF devices, have multiple interfaces with various functions. These functions go beyond providing real-time feedback on the quality of chest compressions, making them quite complex for inexperienced healthcare professionals and laypersons (Gruber et al., 2012; Levitt et al., 2023). Laypersons may be unfamiliar with defibrillators themselves and hesitate to use them as was reported in many previous studies (Pei-Chuan Huang et al., 2021; Slabe et al., 2024). Therefore, the use of defibrillator-integrated AVF devices, which may require knowledge of and proper handling of the defibrillator itself, can lead to confusion and hesitation to use them during stressful cardiac arrest events. Furthermore, the adoption and use of defibrillator-integrated AVF devices require purchasing and carrying a defibrillator, because the AVF devices are not functional as separate units, which may limit their availability and wider usability at the community level and in resource-limited settings.

In most cases, standalone real-time AVF devices are smaller, lighter, and more portable than integrated real-time AVF devices. They are independent units that provide feedback solely on the quality of chest compressions (Gruber et al., 2012). However, many previously marketed standalone real-time AVF devices placed on the patient's chest during CPR are rigid and stiff in structure (Elding et al., 1998; Perkins et al., 2005; Buléon et al., 2013). The rigid structure may cause additional friction on rescuers' hands, potentially leading to discomfort and pain (Perkins et al., 2005; Buléon et al., 2013; Hong et al., 2016). Rescuers with hand discomfort can get exhausted quickly, which may compromise the quality of chest compressions, resulting in reduced positive outcomes after cardiac arrest. Another potential drawback of the standalone AVF devices placed on patients' chests during CPR is the presence of a detached object between the rescuer's hand and the patient's chest, which can lead to inaccurate feedback due to unintentional displacement of the device (Gruber et al., 2012; Ma et al., 2025). The classification of feedback devices for CPR is shown in **Figure 1**.

To minimise pain caused by rigid AVF devices and reduce the risk of a detachable device becoming displaced between the chest and the rescuer's hand, more comfortable, standalone, wearable, real-time AVF technologies have emerged in recent years to help rescuers deliver high-quality chest compressions during CPR.

The strengths and limitations of these wearable real-time AVF devices are described below.



**Figure 1.** Types of Feedback devices used in CPR.

### 2.3.2 Standalone Wearable Real--Time AVF Devices

Standalone wearable Real-time AVF devices integrate various types of sensing technologies to monitor and provide real-time feedback on the performance of chest compressions during CPR (Lu et al., 2018; Ward et al., 2019; S. Lee et al., 2021; Musiari et al., 2021; Xie & Wu, 2023). Real-time feedback devices based on smartwatches have been developed as a novel wearable feedback device to overcome the limitations of the non-wearable devices (Song et al., 2016; J. Lee et al., 2019; Ahn et al., 2017; LaPrad et al., 2024), such as those placed on the patient's chest (Perkins et al., 2005; Smereka et al., 2019; Miller et al., 2020), and handheld devices such as smartphones (J. Park et al., 2016). As a result, some studies reported better feedback accuracy with wearable smartwatch-based feedback devices than with non-wearable, standalone real-time AVF devices (Song et al., 2016; An et al., 2019). However, smartwatches are worn on the wrist, which is far from the actual compression point (the sternum), making them prone to inaccuracies during CPR (J. Park et al., 2016; S. Lee et al., 2021; Ma et al., 2025).

To address the limitations of smartwatches, several scholars have explored alternative wearable devices to monitor the quality of chest compressions during CPR (Gruenerbl et al., 2018; Lu et al., 2018; S. Lee et al., 2021; Musiari et al., 2021; Xie & Wu, 2023; LaPrad et al., 2024). Musiari et al. demonstrated that feedback from a glove's coaching system placed near the compression site improved compression depth and rate during manikin-based CPR (Musiari et al., 2021). Lee et

al. (2021) developed a wearable smart ring that used visual (colour) feedback to guide rescuers to adjust compression depth during CPR (S. Lee et al., 2021). Their proof-of-concept study demonstrated that the prototype smart ring provides accurate feedback on the depth of compression during CPR (S. Lee et al., 2021). Recently, Ma et al. designed a prototype of a liquid silicone-based material to minimise skin injuries associated with rigid AVF services (Ma et al., 2025). In their study, the authors concluded that the newly developed wearable feedback device may provide more accurate depth and rate measurements during chest compressions and may be safer for rescuers. (Ma et al., 2025).

The most significant advantage of the recently designed standalone wearable real-time AVF devices is that they prioritise rescuer comfort while reducing or preventing the risk of device displacement during chest compressions (Musuari et al., 2021; S. Lee et al., 2021; Xie & Wu, 2023; LaPrad et al., 2024). Although they are promising for enhancing comfort and reducing errors, most wearable AVF devices provide feedback on only a subset of chest compression metrics, particularly compression depth and rate (Lu et al., 2018; Musuari et al., 2021; Xie & Wu, 2023; LaPrad et al., 2024). Other metrics, including chest recoil, interruption, and hand positioning, are not targeted in the development of these newly designed standalone wearable real-time AVF devices. Additionally, most wearable real-time AVF devices are still in the prototype or proof-of-concept phase, and considerable research is needed to assess their effectiveness, usability, acceptability, and the extent to which they reduce rescuers' discomfort and sensor displacement during CPR. After outlining the different types of AVF devices for CPR, the following section synthesises their impact on chest compression quality and patient outcomes.

### 2.3.3 Benefits of real-time AVF Devices

#### 2.3.3.1 Quality of Chest Compression during CPR

Several systematic reviews investigated the importance of using real-time AVF devices to monitor chest compression quality during CPR (Kirkbright et al., 2014; An et al., 2019; Gugelmin-Almeida et al., 2021; R. M. Lyngby et al., 2021). All the systematic reviews reported improvement in at least one of the evaluated compression metrics with the use of the feedback devices, and none indicated a decline in performance associated with the devices (Kirkbright et al., 2014; An et al., 2019; Gugelmin-Almeida et al., 2021; R. M. Lyngby et al., 2021). For example, Gugelmin-Almeida et al. conducted a systematic review of randomised controlled trials to assess the effectiveness of real-time AVF devices in improving the quality of chest compressions during CPR training and in actual patient resuscitation (Gugelmin-Almeida et al., 2021). The evaluated outcomes included compression

depth, compression rate, and chest recoil, as performed by healthcare professionals. They concluded that, in most studies, the use of real-time AVF devices improved chest compression performance during CPR training and during actual resuscitation compared with standard CPR groups (Gugelmin-Almeida et al., 2021). While ample evidence shows that AVF devices improve the quality of chest compressions, their true significance depends on their effect on patient survival, as detailed below.

### 2.3.3.2 Impact on Patient Survival

Several systematic reviews have been published recently, investigating the effect of real-time AVF devices on patient outcomes (Miller et al., 2020; S.-A. Wang et al., 2020; R. M. Lyngby et al., 2021; Lv et al., 2022; Sood et al., 2023; Gambolò et al., 2024). Although variation exists among the reviews, most findings indicated that using real-time AVF devices significantly improved at least one of the criteria used to measure patient outcomes, such as ROSC, survival to hospital discharge, or a favourable neurological outcome (Miller et al., 2020; R. M. Lyngby et al., 2021; Sood et al., 2023; Gambolò et al., 2024). Miller et al. conducted systematic reviews of randomised controlled trials comparing the effectiveness of stand-alone AVF devices with conventional CPR (without AVF) on patient outcomes, including ROSC and survival to discharge after IHCA (Miller et al., 2020). In their review, they reported improved ROSC and survival to intensive care unit and hospital discharge with the use of standalone AVF feedback devices. Similarly, Wang et al. (2020) reported a survival benefit with the Cardio First Angel device (a standalone AVF device) but not with AED-integrated feedback devices. Although further studies are needed to confirm the benefit of standalone real-time AVF over defibrillated integrated AVF devices, the initial evidence suggests that standalone real-time AVF may improve survival after cardiac arrest (Miller et al., 2020).

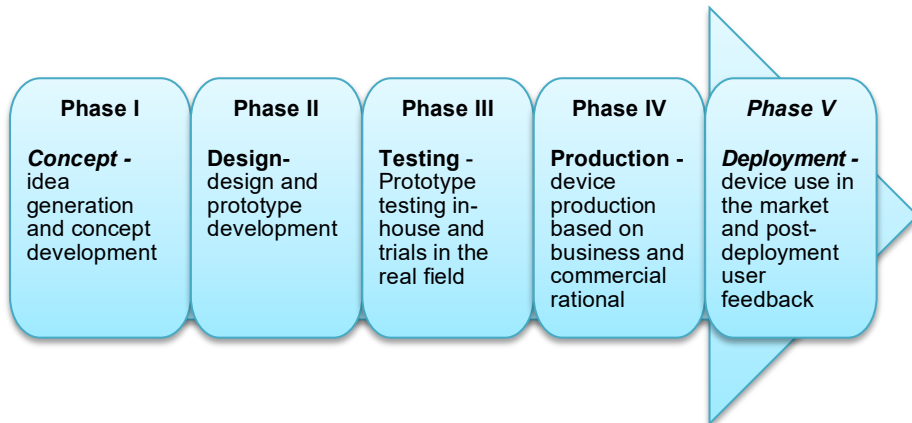
Based on the available evidence, the 2020 ILCOR guidelines recommended the use of AVF devices as part of a comprehensive quality improvement programme for cardiac arrest in clinical practice, but advised against their use in isolation (Olasveengen et al., 2020). Although the recommendations are considered weak due to a lack of high-quality evidence, the potential benefit of real-time AVF devices in CPR remains promising. This promise motivated us to design a safer, portable, wearable AVF device that can be used both in and out of hospitals to improve patients' survival after cardiac arrest.

## 2.4 Methodological Approach

### 2.4.1 Medical Devices Development Process

The medical device development (MDD) process outlines the stages of development, regulation, and implementation for medical devices. The step-by-step MDD process may vary because some of the MDD processes focus on the regulatory and business aspects of the development process (Marešová et al., 2020; Medina et al., 2013), while others concentrate more on the initial stage of development, with a greater emphasis on stakeholder involvement (Shah et al., 2009; Money et al., 2011). In the literature, the MDD process is typically classified into five stages, though the nomenclature and details of each stage vary. For example, according to the USA Food and Drug Administration (FDA), the MDD process comprises five steps: Device Discovery and Concept, Preclinical Research and Prototype, Pathway to Approval, FDA Review, and FDA Post-Market Safety Monitoring. The stage-gate process, which also comprises five stages, is arguably the most widely used approach in the literature (Pietzsch et al., 2009; Soenksen & Yazdi, 2017; Marešová et al., 2020). The five phases of the stage-gate process are initiation, formulation, design and development, final validation and product launch, and post-launch assessment (Pietzsch et al., 2009). The stage-gate process proposed by Pietzsch et al. (2009) has been criticised for its linear approach (Goldenberg & Gravagna, 2017; Marešová et al., 2020), as medical device technology development is typically cyclical, with many iterations expected. The stage-gate process for medical device development has also been criticised for focusing primarily on successful regulatory approval pathways while overlooking the involvement and potential benefits for most stakeholders (Goldenberg & Gravagna, 2017).

After reviewing the developmental stages of medical devices in the literature, Shah & Robinson (2006) classified the life cycle of medical device development into five phases: concept phase - idea generation and concept development, design phase - design and prototype development, testing and trials phase - prototype testing in-house and trials in the real field, production phase - device production based on business and commercial rational, and deployment phase - device use in the market and post-deployment user feedback (**Figure 2**). This work is guided by the MDD process framework proposed by Shah & Robinson (2006), alongside a user-centred design (UCD) approach and design research. It outlines the first three phases of development, as discussed in the following sections and illustrated in the conceptual framework (**Figure 5**).



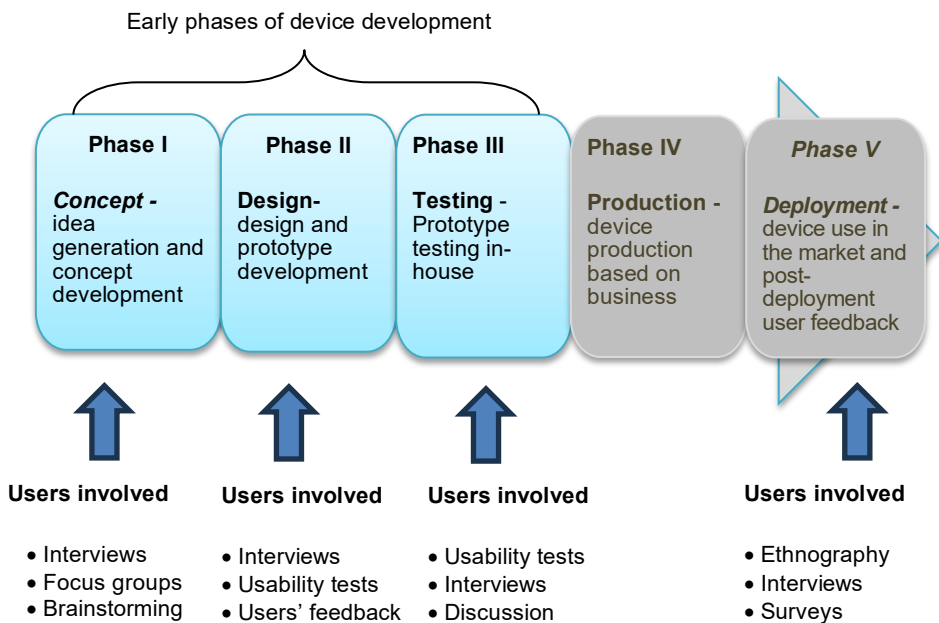
**Figure 2.** The phases of the medical device development process as described by Shah & Robinson (2006).

## 2.4.2 User-Centred Design (UCD)

Traditionally, manufacturers initiate medical device development based on the product's financial profitability, making enquiries to address market trends and identify lucrative sectors and investment locations (Makobore et al., 2022). End users, such as healthcare professionals and patients, had a limited impact on the development of medical products (Ahluwalia et al., 2018). Therefore, there was a significant disconnect between manufacturers and users, as early medical device innovations usually relied heavily on engineers' defined specifications (Ahluwalia et al., 2018). This primarily breaches the ethical issue of equitable and sustainable utilisation of medical products and technology (Ahluwalia et al., 2018). Focusing solely on profits while disregarding user needs can have serious consequences, especially in resource-limited settings (De Maria et al., 2022), where cost is often the primary barrier to adopting health-related technologies. As a result, although most people live in low—and middle-income countries, 76% of the global medical devices are used by just 13% of the population in developed countries (Arasaratnam & Humphreys, 2013; Piaggio et al., 2021).

Acknowledging this reality, modern medical product development practices strongly emphasise the importance of specifying the context of use and involving users from the beginning to ensure that health technologies are suitable for their intended users and the contexts in which they will be utilised (Makobore et al., 2022; Tsai et al., 2023; Kip et al., 2025). To ensure usability and acceptability, various frameworks and roadmaps have been developed to guide designers, developers and researchers in effectively involving users and other stakeholders in different phases of medical technology development (Harte et al., 2017; van der Bijl-Brouwer &

Dorst, 2017; Vaisson et al., 2021; Kip et al., 2025). Based on their review of user involvement in the development of medical devices, Shah et al. proposed a theoretical framework for engaging users in the developmental lifecycle of medical devices (Shah et al., 2009). According to their findings, users can be involved in the four stages of the development life cycle: the concept, design, testing, and deployment stages (Shah & Robinson, 2006; Shah et al., 2009). User-Centred Design (UCD) was achieved through various methods, including brainstorming sessions, user discussions, ethnographic, user-expert meetings, focus groups, individual interviews, usability testing, and user feedback (**Figure 3**).



**Figure 3.** User's involvement in the medical device development process as described by Shah & Robinson (2009).

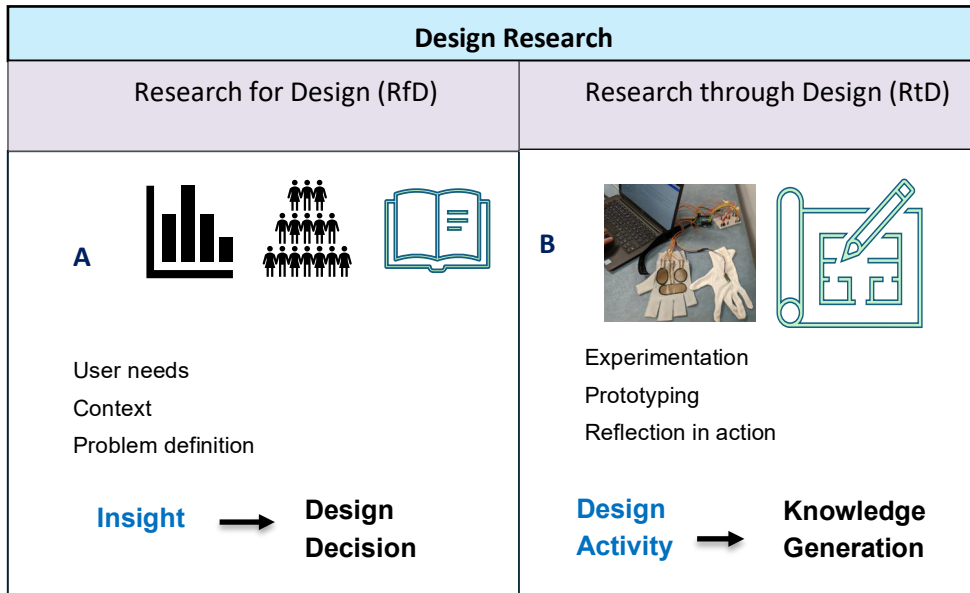
In this study, the UCD approach was operationalised and integrated into the MDD process by actively involving stakeholder groups, defined as end users, at multiple stages of the early development phases (concept, design, and testing) (**Figure 5**). The end users considered and involved in the development of the resuscitation glove (ResuGlove) included laypersons without formal medical training, first responders (first aiders and paramedics), nurses, nursing students, physicians, and CPR educators. Identifying these groups as end users and engaging them throughout the development process ensured that the design and evaluation of the feedback device were grounded in the needs, experiences, and contextual realities

of its users. User considerations and involvement were addressed through multiple complementary methods. A systematic review was conducted to identify gaps in the literature on the effectiveness and usability of marketed feedback devices; focus groups and individual interviews were used to define user requirements and explore factors influencing acceptability; iterative user feedback informed the development of a feasible and viable device; and prototype testing was undertaken to evaluate the usability and effectiveness of the newly developed device (**Figure 5**).

### 2.4.3 Design Research

Design and research have historically been seen as separate activities (J. Zimmerman & Forlizzi, 2014). The purpose of research is perceived as the production of knowledge that can be applied beyond the work of its producers, whereas design is typically viewed as the creation of a solution to a specific problem that can be implemented in the real world (Stappers & Giaccardi, 2014). The concept of using design research to enhance the design process emerged in the 1960s, first noted at a conference on design methods held at Imperial College London in 1962 (Jones & Thornley, 1963). Despite its growing popularity and promise, a consensus definition has yet to be established, as it remains contested, broad, and ambiguous (Green & Lindley, 2021).

Design research is a methodological approach to searching and gathering information about design and design-related activities (Bayazit, 2004). Practitioners involved in design conduct research for several reasons, including framing existing problems, identifying user needs and preferences, brainstorming possible solutions, testing the usability of concepts, and assessing the marketability of ideas and products (Visocky O'Grady & Visocky O'Grady, 2017). Design research can foster interdisciplinary collaboration and UCD by incorporating diverse research methodologies and promoting innovative solutions to complex challenges (J. Zimmerman & Forlizzi, 2014; Tseklevs et al., 2025). It is a broader concept that typically encompasses a wide array of methodologies, including Research for Design (RfD) and Research through Design (RtD), two distinct yet closely related approaches in design research (Stappers & Giaccardi, 2014; J. Zimmerman & Forlizzi, 2014; Jian, 2017) (**Figure 4**).



**Figure 4.** Design research: Research for design (A) and Research through design (B).

**Research for Design (RfD)** is primarily conducted at the early stage of design, focusing on gathering and synthesising information to assist designers in identifying the appropriate problem, understanding user requirements, and providing data to shape and inspire design solutions (Stappers & Giaccardi, 2014; J. Zimmerman & Forlizzi, 2014). In this methodology, research plays a fundamental role in the design process, informing design decisions through research (Stappers & Giaccardi, 2014) (**Figure 4A**). Research methods used may include systematic reviews, surveys, interviews, ethnography and other techniques to gather the necessary information to inform a specific design that aims to achieve an effective solution (Stappers & Giaccardi, 2014; Visocky O’Grady & Visocky O’Grady, 2017). With an emphasis on UCD, research for design seeks to understand how users engage with an existing product or service, offering crucial insights that inform the creation of a more efficient and user-friendly product (Stappers & Giaccardi, 2014; Visocky O’Grady & Visocky O’Grady, 2017; Rodriguez et al., 2023).

Based on the principle of RfD, this work screened the literature to identify gaps in CPR feedback devices, followed by a systematic review and meta-analysis of real-time, standalone AVF devices. The systematic review and meta-analysis aimed to identify gaps in effectiveness and usability for these standalone real-time AVF devices. Semi-structured interviews were also conducted to identify user requirements and factors that may influence the acceptability of the real-time AVF device. This information, supported by expert consultation, informed the initial UCD decisions for the wearable sensor-embedded resuscitation ResuGlove for CPR.

In contrast, **research through design (RtD)** is a research approach in which the design process becomes a method of inquiry, and designing is seen as a form of generating knowledge (Stappers & Giaccardi, 2014; Prochner & Godin, 2022) (**Figure 4B**). Hence, RtD is seen as an independent method that uses making and projection as instruments to learn about people, technology, and the world (J. Zimmerman & Forlizzi, 2014). Therefore, RtD is not about the successful completion of a marketable product but about building prototypes, testing hypotheses and exploring possibilities beyond a successful completion of a particular product (Stappers & Giaccardi, 2014). As such, unlike RfD, where the gathered information might be used by other designers, in RtD, the designers involved with the prototype must navigate the real-world obstacles that hinder building the best bridge between the product and its users (Stappers & Giaccardi, 2014).

In this study, RtD was used to collect information through an iterative design process. This method was employed to explore the potential of sensor-embedded, standalone AVF devices to improve CPR quality and to develop knowledge and understanding of the technology, multidisciplinary collaboration, and user interactions during development. As such, the researchers' and developers' experiences in interdisciplinary collaboration, along with the detailed development process, have been published in the proof-of-concept study (Paper III) under an open-access license. The prototypes will also be available to other researchers and designers to further develop the concept across various contexts and populations.

Therefore, this study employed an integrated framework that combines the MDD process, the UCD approach, and design research, all of which are essential to the conceptualisation, design and evaluation of useful medical devices. In this context, ResuGlove's usefulness is defined by its effectiveness in guiding CPR performance (compression depth, compression rate, and chest recoil) and its usability (user needs, interaction, and acceptability). These two aspects of the ResuGlove, effectiveness and usability, are systematically integrated and assessed across all phases of development, from initial evidence synthesis to prototype testing. **Figure 5** (Conceptual Framework) illustrates the relationships among the MDD process, UCD, design research, and the studies conducted during the early-stage development of the ResuGlove.

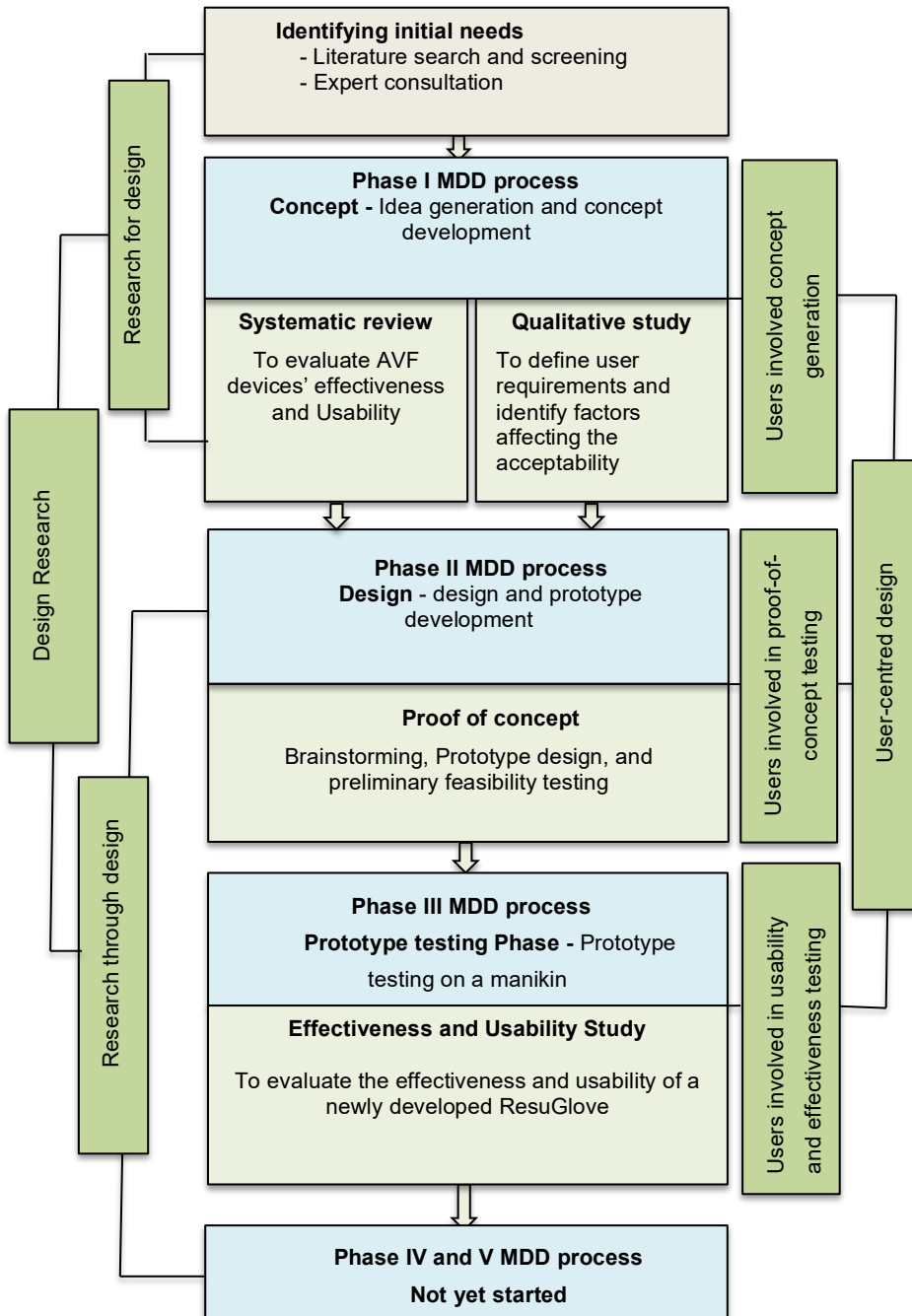


Figure 5. Conceptual framework of the study.

## 2.5 Existing Gaps and Opportunities

### Research Gaps and Opportunities

Despite the large volume of published articles on the effectiveness of real-time AVF devices in improving chest compression quality and patient outcomes, no systematic reviews have exclusively evaluated the effectiveness and usability of standalone real-time AVF devices when used by laypersons. Prior systematic reviews have either excluded standalone AVF devices and laypersons or combined them with integrated AVF devices and healthcare professionals. Additionally, there is a significant gap in understanding how these devices diffuse and the factors influencing their acceptability across different healthcare settings and user groups. For example, limited information exists on how the size, weight, cost, and complexity of AVF devices affect their usability and acceptability for both healthcare providers and laypersons during CPR training and in actual patient resuscitation.

We conducted a systematic review to address the existing gaps regarding the effectiveness and usability of standalone AVF devices. This systematic review established a comprehensive understanding of the effectiveness and usability of these devices, informing the development of a new standalone real-time wearable AVF device. A qualitative study was required to thoroughly explore users' experiences with AVF devices, identify their needs, and understand the factors influencing their acceptance. This ensures that the development of new real-time AVF devices is based on real-world requirements and user preferences, rather than relying solely on theoretical assumptions and financial incentives.

### Design Gaps and Opportunities

Many of the first real-time AVF devices developed for training and clinical use are rigid and inflexible, and are placed on patients' chests (Perkins et al., 2005; Buléon et al., 2013; González-Otero et al., 2017). The rigid, inflexible structure of the devices may increase friction on the rescuer's hands during chest compressions, potentially leading to hand discomfort (Perkins et al., 2005; Hong et al., 2016; González-Otero et al., 2017). This may lead to premature exhaustion of rescuers, resulting in ineffective compression during CPR. Another potential drawback of the rigid AVF devices placed on chests during CPR is the presence of a detached object between the rescuer's hand and the patient's chest, which can lead to inaccurate feedback due to possible unintentional device displacement, particularly during patient transport (Gruber et al., 2012). Real-time feedback devices based on smartwatches have been developed and evaluated to overcome the limitations of the

rigid standalone real-time AVF devices. However, smartwatches are often worn far from the actual compression point (the sternum), which may reduce accuracy and make it harder to observe feedback during compression (Ahn et al., 2021). In addition to smartwatches, scholars have investigated other wearable devices for monitoring the quality of chest compressions during CPR (Dellimore et al., 2013; S. Lee et al., 2021; Musiari et al., 2021). However, many wearable, real-time, standalone AVF devices are still at the prototype or proof-of-concept stage (Dellimore et al., 2013; S. Lee et al., 2021; Musiari et al., 2021). Consequently, significant work and research are needed to evaluate their effectiveness, usability, acceptability, and the actual benefits of reducing rescuers' discomfort, as well as the potential benefits of reducing sensor displacement during CPR (Dellimore et al., 2013; Gauna et al., 2016; S. Lee et al., 2021; Ward et al., 2019; Musiari et al., 2021). Moreover, most wearable devices only monitor and provide feedback on a subset of chest compression metrics, particularly compression depth and rate. Other metrics, including chest recoil, interruption, and hand positioning, are not targeted in the development of these wearable feedback devices (Dellimore et al., 2013; Musiari et al., 2021).

In conclusion, although there is sufficient evidence to support the claim that real-time AVF devices improve specific metrics of chest compression, there are still design-related limitations that need to be addressed to maximise the effectiveness, usability and acceptance of real-time AVF devices. Rigid devices should be replaced by soft and flexible, user-friendly devices to minimise the discomfort of the rescuer's hands (Cho, 2009; Gruber et al., 2012). Potential errors in feedback caused by sensor displacement or remote placement can be mitigated by developing a wearable device with sensors securely mounted on the rescuer's palm or the patient's chest. Moreover, it is essential to develop wearable, standalone, real-time AVF devices with interfaces that can monitor, provide reliable feedback on correct hand positioning, complete chest recoil, and interruptions during real patient resuscitation. These metrics are either absent or not reliably monitored in the previously designed wearable, standalone, real-time AVF devices, as no conclusive evidence was found on the advantage of the real-time AVF device in improving these metrics (Dellimore et al., 2013; S. Lee et al., 2021; Musiari et al., 2021).

# 3 Aims

The overall aim of this study was to develop a concept for a wearable CPR feedback device, design an early-stage prototype, and test it in a controlled simulation environment. The research was conducted within the framework of the MDD process, which describes the three phases of early-stage development: Concept – idea generation and concept development (Phase I); Design – design and prototype development (Phase II); and Testing – in-house prototype testing (Phase III). Emphasising the research process helps keep the reader engaged by showing the structured development within the MDD framework. This work included two published papers in the first phase and one in each of the second and third phases of the development process.

The study addressed the following specific objectives and research questions.

## **Phase I: Concept - idea generation and concept development**

The first objective (Paper I) in Phase I was to examine the existing evidence and gaps in the literature, focusing on the effectiveness and usability of AVF devices for improving chest compression quality during CPR.

Specific research questions

- Do standalone AVF devices improve chest compression quality metrics (rate, depth, recoil, and hand positioning) during simulated layperson CPR on manikins? (Paper I)
- Do standalone AVF devices used during layperson CPR on manikins enhance trainees' confidence and satisfaction? (Paper II)

The second objective in Phase I was to gather qualitative insights to inform a UCD by identifying user requirements and factors influencing the acceptability of AVF devices.

Specific research question:

- What are the user needs and factors associated with the acceptability of AVF devices that monitor chest compression performance during CPR? (Paper II)

## **Phase II: Design- design and prototype development**

The objective of Phase II was to design and evaluate the feasibility and viability of newly designed sensor-embedded, soft, and flexible textile-based wearable gloves for monitoring chest compression performance during CPR.

Specific research questions:

- Is a sensor-embedded, flexible, textile-based ResuGlove feasible and viable for monitoring chest compression performance during CPR? (Paper III)
- What ergonomic features may impact the usability of the ResuGlove from the perspective of end users? (Paper III)

## **Phase III: Testing -prototype testing in simulation**

The objective of Phase III was to evaluate the effectiveness and usability of the newly designed ResuGlove, intended to monitor compression quality during CPR.

Specific research questions:

- Does the newly designed ResuGlove improve compression quality when compared with standard CPR?" (Paper IV)
- Is the usability of the designed ResuGlove measured by the SUS scale acceptable to users? (Paper IV)

# 4 Materials and Methods

## 4.1 Overview of the ResuGlove Development Process

This study employed a multi-stage, iterative research approach that combined various methods. The overall process adopted a multidisciplinary approach, involving clinical researchers, engineers, designers, and end users, ensuring that each phase informed the next in a structured, evidence-based manner. The research was organised into four interconnected studies (Papers I-VI), each targeting a different but complementary objective. Researchers and developers use various assessment methods during the first phase of medical device development to ensure technological and clinical viability, with literature reviews and stakeholder involvement being the most common (Markiewicz et al., 2014). Similarly, in this study, a systematic review (Paper I) and user interviews (Paper II) were conducted in the first phase of development to identify existing gaps in the literature and define user requirements and factors affecting acceptability for initiating UCD (**Figure 6**).

Clinical researchers first screened the literature to determine whether a systematic review of AVF devices was warranted. The initial literature search identified numerous systematic reviews on real-time AVF devices; however, none assessed the effects of real-time standalone AVF devices when used by laypeople. As a result, clinical researchers conducted a systematic review to evaluate the effectiveness and usability of available standalone AVF devices designed to improve chest compression quality in controlled, manikin-based scenarios. The systematic review conducted by clinical researchers identified key characteristics that affect the efficacy and usability of real-time standalone AVF devices. These findings provided significant information for the design and development of a novel, portable, real-time, standalone AVF device.

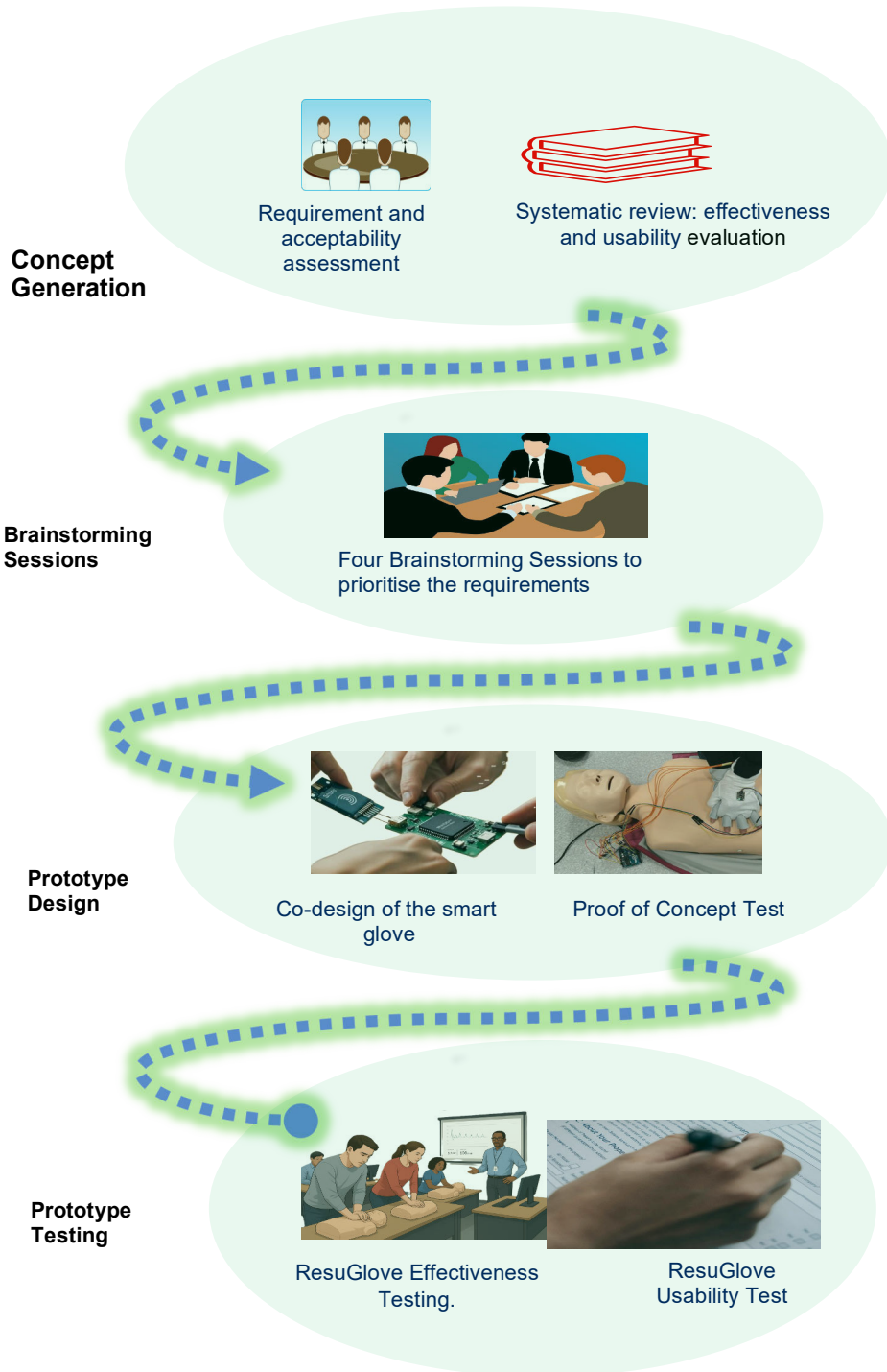
After gaining a basic understanding of the AVF device through a preliminary literature search, expert consultation, and systematic reviews, the second step in the first phase of the MDD process was to define user requirements and identify factors that affect acceptability. Therefore, a purposive qualitative study using focus groups, dyadic, and individual interviews was conducted to identify user requirements, design preferences, and usability factors that affect the acceptability of AVF devices.

The qualitative needs assessment study (Paper II) employed a user-centred approach to define user requirements and factors affecting acceptability, thereby clarifying the design requirements for developing a new, real-time, standalone AVF device.

Following the synthesis of the systematic review and interview data, several brainstorming sessions were organised among clinical researchers, engineers, and designers to identify and prioritise the most critical needs. These iterative brainstorming sessions and interdisciplinary collaboration led to the development of concepts and ideas for the early-stage development of a novel, real-time, wearable AVF device, the ResuGlove (**Figure 6**). After four extensive brainstorming sessions, the ResuGlove materials, the sensor types to be incorporated into the glove, and the chest-compression metrics to be monitored were defined and agreed upon by the team.

The effectiveness and usability gaps (Paper I) and user requirements (Paper II) identified in the first two studies, along with the needs prioritised in the iterative brainstorming sessions, served as the basis for the ResuGlove prototype design. Engineers and designers conducted the iterative prototype design. A small-group test conducted by a team of researchers, including a clinical researcher, evaluated whether the prototype interface met the specified requirements. This small-group test helped the researchers identify unmet requirements, which guided the development of the second prototype. In this second phase, the proof-of-concept study (Paper III) described and summarised the iterative prototype design process. This published study discussed the preliminary feasibility, potential viability, and limitations of the newly designed ResuGlove prototype with embedded sensors.

In the third phase, a manikin-based randomised crossover trial (Paper IV) was conducted to assess the usefulness of the ResuGlove, with an explicit focus on balancing effectiveness and usability. Effectiveness was measured using chest compression parameters, including compression depth, rate, and chest recoil, while usability was evaluated using the SUS usability questionnaire. This dual approach recognises that improvements in CPR performance are not enough if the device is not intuitive and acceptable to users. This study involved close collaboration between clinical researchers and engineers to thoroughly assess the performance of the designed prototype in terms of technical accuracy and clinical usability. ResuGlove was compared with standard manual CPR to evaluate its impact on compression quality and user experience. Key strengths and limitations of the designed ResuGlove prototype are highlighted, providing valuable insights to guide further refinement and the development of future versions of the device. The process and main steps of early-stage ResuGlove development are illustrated in **Figure 6**.



**Figure 6.** Early-Stage ResuGlove Development Process.

## 4.2 Study Design

This study comprised three phases and four studies, utilising mixed methods designs tailored to each phase and its specific objectives. The methods were chosen to effectively address the research objective in each phase of the study, as detailed in the following paragraphs and **Figure 7**. Two studies were conducted in the first phase, and one each in the second and third phases of the MDD process.

A systematic review (Paper I) was conducted in the first Phase of development to identify limitations and gaps in the literature to establish a scientific basis for developing the new device. The primary focus of the systematic review was to evaluate the effectiveness and usability of real-time, standalone AVF devices for inexperienced rescuers. Following the systematic view, user interviews (Paper II) were conducted to gather qualitative data to inform the UCD. In this study, semi-structured focus groups, dyadic interviews, and individual interviews were used to define user requirements and identify factors associated with device acceptability.

Based on findings from the studies conducted in the first phase of development, an iterative prototype design process was implemented in phase II of the MDD. The proof-of-concept study (Paper III) described and summarised the brainstorming sessions that led to the final idea and the iterative prototype design process. It also assessed the preliminary feasibility and potential viability of the newly designed wearable sensor-embedded ResuGlove. In this study, researchers employed the RtD approach to the development of the wearable AVF device, creating an initial functional prototype to monitor chest compression quality. This method was adopted because researchers could continuously assess design challenges and refine the process by developing a thorough understanding of the design and development context (J. Zimmerman & Forlizzi, 2014).

In Phase III of the development process, a manikin-based randomised crossover study (Paper IV) was conducted to evaluate the effectiveness of the designed prototype. The quality of chest compressions when rescuers used ResuGlove-assisted CPR with real-time feedback was compared to that of standard CPR (CPR without an AVF device). Participants completed the SUS usability survey immediately after performing 2 minutes of chest compressions guided by the ResuGlove.

Phases	Studies	Objectives	Study Design	Expected outcome
Phase I	Study I	To identify existing evidence and gaps, with a focus on the effectiveness and usability of AVF devices.	Systematic Review (Paper I)	Summary of AVF effectiveness, limitations, and existing gaps.
	Study II	To gather qualitative input for user-centred design by defining user requirements and device acceptability	Qualitative Study (Paper II)	Understanding of user requirements and identifying factors affecting Acceptability
Phase II	Study III	To design a prototype and evaluate the preliminary functionality and viability of the designed prototype	Proof of Concept Study Paper (III)	Initial evidence of technical functionality, viability, and usability
Phase III	Study IV	To evaluate the effectiveness and usability of the designed ResuGlove prototype	Randomised Crossover Study (Paper IV)	ResuGlove effectiveness and SUS usability scores.

**Figure 7.** Summary of study phases, objectives, design, and expected outcomes.

## 4.3 Study Participants, Settings and Sampling

### 4.3.1 Phase I: Idea Generation and Concept Development

Two studies were conducted in the first phase of the ResuGlove development process, comprising a systematic review and a qualitative study based on focus groups and interviews. The systematic review study (Paper I) followed the predefined PICO criteria (population, intervention, comparator and outcome). The primary studies were included when populations (P) were rescuers without exposure to real patient resuscitation; the intervention (I) was chest compression using the real-time standalone AVF device in a simulated manikin; the comparators (C) were standard CPR without the use of an AVF device; the outcome (O) included one or

more of the chest compression parameter; the study design was a randomised controlled trial. There were no limitations on the settings in which the studies were conducted. The systematic review included peer-reviewed studies published between January 2010 and January 2022. The time frame for the database search was based on the year in which the ERC and AHA guidelines first recommended the use of feedback devices during CPR training to improve chest compression performance (Bhanji et al., 2010; Soar et al., 2010), and on the last day the database was searched. A total of 16 studies were included in the systematic review.

In the qualitative user interviews study (Paper II), participants were selected from departments that actively participated in life-saving missions, including the Emergency and Intensive Care Departments of Turku University Hospital, the Ghana Red Cross Society-Ashanti Branch, Komfo Anokye Teaching Hospital in Ghana, and Southwest Finland Emergency Services. Twenty-two volunteers participated in the study, including paramedics, emergency and intensive care nurses, anaesthesiologists, and first aid-trained Red Cross personnel. Participants who received basic resuscitation training and had at least one year of experience in providing life support to patients with cardiac arrest were included in the study. A purposive, maximum-variation sampling method was used to recruit respondents from diverse backgrounds, experiences, and geographic locations (Kuper et al., 2008). This approach enables researchers to purposefully select participants who represent a variety of viewpoints, thereby avoiding the overrepresentation of a situation by a single group with similar experiences and backgrounds (Mays & Pope, 2000; Johnson et al., 2020) (Details are provided in Paper II).

### 4.3.2 Phase II: Design and Prototype Development

Wearable smart textiles should incorporate expertise from various disciplines, including electronic engineering, data science, and textile and industrial design (Townsend et al., 2017). Moreover, engaging healthcare professionals and other stakeholders is critical in developing and implementing healthcare technology to enhance its effectiveness, safety, and acceptability in real-world situations (Shah et al., 2009; Smith et al., 2019). Thus, the prototype design process and the proof-of-concept study (Paper III) adopted an interdisciplinary approach, integrating knowledge and methods from all collaborating disciplines (see Table 1 of Paper III for details).

To foster innovative solutions that meet the identified requirements and address existing gaps, the design process for the ResuGlove began with multiple brainstorming sessions with a multidisciplinary team, including one data scientist, two smart textile experts, five clinical researchers, and three engineers. Refer to Table 1 in Paper III to see their roles in the proof-of-concept study. Four

brainstorming workshops were held to prioritise solutions to the needs and gaps identified through an initial literature search, a systematic review, user interviews, and consultations with team members experienced in CPR and AVF device use.

Three of the brainstorming workshops were held online to identify and prioritise the most critical chest-compression metrics for which this study aimed to develop solutions. Compression depth, rate, and chest recoil were among the chest-compression metrics intended to be addressed by the recently developed ResuGlove. Detecting correct hand positioning, compression interruption, and the possibility of including features to detect patient pulse were also discussed, but deferred for future consideration, as addressing all requirements and needs simultaneously is not always feasible due to time and resource constraints (Tse et al., 2017).

Another focus of the brainstorming sessions was on selecting the most appropriate sensors and materials to address usability challenges and other deficiencies in existing real-time, standalone AVF devices. The fourth workshop was held in person to demonstrate the components of high-quality chest compressions to non-medical team members. This enabled non-healthcare professionals with no prior CPR training to develop a comprehensive understanding of the requirements for high-quality CPR.

Several design options and materials were discussed in the brainstorming sessions, including different types of sensors, smart gloves, smart vests, and a smart chest blanket, to address the identified gaps and requirements through an initial literature search, systematic review, user interviews, and consultations with research team members who have experience in CPR and the use of AVF devices. Finally, participants proposed the design of a soft, flexible, lightweight, easy-to-use, and hand-adaptable portable ResuGlove made from textiles, featuring embedded sensors that monitor the quality of compression performance (details are described in paper III).

#### 4.3.3 Phase III: Effectiveness and Usability Testing

The effectiveness and usability study (Paper IV) was conducted at the University of Turku Simulation Centre. Nursing students in their bachelor's degree programme at Turku University of Applied Sciences who had previously completed basic life support training were recruited for the study. Students with any health conditions that could affect their performance during chest compressions were excluded from the study. An invitation letter outlining the study aim and other details, such as the study location, date, and voluntariness, was sent to the nursing students' institutional email addresses. Students were asked to express their interest by sending an email or a short message via the phone number provided in the invitation letter.

Our unpublished pilot study, conducted in 2022 with eight participants, informed the sample size calculation. Assuming a 20% dropout rate, the required sample size was 30. A total of 29 participants completed the study, after one person left without providing a reason (Details are provided in Paper IV).

## 4.4 Data collection procedures

### 4.4.1 Phase I: Idea Generation and Concept Development

In the systematic review (Paper I), six electronic databases (Cochrane Central, Embase, PubMed, Web of Science, CINAHL, and PsycINFO) were searched on October 31, 2020, and updated on January 15, 2022. To find any relevant studies missed by the database search, a manual search of the reference lists of the included studies was conducted. Search strings using broad terms were developed with assistance from information specialists to include laypersons, standalone AVF devices, and simulation-based CPR training (see search details in Appendix 1).

The bibliographic references were imported into Zotero to remove duplicates. After duplicate checking, the search results were transferred to Rayyan QCRI, a systematic review management software (Ouzzani et al., 2016), where two reviewers independently screened the titles, abstracts, and full texts.

Risk-of-bias assessment and data extraction of the selected full articles were performed by the same researchers who conducted the eligibility screening. The Cochrane data extraction template for randomised trials, modified to suit our purpose, was used during data extraction. The Risk of Bias 2 (RoB 2) tool, a standardised Cochrane risk assessment for randomised controlled trials, was used to assess the risk of bias in this study (Higgins, 2020).

The total number of articles identified through electronic database searches and hand searches of included bibliographies was 1374. After removing all duplicates, screening titles and abstracts, and reviewing full texts, 16 primary sources were included in the final meta-analysis and narrative synthesis. Refer to the Prisma flow diagram in Figure I of Paper I, which illustrates the screening process.

In the qualitative needs assessment study (Paper II), data were collected through semi-structured focus groups, dyadic interviews, and individual interviews with departments that actively participate in life-saving activities in both Finland and Ghana. Collecting data from diverse backgrounds enabled the researcher to better understand the needs from both the Global South and the Global North perspectives. The study was guided by the Unified Theory of Acceptance and Use of Technology (UTAUT) Model (Venkatesh et al., 2003). We used the UTAUT model because it is the most comprehensive technological acceptance theory, derived from consolidating eight commonly used Technology Acceptance theories. The original

validation study of the theory found that the UTAUT model explains the variation in technology acceptance more effectively than the individual models (Venkatesh et al., 2003). Performance expectancy, effort expectancy, social influence, and facilitating conditions are the four constructs that underpin the UTAUT model. The constructs of the UTAUT model were used to develop interview questions and to guide data analysis.

Two researchers conducted the interview sessions online via Zoom. Multiple interviews were scheduled, and participants with similar backgrounds and experiences were grouped into the same focus group and assigned to the same dyadic interview session. Professionals involved in life-saving patient care often have very tight schedules. As a result, finding a time that suited all participants for a focus group discussion was proving challenging. As a result, seven dyadic interviews (two participants each) and two individual interviews were conducted, in addition to the two focus groups with three participants each (see paper II for details).

In fact, including data from the three types of interviews significantly enhanced the rigour of our study. Focus group interviews facilitated the generation of data and insights by allowing participants to share and comment with one another (Lobe et al., 2022). In contrast, individual interviews offer researchers the opportunity to gather in-depth data by allowing interviewees to express their experiences and opinions in greater detail (Morgan et al., 2013). Dyadic interviews fill an interesting gap between individual interviews and focus groups, offering the depth and detail of one-on-one interviews while also maintaining the interaction present in focus groups (Morgan et al., 2013; Lobe et al., 2022). The semi-structured questions and probes remained consistent throughout all interviews.

The interview sessions averaged 57 minutes (range: 36-75 minutes). Sampling was discontinued once a comprehensive understanding of the phenomenon under study was reached, a point often referred to as saturation (Kuper et al., 2008). As advised by Elo and Kyngäs (2008), the initial analysis began after a few interviews to confirm data saturation (Elo & Kyngäs, 2008). The interviews were recorded via Zoom and stored securely in the University of Turku Seafire. The audio data was transcribed verbatim to facilitate coding and analysis.

#### 4.4.2 Phase II: Design and Prototype Development

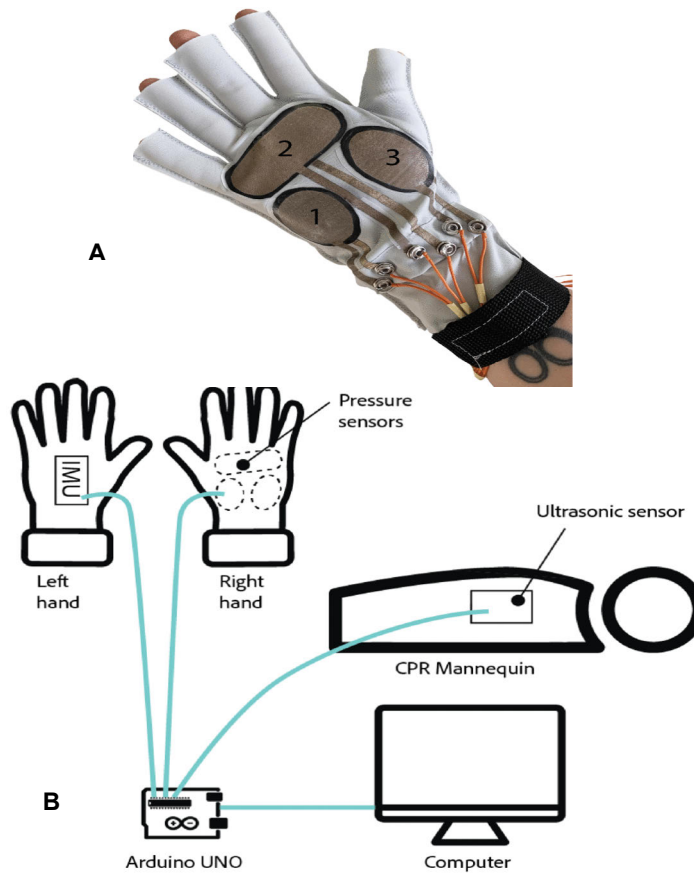
The insights from the brainstorming session were translated into product characteristics to address the limitations and requirements identified in the first two studies. The initial features were designed, and technical viability and functionality were tested internally in the proof-of-concept study (Paper III), primarily to obtain initial data from textile-embedded sensors connected to a computer via an Arduino setup (**Figure 9**). An Arduino setup is a microcontroller-based system that collects,

processes, and transmits sensor data for various applications (Goyal et al., 2024; Prabowo et al., 2024).

The first prototype design was to identify the most appropriate sensors for monitoring compression quality. Since the critical aspect of CPR is the pressure exerted on the chest, capacitive and resistive pressure sensors were selected for the prototype due to their flexibility, lightweight, and sensitivity, as well as their adaptability when integrated into wearable technology to monitor human motion (Li et al., 2020). The two pressure sensors were evaluated to determine which one was most suitable for a reliable, effective monitoring system of chest compression quality. To assess sensor noise, two sets of square samples (4×4 cm and 6×6 cm) were fabricated for the capacitive and resistive pressure sensors, respectively, to collect data and determine which type was best suited to the first ResuGlove prototype (a more detailed explanation can be found in Paper III).

The second step of the prototype focused on determining the number and placement of pressure sensors to be integrated into the ResuGlove. Following a practical demonstration by resuscitation experts on proper hand positioning and CPR techniques, the contact points on the chest were clearly marked with paint stains as visual reference markers (Figure 5 in Paper III), guiding the team on the number and position of the sensors. Ultimately, researchers decided to incorporate three pressure sensors into the palm side of the right-hand glove (**Figure 8 A**).

The final ResuGlove prototype consists of a pair of gloves, one for each hand, made of elastic knitted polyamide and cotton fabrics. This prototype was preferred for its simplicity and quick production in a laboratory setting. In addition to the pressure sensors, an Inertial Measurement Unit (IMU) was mounted on the dorsal side of the left-hand glove to complement them in detecting motion and orientation via accelerometers. The sensors were linked to an Arduino board, which collected sensor data and transmitted it to a laptop for audio feedback (**Figure 8 B**).

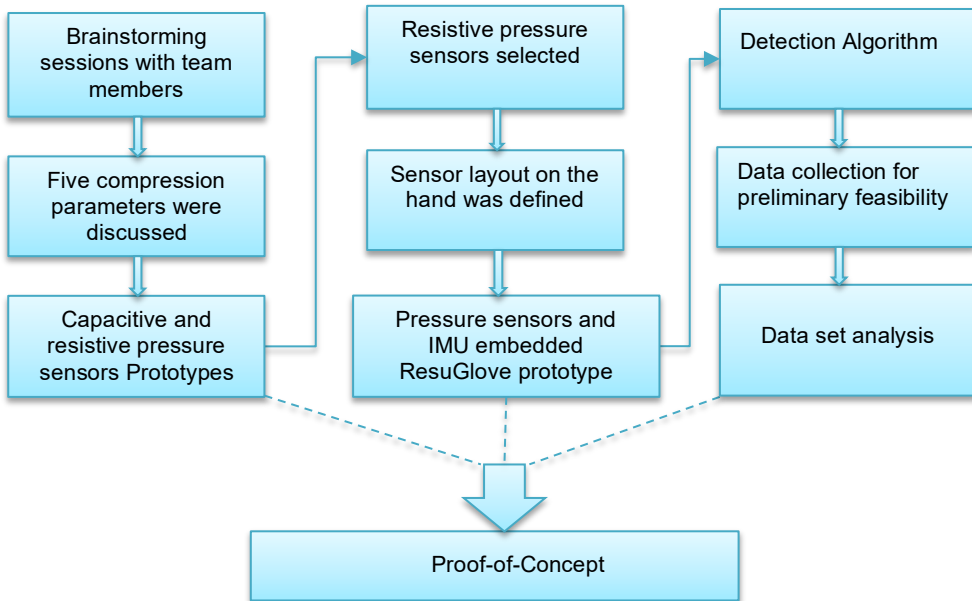


**Figure 8.** Final right-hand ResuGlove prototype (A) and the setup of the chest compression monitoring system during chest compression (B). Modified from Figures 6 and 7, Paper III.

Finally, the designed ResuGlove prototype was tested in-house with 9 participants (four CPR experts and five laypersons) at the University of Turku simulation centre. We informed potential participants about the study, including the demonstration's time and location. Only those who agreed received further details. Participation was voluntary, and participants were free to withdraw at any time without providing a reason. Consent to participate in the study was assumed upon entering the University of Turku simulation centre to take part.

To minimise fatigue during compression, each participant performed 30 compressions per set (three sets) while wearing the ResuGlove prototype. Participants also took a 10-minute break after each set of compressions to allow time to recover. Participants were asked to provide their opinions on the ResuGlove after completing rounds of chest compressions, enabling the researchers to incorporate their feedback into future prototype modifications. To enhance the device's

performance and usability, participants were asked to indicate which features or interfaces they would like to see improved. The design process for a ResuGlove prototype is shown in **Figure 9**.



**Figure 9.** Design process of low-cost fast prototyping methods for CPR quality monitoring (modified from Figure I in Paper III).

#### 4.4.3 Phase III: Effectiveness and Usability Testing

The usefulness of the ResuGlove was assessed by evaluating its effectiveness in improving chest compression quality and its usability from the user's perspective. A simulation-based randomised crossover trial (Paper IV) was conducted to test the effectiveness of the ResuGlove. This design was chosen because it minimises bias by allowing each participant to act as their own control. Twenty-nine participants who volunteered and signed a paper-based consent form prior to enrolment were randomly allocated to one of two intervention groups: Group 1 (14 participants) and Group 2 (15 participants). Participant allocation was determined using an online random number generator (Urbaniak & Plous, 2013). First, a researcher experienced in CPR demonstrated how to deliver chest compressions using the newly developed ResuGlove and respond to the device's feedback. In addition to being able to ask questions, participants were informed they could leave the study at any time without having to give a reason. During the two-minute compression session, participants knelt close to the Resusci Anne QCPR manikin, which was placed on a hard surface.

In period 1, group 1 performed continuous hand-only CPR while wearing the ResuGlove with a running feedback program for 2 minutes, whereas group 2 performed the same procedure without the ResuGlove. In period 2 (following a half-hour washout period), group 2 delivered hand-only CPR for 2 minutes while wearing ResuGloves, with continuous feedback. Group 1 followed the same procedure as group 2, but without the ResuGloves. During data analysis, participants who delivered chest compressions guided by the ResuGlove in both periods were categorised as the ResuGlove CPR group, and those who delivered chest compressions without the ResuGlove in both periods were categorised as the standard CPR group. The details are shown in Figure 2 of Paper IV.

The Resusci Anne QCPR, a Laerdal Medical training manikin linked to the android QCPR app, was used to perform chest compression and record chest compression parameters. Chest compression data collected from both the standard CPR group and the ResuGlove group were recorded in the QCPR app and immediately extracted for analysis. In the ResuGlove CPR group, the newly developed device, connected to a laptop via an Arduino Uno board, provided real-time audio feedback on the quality of chest compressions. The feedback mechanism provided by the ResuGlove is illustrated in Figure 1 of Paper IV. In addition to guiding rescuers on compression quality, the ResuGlove feedback also instructed them when to initiate and terminate chest compressions based on the preset compression duration of two minutes.

To evaluate the ResuGlove's usability, participants completed the System Usability Scale (SUS) immediately after performing 2 minutes of CPR guided by the ResuGlove. The SUS questionnaire has been a reliable tool used for decades to evaluate the usability of various technological innovations (Brooke, 1996; Bangor et al., 2008, 2009; Weenk et al., 2020; Kim & Xiong, 2022). Better product usability is indicated by higher SUS scores, which range from 0 to 100 (Brooke, 1996; Bangor et al., 2008). The SUS questionnaire has a total of ten items, with even-numbered statements phrased negatively and odd-numbered statements phrased positively. Each item in the SUS questionnaire uses a 5-point rating scale, allowing participants to indicate how strongly they agree or disagree with each statement.

## 4.5 Data Analysis

### 4.5.1 Phase I: Idea Generation and Concept Development

Two studies were conducted in phase I: a systematic review and a qualitative study. The results of the included studies in the systematic review were analysed and summarised using a meta-analysis and a narrative synthesis (Paper I). In some studies, all the chest compression parameters were analysed and reported. In

contrast, others evaluated and reported only a subset of these parameters. As a result, the number of eligible studies for the meta-analysis varied considerably across compression metrics. For instance, the analysis of the mean difference in compression depth was applicable to twelve studies. Conversely, only eight articles qualified for analysis of the mean difference in chest recoil, and just two for analysis of the mean difference in hand positioning. Because of substantial heterogeneity among the included studies, it was not possible to estimate the mean difference in compression rate.

We used the random effects model for the meta-analysis because we expected variation in the true effect caused by heterogeneity among the studies (Dettori et al., 2022). Because of its advantage in assessing the heterogeneity among studies of various sizes and types, the  $I^2$  statistic was used to measure the effect of heterogeneity (Higgins et al., 2003). Meta-analysis was avoided when the  $I^2$  value was high (>75%), according to Higgins et al.'s categorisation (Higgins et al., 2003). Three subgroups were analysed in the meta-analysis to determine whether the overall effect differs among the groups: study design (crossover vs. parallel), risk of bias ("some concern" vs. "low risk"), and the duration of the chest compression (2 minutes vs. > 2 min) (See for details in Paper I).

The second study (Paper II) in phase I employed thematic analysis to analyse the collected qualitative data, following the steps outlined by Braun and Clarke (2006). Familiarising oneself with the data, developing initial codes, searching for subthemes, assessing those subthemes, and abstracting them into comprehensive themes were all part of the analysis process (Braun & Clarke, 2006). Data were analysed deductively following the UTAUT model. A structured categorisation matrix was developed for the deductive analysis based on the UTAUT model, as recommended by Elo and Kyngäs (2008). The developed matrix was used as a lens to group codes with comparable meanings. The deductive coding was designed to reflect the four constructs of the UTAUT model: performance expectancy, effort expectancy, social influence, and facilitating conditions (for details, refer to Table 2 in Paper II). The first author primarily conducted the analysis, while the other co-authors, who were experienced in qualitative research, were in constant consultation to support concept development and to supplement alternative interpretations, ensuring trustworthiness (Elo & Kyngäs, 2008).

## 4.5.2 Phase II: Design and Prototype Development

The proof-of-concept study (Paper III) summarises the developmental steps and the initial feasibility and viability of the designed ResuGlove. Standalone chest compression monitoring devices typically use accelerometer sensors to detect compression depth and rate (Dellimore et al., 2013; Hermann et al., 2021; S. Lee et

al., 2021). The simplest way to derive displacement from acceleration is the bandpass method, which involves double integration. However, this method is not effective at detecting complete chest recoil (Hermann et al., 2021). Consequently, in this work, accelerometer sensors are complemented by pressure-based sensors to enable robust monitoring of complete chest recoil, which makes our method different from most standalone wearable AVF devices that use accelerometer sensors only.

The pipeline began with 3-axial acceleration data, which was subjected to principal component analysis (PCA). PCA is a dimensionality reduction technique that transforms multidimensional data into new axes (principal components) that capture the most considerable variations (Jolliffe & Cadima, 2016). The PCA was applied to the 3-axis acceleration data to identify the main movement direction, corresponding to acceleration along the depth of chest compression (acceleration along depth) (Figure 9, Paper III). Then, the depth-aligned acceleration signal was segmented into individual compression cycles using a compression-splitting algorithm, yielding meaningful units.

Next, a subset of the classical bandpass method was incorporated. When using the double-bandpass integration method, the filter parameters should be reset in between compressions because the CPR is cyclical. This will prevent error accumulation and ensure that the estimated compression depth signal remains stable (Gauna et al., 2016). In the original bandpass method, filters were reset at the zero crossings of the velocity estimates (Gauna et al., 2016). The drawback of this technique is that it loses track of the chest's actual position after each compression (chest recoil), as the initial conditions are always reset to zero, assuming full release after every compression (Gauna et al., 2016). The modified method used in this study resets the filters based on threshold pressure readings, addressing the limitation of the original method.

In a bandpass method, a high-pass filter is used in conjunction with a low-pass filter. In this work, a fourth-order Butterworth high-pass filter with a cutoff frequency of 0.6 Hz was used to remove low-frequency noise, and the low-pass step was performed using a cumulative trapezoidal rule for integration. The depth-aligned acceleration was high-pass filtered to eliminate low-frequency noise, then numerically integrated to obtain the velocity profile for each compression. After a second high-pass filter and integration stage, the displacement profile for each compression was obtained (Figure 9 in Paper III).

Finally, we reached a point where we can estimate the single displacement during a single compression. Prominence-based peak detection (prominence threshold of 0.2 in a  $[0, 1]$  normalised signal) in the SciPy library was then employed to identify the highest compression point (Peaks) and lowest (deepest) compression point (Troughs) within each compression cycle (Virtanen et al., 2020). Prominence-based peak detection was applied, enabling computation of compression rate (peak-to-peak

intervals) and compression depth (peak-to-trough displacement). Ultimately, the threshold pressure data provided supporting evidence for identifying full chest recoil by comparing it with a baseline threshold pressure.

Three primary errors, including instantaneous depth error, depth estimate error, and frequency estimate error, were measured to assess the accuracy of our approach in developing a wearable chest compression monitoring device during CPR. The error distributions of the three-accuracy metrics were summarised using measures of central tendency and dispersion. Instantaneous depth and depth estimate errors were presented as mean ( $\mu$ ) and standard deviation ( $\sigma$ ), while the frequency estimate error was displayed as mean and interquartile range. The median absolute difference was also calculated to enable comparison with previously published studies. No inferential statistics were employed, as the study's statistical analysis was aimed to characterise performance rather than evaluate group differences.

#### 4.5.3 Phase III: Effectiveness and Usability Testing

Two outcomes were analysed separately in this phase of the study (Paper IV): effectiveness and usability. The data for effectiveness were analysed using both descriptive and inferential statistics. The Shapiro-Wilk test and a quantile-quantile (QQ) plot were first used to visually evaluate the normality of the data. Mean and standard deviation were used to report normally distributed data, such as compression depth and rate. The medians and interquartile ranges were used to report non-normally distributed data, such as the percentages of adequate compression depth and chest recoil. Treatment, period, and residual carryover effects were evaluated using linear models specifically designed for crossover studies. No carry-over or period effects were detected (in all instances,  $p$ -values  $> 0.298$ ).

The Wilcoxon signed-rank test was used for variables whose studentised residuals were not normally distributed. The proportions of participants (paired nominal data) who delivered chest compressions within the recommended range were compared using McNemar's test. All Data were analysed using the Statistical Analysis System (SAS) software, Version 9.4. The significance threshold for our data analysis was set at  $p < 0.05$  (two-tailed).

The average SUS score was analysed according to the SUS scoring criteria described by Brooke (1996). Initially, one is subtracted from the score of the odd numbers (positively worded items) (score  $- 1$ ), and then the score of the even numbers (negatively worded items) is subtracted from 5 ( $5 - \text{score}$ ). Finally, the resulting scores are added together and multiplied by 2.5 to produce a composite score that reflects the product's overall usability (Brooke, 1996)

Previous studies have shown that the average SUS scale can be analysed in various ways. In this study, the usability score of the new device was interpreted

using the SUS acceptability categories (Bangor et al., 2008). According to the SUS acceptability category, a product's usability is classified as unacceptable (<50), marginal (50–70), or acceptable (>70). Furthermore, the mean and standard deviation for each item were calculated to quantify the score for each SUS statement.

## 4.6 Ethics Considerations

The study was carried out in accordance with the Declaration of Helsinki 2004 and the ethical standards for research involving human subjects established by the Finnish National Board on Research Integrity (World Medical Association, 2004; FINNISH NATIONAL BOARD ON, 2019). Multiple ethical committee clearances, institutional permissions, and informed consents obtained in each phase of the study will be discussed below.

The first study in Phase I (Paper I) was a systematic review that synthesised existing published studies without involving direct human subjects. Therefore, there was no need to seek ethics committee approval or obtain permission to collect and analyse the data. However, the data was handled carefully using sound scientific methods to ensure validity and reliability. The Prisma reporting checklist was followed to enhance the transparency and completeness of the reported findings (Page et al., 2021).

In the second study, in Phase I (Paper II), ethical approval was received from the Ethics Committee for Human Science Research at the University of Turku, Finland (number 10/2021), as well as the Human Research, Publications, and Ethics Committee in Ghana (dated 5/2021). The Ghana Red Cross (6/2021), Turku University Hospital (T158/2021), and Southwest Finland Rescue Department (8/2021) all granted permission to carry out the study. Participants were allowed to choose whether to participate, and they were informed they could withdraw at any time without providing a reason. They had the right to ask questions, refuse to answer a specific question, and request clarification. Data minimisation was strictly followed, and personal data, such as name, age, salary, address, and location, was not collected during the interviews. Robust data protection measures were applied through pseudonymisation and the confidential storage of the collected data on a secure cloud server maintained by the University of Turku.

Phase II (Paper III) involved a multiprofessional, iterative prototype design, including sensor selection and integration with ResuGlove materials. Small, iterative testing of sensors and materials was conducted repeatedly in a laboratory setting, culminating in final testing at a simulation centre with four healthcare professionals experienced in delivering high-quality CPR and five laypersons who received brief training in chest-compression-only CPR. Personal data were not collected, and no harm was expected from participation. Participants with any CVD or any acute or

chronic hand pain that could compromise chest compression performance were excluded from the study. Since the study had no anticipated risk of injury and no personal data were collected, ethical approval was not required. Consent to participate was assumed when participants voluntarily arrived at the University of Turku's simulation centre to attend the study.

The University of Turku's Ethics Committee for Human Sciences approved the study in Phase III (Paper IV) (statement nr 13/2022). Subsequently, Turku University of Applied Sciences granted permission to collect data (statement nr 9/2023). Participant autonomy was maintained by permitting voluntary participation and the right to withdraw at any time without needing to justify their decision. Participants did not gain any direct benefits, and no significant risks were expected aside from possible mild discomfort from wearing a tight ResGlove during compression. Every participant was given a thorough oral explanation of the study on the day of data collection. Afterwards, each participant signed a paper-based informed consent form before joining the study group.

# 5 Results

The main findings of the study are summarised in this chapter, while the detailed results are presented in the published original Papers (I-IV). The results in this chapter are organised sequentially according to the MDD process framework presented by Shah & Robinson (2006), which describes the early-stage development of medical devices.

## 5.1 Phase I: Concept- Idea Generation and Concept Development

In the first phase of ResuGlove development, a systematic review (Paper I) was conducted to assess the limitations and gaps in the literature on feedback devices, focusing on the effectiveness and usability of standalone AVF devices used by laypersons. To ensure user involvement from the early stages of development, a qualitative study (Paper II) was conducted to determine user requirements and identify factors affecting the acceptability of real-time AVF feedback devices.

### 5.1.1 Systematic Review (Paper 1)

#### 5.1.1.1 Characteristics of the Included Studies

Sixteen studies were eligible for inclusion in this systematic review and meta-analysis (**Table 1**). Two studies assessed as high risk of bias were excluded from the meta-analysis of all outcomes. All studies assessed compression depth and rate as outcomes. Twelve studies evaluated chest recoil, six evaluated hand positioning, only four evaluated skill retention, and five evaluated usability with respect to satisfaction and safety (**Table 1**). Nine of the studies were conducted in Europe, and seven in Asia. Six studies had sample sizes greater than 100 participants; five recruited 50–100 participants; and the other five recruited  $\leq 50$  participants (Details of the included studies' characteristics are provided in Supplemental Table 1, Paper I).

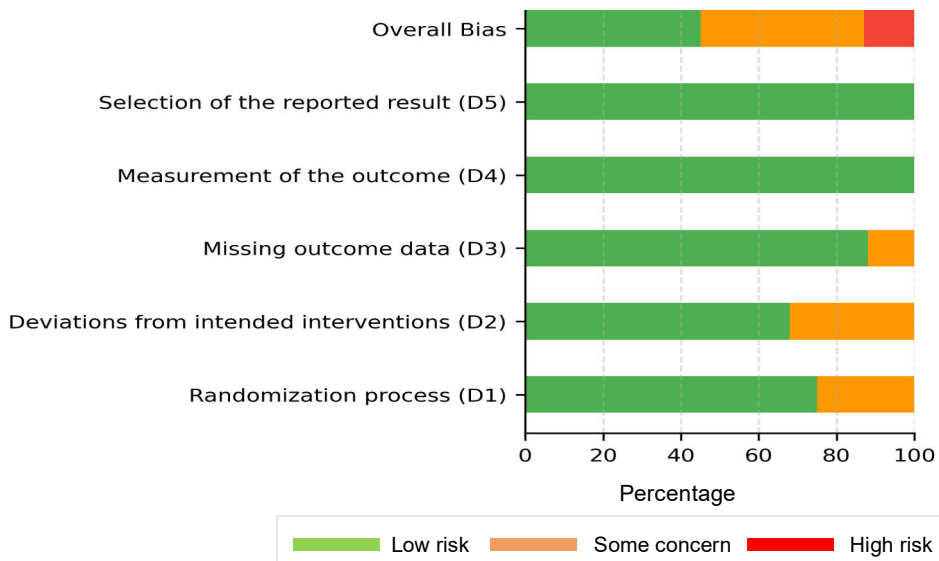
**Table 1.** Included studies, evaluated outcomes, and excluded studies from meta-analysis.

Study ID	Evaluated Outcomes						
	EMA	Primary Outcomes			Secondary outcomes		
		Yes	CCD	CCR	CR	HP	SR
Ahn 2017		√	√	√			
Ahn 2021		√	√	√			√
Buléon 2013	√ <sup>HR</sup>	√	√	√		√	
Dong 2020		√	√	√			
Eaton 2018		√	√				
Lee 2017		√	√	√			
Liu 2018		√	√				
Park 2014	√ <sup>HR</sup>	√	√	√	√		√
Plata 2019		√	√	√	√		
Plata 2021		√	√	√	√		
Sevil 2021		√	√	√		√	
Smereka 2019		√	√	√	√	√	√
Song 2015		√	√	√			
Suet 2020		√	√	√	√	√	
Wutzler 2018		√	√				√
Zapletal 2013		√	√		√		√

**Abbreviations:** EMA = Excluded from meta-analysis; HR = high risk of bias; CCD = Chest Compression Depth; CCR = Chest Compression Rate; CR = Chest Recoil; SR = Skill Retention.

In the overall risk of bias assessment, seven studies (43.8%) were classified as ‘low risk’, seven (43.8%) as ‘some concern’ and two (12.5%) as ‘high risk’ (**Figure 10**). Based on the Cochrane risk-of-bias tool for randomised trials (RoB 2) (Higgins, 2020), studies were categorised as having an overall "high risk" of bias if they had at least one instance of "high risk" or two instances of "some concern" across the five domains (D1-D5) (**Figure 10**). For more information, refer to Figure 2 in Paper I. Two studies were excluded from the meta-analysis of all outcomes because they were classified as high risk in the overall risk-of-bias assessment (Buléon et al.,

2013; S.-S. Park, 2014). Therefore, of the 16 studies, 14 were eligible for meta-analysis, though the number of studies included in meta-analysis per outcome varied.



**Figure 10.** Risk of bias assessment summary (Modified from Supplementary Figure 1 in Paper I).

### 5.1.1.2 Effect on the Quality of Chest Compressions

#### Compression Depth

All studies assessed chest compression depth; however, only 12 were included in the meta-analysis (**Table 1**). A meta-analysis of the 12 included studies revealed a significantly deeper compression [2.22 mm (95% CI: 0.88–3.55;  $P = 0.001$ )] when standalone AVF devices were used to monitor compression quality during CPR (Figure 3 in Paper I). A subgroup analysis was conducted based on risk of bias (low risk versus some concern), CPR duration (2 minutes vs. >2 minutes), and study design (crossover versus parallel). Participants in the ResuGlove groups still delivered deeper compressions than those in the standard CPR groups (Supplementary Figure 4 in Paper I).

Participants in the AVF group delivered significantly deeper compression in two of the four studies excluded from the meta-analysis (Buléon et al., 2013; Eaton et al., 2018). In most studies, the improvement did not reach the level recommended by the resuscitation guidelines. Only one study, which was assessed as having a high risk of bias, reported a significant negative effect of standalone AVF devices on the quality of compression depth during CPR (S.-S. Park, 2014).

## Compression Rate

All studies evaluated chest compression rate (**Table 1**). Studies evaluating the compression rate showed considerable heterogeneity ( $I^2 = 89\%$ ), precluding an overall meta-analysis (Figure 4 in Paper I). Heterogeneity was moderate for subgroups with “low risk of bias” and for the “two-minute CPR”, where meta-analysis was performed (Supplementary Figure 5 in Paper I). Although a slight reduction in the compression rate was observed with the use of the AVF device [-1.91 min (95% CI: -5.01–1.19;  $p = 0.25$ ) in studies with low risk, the decrease was not statistically significant. In contrast, a statistically significant decrease in the rate of compression was observed when rescuers performed CPR for 2 minutes with an AVF device [3.11 min (95% CI: -5.34–0.88;  $p = 0.006$ )].

Narrative synthesis of compression rates revealed that 8 of 16 studies reported significant differences between the standard CPR and AVF groups. In five of the eight studies, participants guided by the AVF device delivered fewer compressions per minute. One study compared three standalone AVF devices (Zoll Pocket-CPR, CPRmeter, and smartphone) with standard CPR (Zapletal et al., 2014). Once again, participants who performed CPR with Zoll Pocket-CPR and a smartphone delivered fewer compressions per minute than those who performed standard CPR. Moreover, in 11 studies, rescuers provided compressions within the recommended range outlined in resuscitation guidelines when using the AVF device. In contrast, only eight studies reported a compression rate within the recommended range of 100 to 120 compressions per minute when rescuers followed the standard CPR.

## Chest Recoil and Hand Positioning

Twelve of the sixteen included studies assessed the quality of chest recoil during CPR (**Table 1**). Only eight of these were eligible for inclusion in the meta-analysis. There was no significant improvement in the quality of chest recoil when AVF devices were used to guide chest compressions during CPR (-0.03% (95% CI: -0.59–0.52;  $p = 0.90$ ) (Figure 5A in paper I). The narrative synthesis indicated that only 2 of 12 studies documented improvements in chest recoil quality when standalone AVF devices were used to guide participants during CPR (Plata et al., 2019, 2021). Six studies evaluated correct hand positioning on the chest (Table 1). Two studies were eligible for meta-analysis, and no significant improvement was found with the use of standard AVF devices [1.97% (95% CI: -2.58–6.52;  $p = 0.40$ )] (Figure 5B in paper I). In the narrative synthesis, only 2 of the 6 studies reported improved hand placement on the chest during CPR.

#### 5.1.1.3 Effect on Skill Retention

The impact of AVF device use on skill retention was assessed in four studies (**Table 1**). Only one study reported deeper compressions at the second time point when AVF devices guided rescuers during CPR (Smereka et al., 2017). Compression rates at the second time point differed significantly across the three studies (Smereka et al., 2019; X. Dong et al., 2020; Sevil et al., 2021). This difference may not be clinically significant, as compression rates in both groups were within the recommended range. Two studies reported improvement in chest recoil at the second time point when AVF devices guided rescuers during CPR (Smereka et al., 2019; Suet et al., 2020). Two studies evaluated retention of correct hand-positioning skill, and no improvement was observed between the groups (Smereka et al., 2019; Sevil et al., 2021). Details are provided in Supplementary Table 3 of Paper I.

#### 5.1.1.4 Usability of the Standalone AVF Device

In five studies, researchers evaluated usability in terms of participants' preferences, confidence and satisfaction with the use of AVF devices during CPR (S.-S. Park, 2014; Zapletal et al., 2014; Wutzler et al., 2018; Smereka et al., 2019; Ahn et al., 2021) (**Table 2**). They evaluated satisfaction and usability using different scales. Participants' satisfaction and confidence in using real-time standalone AVF devices varied significantly across studies, with most participants favouring standalone AVF devices (Zapletal et al., 2014; Wutzler et al., 2018; Smereka et al., 2019; Ahn et al., 2021). However, a significant number of participants reported hand discomfort and pain when using rigid standalone AVF devices, as detailed in **Table 2**.

**Table 2.** Usability in terms of confidence and satisfaction with the use of the standalone audiovisual feedback device during cardiopulmonary resuscitation

Included Study	Method of Assessment	Description of the Assessment	Result
Ahn 2021	SUS	Participants completed the SUS questionnaire to evaluate the device's learnability and usability.	The mean overall evaluation score was 83.9, which was acceptable.
Park 2014	"The researcher developed a 5-point scale item to evaluate performance."	The 5-Pain Scale was administered to the smartphone group. The questionnaires were distributed after both groups completed the final CPR performance.	Many had negative opinions. The main reasons for the negativity included hand back pain (48.5%), unstable posture (21.25%), slipping (18.2%), and inaccurate compression site (6.1%).
Smereka 2019	"The subjects' confidence was measured on a 100-point scale."	"Self-assessed confidence of chest compression quality was measured with a 100-point scale (1: no confidence; 100: full confidence)."	"The self-assessed confidence in chest compression quality had a median of 71 (IQR 64–79) in the control and 91 (IQR 83–96) in the CPR group (P<.001)."
Wutzler 2018	Six-item questionnaire on self-estimation	After performing chest compressions in both groups, all participants completed a six-item questionnaire on self-estimation	Over half (54.2%) found non-feedback compressions insufficient, and among those who performed ineffective trials with the feedback device, 92.3% felt more secure using it.
Zapletal 2014	"Answers were rated on a 10-point Likert scale (most difficult = 1 to easiest = 10)."	"After performing compressions, participants rated the AVF device versus standard BLS and indicated which method they would prefer in a real-life resuscitation."	Injuries (blisters) occurred in 8 participants (13%) using PocketCPR, 7 (12%) using CPRmeter, and 7 (12%) using a smartphone, compared with only 2 participants (3%) during Standard CPR. In a hypothetical real-patient resuscitation scenario, 45% of participants preferred Standard CPR, while 53% preferred using an AVF device (p = 0.376).

**Abbreviations:** SUS = System Usability Score; CPR = cardiopulmonary resuscitation, AVF = Audiovisual feedback; IQR = Interquartile Range; BLS = Basic Life Support

### 5.1.2 Qualitative Study (Paper II)

Twenty-two participants were interviewed, including four from Ghana and eighteen from Finland. Five had over 20 years of work experience, nine had 10-20 years of experience, and eight had less than 10 years of experience (Details of participants' characteristics are provided in Table 1 of Paper II). Ten themes and twenty-five sub-themes were identified within the four UTAUT constructs (performance expectancy, effort expectancy, social influence, and facilitating conditions) that define user needs, requirements, and factors influencing the acceptability of AVF devices (Details are in Figure 1, Paper II). A detailed description of these themes and their associated sub-themes within each construct is presented below.

#### Performance Expectancy

Three themes emerged within the performance expectancy construct: perceived usefulness, outcome expectations, and applicability across various situations. Nine sub-themes were identified under these three themes. **Table 3** illustrates the themes, sub-themes, and examples of participants' quotes within the performance expectancy construct.

The result indicates that participants of the study would readily accept a newly developed AVF if they find convincing scientific evidence that the device monitors chest compression performance, provides reliable feedback, and eliminates any uncertainty. Furthermore, users would be more likely to accept a device if it offers the option to store recorded data for later use, allowing them to examine how compression and other factors were managed during CPR. Likewise, participants believed that feedback devices can help them achieve their goals more effectively if they include a feature that detects pulse during CPR and enhances attention, thereby enabling them to deliver high-quality compressions to improve survival after cardiac arrest. Participants preferred AVF devices in various sizes and shapes to accommodate rescuers with different hand sizes and to fit the chests of patients of all ages during cardiac arrest. Moreover, participants would like to adopt and use AVF devices that remain reliable even under extreme weather conditions. Lastly, they needed devices that could operate in areas without a reliable power supply (see Paper II for details).

**Table 3.** Themes, sub-themes, and samples of participants' quotes under the performance expectancy construct.

Themes	Sub-themes	Illustrative quotes
Perceived usefulness	Guidance of task performance	<i>"Students like the device because they can immediately see on the screen how fast and how deeply they are performing during CPR."</i>
	Perceived device reliability	<i>"When introducing new equipment, there is always uncertainty about its reliability. The device must be efficient and reliable to ensure there is no uncertainty about its use."</i>
	Option to store and extract data	<i>"The devices we have do not produce printed documentation of how the resuscitation was performed. It would be helpful if the device offered an option to print the recorded data so the entire team could receive feedback on its performance."</i>
Outcome Expectation	Option to detect pulse	<i>"It will be nice if I have something in my pocket that will help me detect if the patient's pulse is returned right while I am doing the chest compression."</i>
	Enhance concentration and attention.	<i>"I can see that even for an experienced person, it is incredibly helpful. When you are sure, your strength will start to fade, and your pace will slow. It is nice when the machine tells you to concentrate and pay attention."</i>
	Improved patient safety and survival	<i>"The best device should help the rescuer maintain a compression level high enough to allow patient survival."</i>
Application in Diverse Situations	Suitable for all people	<i>"If it is just a big one like that for an average adult, and then when there is a need for a younger person to do CPR, it is likely that the person using it will not be getting the right amount of pressure that the heart may require."</i>
	Tolerance to extreme weather situations	<i>"Yes, its cover must be rain- or water-resistant so that at least the inner part of the most engineering or technical mechanical aspect is protected. Sometimes you may be in an area where it is raining, and the device may be disturbed by the rain."</i>
	Reliable and portable power supply	<i>"In Ghana, we have a problem. When it comes to power in the city, we have a proven problem. So, if you come up with any device that uses a lot of power, we will face a problem. It should not consume much power and be rechargeable. It would be great if we could get a solar aspect on it."</i>

### Effort Expectancy

The effort expectancy construct included two themes: user-friendliness and perceived complexity. Six sub-themes were identified under these two themes. **Table 4** illustrates the themes, sub-themes, and samples of participants' quotes under

the effort expectancy construct. Participants in this study realised that devices that are easy to learn and use are preferable for CPR training and patient resuscitation. Most participants stated that it was easier to accomplish their tasks when the AVF devices were small and lightweight and provided clear, easy-to-interpret feedback. Participants occasionally felt overwhelmed by the complexity of the AVF devices, which was associated with difficulties in transport, complex feedback, and challenges in device operation. Participants explained that transporting heavy equipment, along with other resuscitation equipment, poses challenges that may affect the acceptability of large AVF devices. Similarly, audio feedback from AVF devices can sometimes be excessive and confusing, particularly for laypersons, hindering their acceptance and use. Nonetheless, devices that display graphic or digital feedback on small screens were also difficult to read and interpret, particularly in stressful situations. Therefore, the level of complexity depends not only on the device itself but also on the context in which it is used.

**Table 4.** Themes, sub-themes, and samples of participant quotes under the effort expectancy construct.

Themes	Sub-themes	Illustrative quotes
User friendliness	Easy to learn and use	<i>"The devices must be easy to use and adopt, so that they do not require extensive preparation or numerous tasks to remember before use."</i>
	Clear and easy feedback	<i>"The devices should provide feedback on a limited set of precise parameters, such as depth and frequency. It should not provide excessive information, as understanding complex feedback may reduce the quality of CPR."</i>
	Portable and lightweight	<i>"We had a defibrillator with integrated feedback devices, which was significant and challenging to use. We have a smaller one, and it does not seem cumbersome to use. When we go to resuscitate, it is good that our hands can carry all the stuff that we must take there."</i>
Perceived Complexity	Difficult to transport	<i>"Well, we carry a lot of stuff to the floors or wherever we go. Of course, carrying a kilo bundle is more fun than a 50-kilo bundle. Therefore, the feedback devices should be compact and lightweight, with all features integrated. Making the devices as light and small as possible makes our work much more manageable."</i>
	Provide complex feedback	<i>"If the device says, 'press harder' and then suddenly 'you are pressing too hard,' it can confuse and discourage the lay rescuer. They may already feel unsure in the situation, and constant corrections can lead them to believe they are doing everything wrong. A layperson might even stop resuscitation, believing they cannot do it properly."</i>
	Challenging to work with	<i>"When first confronted with these devices, users are often unsure how to interpret them or what they mean. For a layperson, this can be challenging, especially without prior guidance. In my view, it is key to overcoming the usability challenges of these devices. Ideally, the device should be designed so that, whenever it is activated or worn, it automatically provides a brief and precise summary of the required steps."</i>

## Social Influence

The social influence construct consisted of two themes: social factors and organisational influences. Four sub-themes were identified under these two themes. **Table 5** illustrates the themes, sub-themes, and participants' "quotes" under the social influence construct. Although the social influence construct received the least attention during the interviews, two interesting themes emerged within it: social and organisational factors. Many participants agreed they would be motivated to adopt a new AVF device after seeing their colleagues use it correctly. They also tended to trust their senior supervisors' skills and competence and were ready to adopt the AVF

device based on their supervisors' advice. According to participants' experiences, the organisation directed them to use newly introduced devices and had no say in their purchase or implementation. Although they did not participate in introducing the new devices, they were happy to accept any device the organisation introduced, as most had full confidence in the organisation and a positive experience with its previous devices.

**Table 5.** Themes, sub-themes and samples of participants' quotes under social influence.

Themes	Sub-themes	Illustrative quotes
<b>Social factors</b>	Colleagues' influence	<i>"If a colleague recommends a device, it suggests they had a positive experience, so I trust their choice, but I would still want some instructions. I also assume my seniors are experienced and will follow their example in using the device."</i>
	Senior managers' influence	<i>"I think I should assume that my senior might have experience with it. So, whether he is well-trained in the use of it or not, I can trust the experience and could also use it in the same way after I see my manager using it."</i>
<b>Organisational factors</b>	Organisational decision	<i>"Decisions are usually made without informing workers. They do not discuss them at all with the people who use them. We now have a new device. Yesterday, however, we were unaware that such a new device was coming. I would be prepared to implement my organisation's requirements, as I could not do much about them."</i>
	Organisation recommendations	<i>"Well, of course, as a professional, I like to use it if my organisation wants me to use it because it gives a good analysis of the quality of the pressure and that it is effective, so that we can provide the best possible treatment."</i>

### Facilitating Factors

Participants discussed several factors that facilitate the acceptance of AVF devices, grouped into three main themes: staff competence, perceived cost, and device compatibility. Six sub-themes were identified under these three themes. **Table 6** illustrates the themes, sub-themes, and participants' "quotes" within the facilitating factors construct. Participants agreed that regular training enhances users' knowledge and skills, increasing the acceptance of AVF devices. For example, Participants from Ghana were hesitant to adopt the new technology unless they had access to qualified technicians and reliable spare parts. Based on their experience, devices introduced without qualified technicians and spare parts become nonfunctional and are discarded shortly after implementation.

Device cost was among the most frequently discussed issues across all interviews. The majority viewed the high cost of the devices as a barrier to the

diffusion of a new AVF technology. However, it seemed that not only the high cost of the devices, which affects adoption, but also the financial situation of adopting institutions and countries, was a factor. For instance, most Finnish respondents thought that only unreasonably high costs could hinder the adoption and use of these devices. Conversely, individuals from Ghana view cost as a significant obstacle to adopt these AVF devices (Detailed information in Paper II).

A few respondents preferred the physical integration of AVF devices with other multifunctional devices, such as defibrillators, because it is easier to remember these devices. The respondents agreed that new AVF technologies need to be functionally compatible with existing devices in various departments. They observed that devices with similar functions in hospitals or other community settings, such as shopping centres, could be easily adopted (see Paper II for details).

**Table 6.** Themes, sub-themes and samples of participants' quotes under facilitating factors

Themes	Sub-themes	Illustrative quotes
<b>Staff competence</b>	Availability of maintenance technical skills	<i>"We need to identify the device brand, ensure replacement parts are available, and develop a maintenance plan and the skills to keep it running for at least five years."</i>
	Availability of Staff training and knowledge	<i>"Indeed, we need training; even if the device itself is easy, all devices still require some form of training. In general, training is essential for both professionals and laypeople."</i>
<b>Perceived Cost</b>	Financial capacity of the institutions	<i>"If they are of very high quality and priced in a way that individuals or organisations cannot easily afford, then only a few will have access to them in their lives, although every life is precious."</i>
	Cost of the AVF devices	<i>"The devices should include only the most essential components to minimise costs. It should be a critical device that supports survival but should not include unnecessary components that increase cost."</i>
<b>Compatibility</b>	Functional compatibility with other devices	<i>"Feedback devices used in public areas, such as shopping centres, should be compatible with those in emergency units and assess the same parameters in the same way. When the emergency team arrives at the site, they should be able to connect it to their own and continue working with it."</i>
	Physical integrity with other devices	<i>"It is beneficial when the feedback device integrates with the equipment you use, so that it is always with you in a sensible way. It does not need to be remembered separately in any way, but it is an integral part of the equipment that is used anyway."</i>

## 5.2 Phase II: Design and Prototype Development

The proof-of-concept study (Paper III) summarised the iterative design process of a sensor-embedded, flexible wearable ResuGlove that monitors and provides feedback on the quality of chest compressions during CPR. The findings of the proof-of-concept study demonstrated that the soft, flexible wearable ResuGlove, embedded with resistive pressure sensors and IMU, is promising for accurately detecting compression metrics, including compression depth, compression rate, and chest recoil. However, much remains to be done in terms of technical development and usability to make the devices suitable for CPR training and real patient resuscitation. A more detailed account of the sensor setup, accuracy evaluation, and user experiences is presented in the following sections.

### 5.2.1 Sensor Layout

Both the accelerometer and the pressure sensors are used in this ResuGlove design to complement each other in monitoring chest-compression parameters. The accelerometer sensor (IMU) complemented the resistive pressure sensors to increase depth and rate detection accuracy. Conversely, resistive pressure sensors placed on the palm proved to be an appropriate complement to the accelerometer for monitoring complete chest release. Although three pressure sensors were installed on the palm side of the prototype right-hand ResuGlove, the analysed data suggested that a single pressure sensor on the outer palm (Sensor 1, **Figure 8A**) might be sufficient to supplement the IMU. The sensor located on the upper palm (Sensor 2 in **Figure 8A**), beneath the locking fingers, was suitable only for rescuers who use the locking-finger technique during chest compressions in CPR (For more details, refer to Figure 11 in Paper III). The third sensor, located near the thumb, appears to offer no significant advantage in providing reliable readings (Sensor 3 in **Figure 8A**).

### 5.2.2 ResuGlove Accuracy

To evaluate accuracy, results were presented using three different metrics: instantaneous depth error, depth estimate error, and frequency estimate error. Instantaneous depth error denotes the positional error between the new device estimate and the ultrasonic ground truth at each time point. The depth-estimate error was the difference between the depth estimates for each compression provided by our method and the ultrasonic distance. The researchers observed that focusing on individual compression depth improved the accuracy of depth estimation, reducing the instantaneous depth error from  $\mu = 0.04049$  meters,  $\sigma = 0.03487$  to  $\mu = -0.00996$  meters,  $\sigma = 0.02337$ . In the case of instantaneous error, it tends to overestimate depth

and exhibits high variability; however, when depth is measured at the level of individual compressions, the error diminishes significantly and shows less variability. Hence, the current method was not suitable for monitoring instantaneous hand positioning; however, it was relatively effective in assessing individual compression depths (see Figure 12 in Paper III).

The frequency-estimation error was the difference between the compression rate estimated by the ResuGlove and the reference value from the ultrasonic ground truth. Although some outlier estimates appeared, the frequency estimates based on the peak-to-peak difference were nearly perfect. An average error of 8.162 Hz with an interquartile range (IQR) of 0 was achieved. This finding was anticipated because the primary frequency remains unchanged by data filtering, and the frequencies derived from both displacement and ultrasonic ground-truth data were calculated using the same peak-to-peak estimation method.

### 5.2.3 User Experience

Involving users in the development of medical technologies is crucial because it helps account for users' needs, ideas, and experiences. This can improve device designs and user interfaces, thereby increasing usability, functionality, and device quality (Shah & Robinson, 2007). For example, during our iterative development of the ResuGlove prototype, glove size significantly affected the quality of chest compression. Although the sensor-embedded glove fits various hand sizes, wearing it on a large palm increases the risk of sensor damage, whereas on smaller hands, it increases the risk of sensor displacement and increased friction for rescuers, potentially resulting in inadequate compression.

Additionally, the material used in the ResuGlove prototype was ineffective at absorbing sweat, which may compromise rescuers' comfort during prolonged compressions and raise hygiene concerns during actual patient resuscitation. Some participants reported that excessive sweating during compressions increased friction, causing discomfort. Many also expressed concerns about hygiene and the time needed to switch from one rescuer to another during real patient resuscitation, which could unnecessarily prolong compression interruptions.

Finally, the pressure sensors were somewhat flexible. However, their size limited the glove's adaptability to palm movements and affected its fit on rescuers' hands and palms. Nonetheless, the results suggest that the number and size of sensors can be reduced without compromising their ability to monitor chest compression quality.

## 5.3 Phase III: Effectiveness and Usability Testing

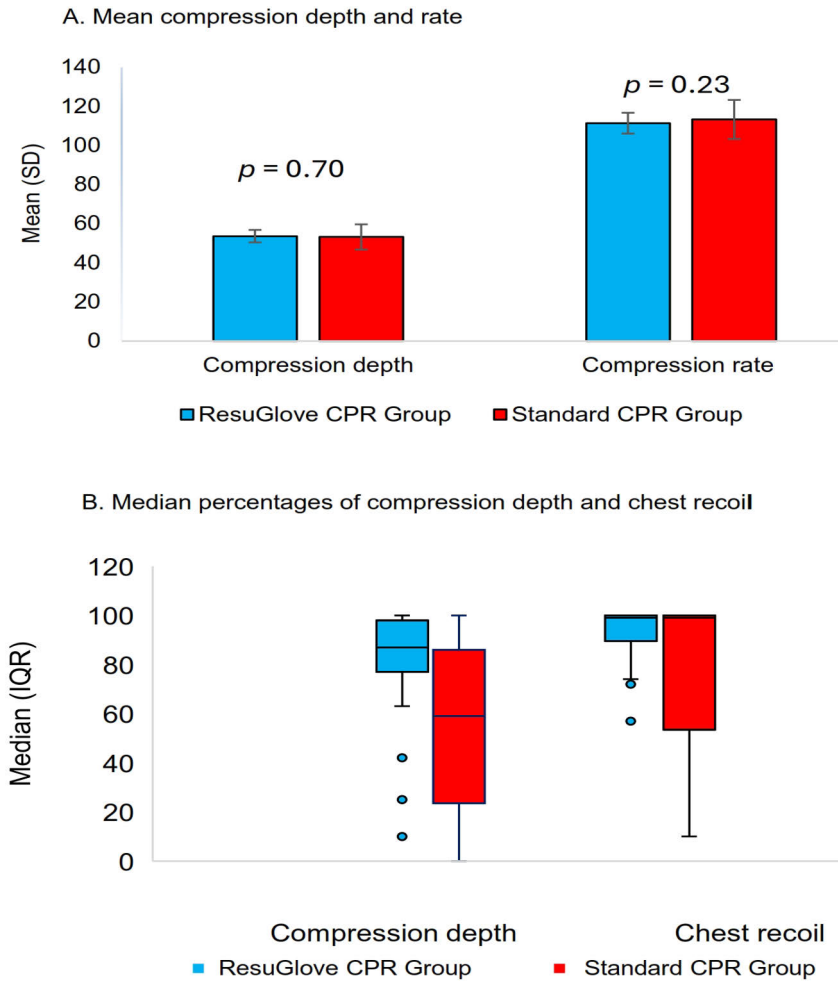
In the third phase of device development (prototype testing), a simulation-based randomised crossover trial (Paper IV) was conducted to assess the effectiveness of the designed ResuGlove prototype in terms of compression depth, rate and chest recoil. To evaluate the usability of the designed ResuGlove prototype, participants completed the SUS survey right after performing 2 minutes of chest compressions guided by the ResuGlove. This study provided empirical evidence on the device's effectiveness and usability in a controlled simulated CPR scenario.

A total of 29 nursing students from Turku University of Applied Sciences participated in this study. All students had basic resuscitation training, and the majority (79.3%) were women (details of the participants' demographic characteristics are shown in Table 1 of Paper IV).

### 5.3.1 ResuGlove Effectiveness

Data was examined to determine if there was a significant difference in mean compression depth and compression rate between the standard CPR group and the ResuGlove CPR groups. No statistically significant differences were observed between the two groups in terms of mean compression depth in mm (53.69 vs. 53.28,  $p = 0.70$ ) and the mean compression rate per minute (111.48 vs. 113.38,  $p = 0.23$ ) (**Figure 11A**). However, participants using the ResuGlove achieved a significantly higher proportion of compressions at adequate depth, with a median of 87% (IQR 77–98%), compared to those performing CPR without guidance from the ResuGlove, median of 59% (IQR 23.4–86%),  $P = 0.006$  (**Figure 11B**).

The median percentage of complete chest recoil was the same in the two groups. Nevertheless, the finding indicated that the difference between the two average ranks was statistically significant, favouring the ResuGlove CPR Group, with a median of 99% (IQR, 89.5–100%) versus the standard CPR Group, with a median of 99% (IQR, 53.5–100%),  $P = 0.008$ . Although the median remains the same in both groups, the lower quartile differs significantly between them (ResuGlove CPR Group: 89.5% vs. Standard CPR Group: 53.5%), which explains the significant difference between the two groups (Details are provided in Figure 4 of Paper IV).

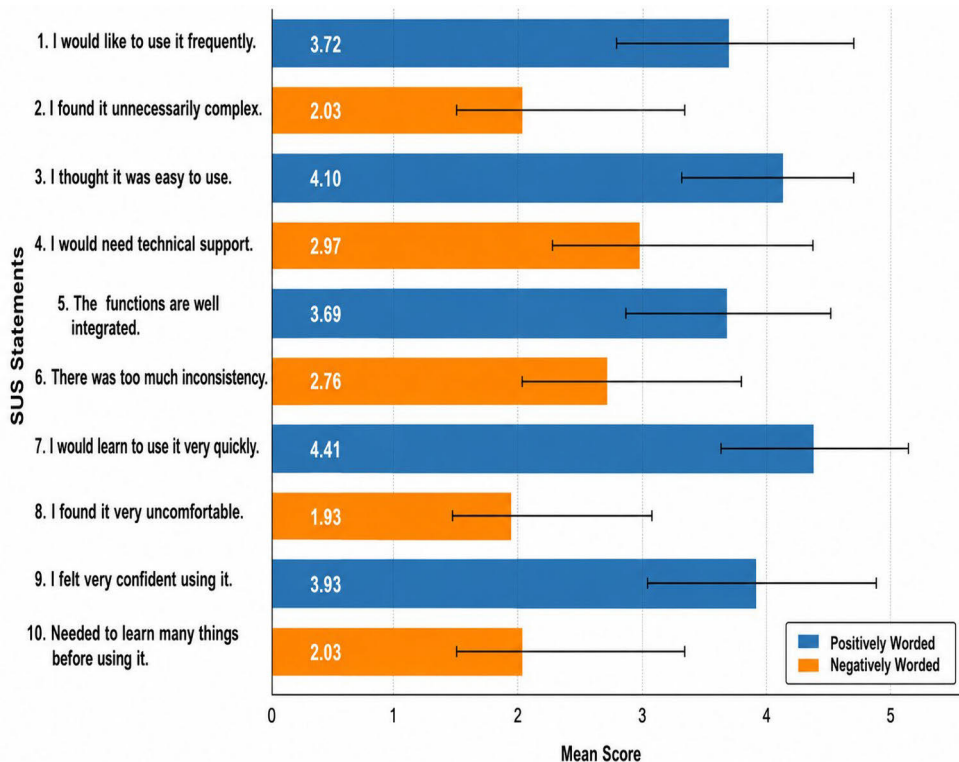


**Figure 11.** The outcomes of chest compression parameters. Modified from Figure 3, Paper IV.

The data were also analysed to determine whether there was a significant difference between the two groups in the number (proportion) of patients who performed adequate chest compressions, as measured by compression depth (50-60 mm), rate (100-120 per minute), and complete chest release. The McNemar's test showed that a significantly larger number (proportion) of participants guided by the ResuGlove achieved chest compressions at adequate depth (ResuGlove CPR 82.8% vs Standard CPR 41.4%;  $P = 0.001$ ) and rate (ResuGlove CPR group 96.6% vs Standard CPR group 72.4%;  $P = 0.012$ ) than those in the Standard CPR Group. No improvement was observed in the number (proportion) of participants who achieved complete chest release with the use of ResuGloves (ResuGlove CPR 48.3% vs Standard CPR group 48.3%;  $P = 1.00$ ) (For details see Table 2 in Paper IV).

### 5.3.2 ResuGlove Usability

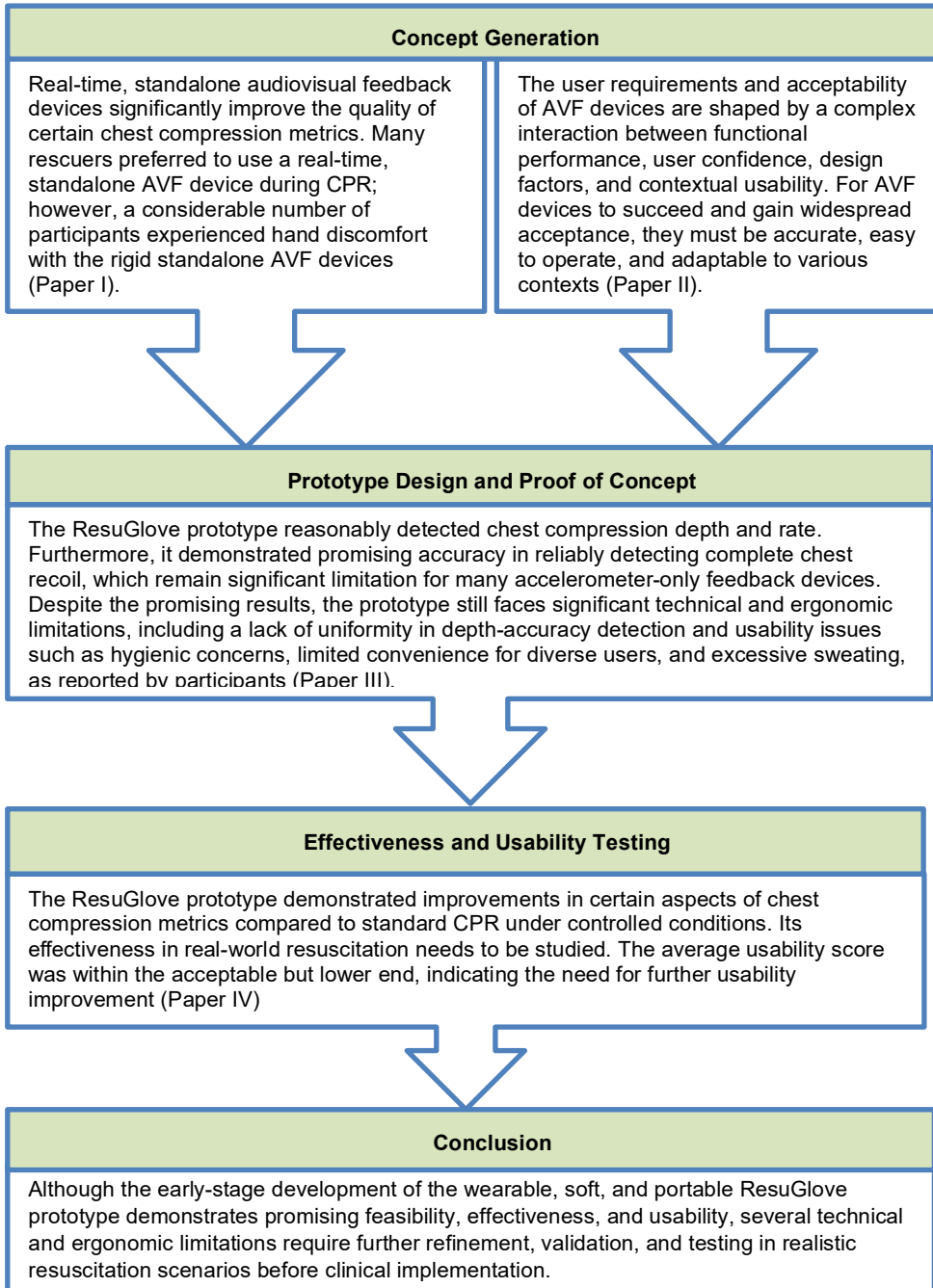
Finally, we evaluated the usability of the ResuGlove using the SUS questionnaire. According to Bangor et al., evaluating product acceptability based on the SUS score involves classifying usability into three categories: acceptable (above 70), marginal (between 50 and 70), and unacceptable (below 50) (Bangor et al., 2008). The ResuGlove's usability SUS average score was 70.4 out of 100.



**Figure 12.** Mean Ratings for System Usability Scale Statements.

In addition to the average score, the mean and standard deviation for each item were calculated to identify the specific aspects of each statement. The maximum possible positive and negative scores were 5. All odd items reflecting positive usability aspects had scores above 3, and all even items reflecting negative aspects had scores below 3. The subjective ratings indicated that the device was “easy to learn”, “able to learn quickly”, “comfortable”, and “not too complex”. However, some participants rated the device as inconsistent and reported needing technical support to learn to use it. Details of the average scores for the 10 SUS usability assessment items are presented in **Figure 12**.

## 5.4 Summary of the Results



**Figure 13.** Summary of the findings.

# 6 Discussion

This work focused on the development and evaluation of an early-stage, real-time, wearable feedback device for monitoring the quality of chest compressions during CPR. The results of the four sequential and complementary studies, informed by user insights, iterative design, and experimental testing, demonstrated the feasibility and potential of the wearable ResuGlove for monitoring and providing real-time feedback on chest-compression quality during CPR. The novel ResuGlove AVF device has significant potential to improve CPR quality by minimising rescuers' hand discomfort and enhancing secure wearability at the compression site, which reduces the risk of errors caused by displacement during CPR. It also has the potential to better detect leaning during compressions and improve chest recoil by integrating pressure sensors and accelerometers into a single device. At the same time, the findings underscore key technical, usability, and contextual challenges that must be addressed during the device's future refinement. The following discussion critically interprets these results, examines the strengths and limitations of the work, outlines directions for future design and research, and considers the broader implications for clinical practice and research.

## 6.1 Discussion of the Results

The first two studies (Papers I and II) informed the design of soft, flexible, and real-time standalone AVF devices by exploring gaps in the literature (Paper I) and by defining user requirements and factors affecting the acceptability of real-time AVF devices (Paper II). The systematic review (Paper I) revealed that real-time standalone AVF devices can improve specific chest-compression metrics, but not to the level recommended by international resuscitation guidelines. Moreover, despite greater satisfaction and confidence with the standalone AVF devices, a significant number of rescuers reported increased discomfort and hand pain with the rigid standalone AVF devices. The interview-based qualitative study (Paper II) revealed that a complex interaction among functional performance, accuracy and reliability, design factors, and contextual usability shapes user requirements and the acceptability of real-time AVF devices. The two studies conducted in the first phase of development, therefore, yielded significant findings that informed the iterative design of the

ResuGloves prototype. The iterative design of the ResuGlove prototype is summarised and reported in the proof-of-concept study.

The proof-of-concept study (Paper III) demonstrated that a soft, flexible, secure, hand-adaptable, standalone AVF device, equipped with pressure and accelerometer sensors, could be a feasible and viable alternative to currently available rigid, real-time AVF devices placed between the rescuers' hands and the patient's chest during CPR. It has the potential to reduce rescuers' hand discomfort, reduce chest injury in patients, minimise sensor displacement during CPR, and enhance the likelihood of full chest release. However, the finding also demonstrates that the device, in its current form, has several limitations. These include the need to improve sensor accuracy, address potential discomfort caused by glove size and excessive sweating, and overcome durability and integration challenges. These issues require careful attention during future refinement and development.

A randomised crossover simulation study revealed that the ResuGlove improved some chest compression metrics compared with standard CPR (Paper IV), an encouraging finding. Future simulation and clinical studies should compare the device with similar standardised real-time AVF devices to determine the specific advantages of the ResuGlove over marketed standalone AVF devices, particularly in reducing discomfort and minimising errors caused by sensor displacement. The usability of the designed device was also encouraging, with the average score falling within the acceptable range. However, the usability score was at the lower end of the acceptable range, indicating that further work is needed to improve the device's usability and user acceptance in real-world settings.

This work contributes to the growing body of evidence supporting the development of technology-assisted CPR. Besides, it deepened our understanding of the interdisciplinary UCD processes required to address users' real needs. The development of the ResuGlove is ongoing, as significant work remains on technical design and ergonomics to ensure a proper fit between the device's function, its intended purpose, and the needs of end users before it can be used for CPR training and patient resuscitation.

The subsequent sections analyse the results from each phase of the study in detail, reflecting on the evolution of user needs, design choices, and performance evaluation throughout the development process. Discussion of the developmental phases provides a comprehensive overview of the ResuGlove's development and evaluation, highlighting key insights, challenges, and areas requiring further refinement.

## 6.1.1 Phase I: Idea Generation and Concept Development

This section starts by discussing the results of the first phase of development, which includes two initial studies: a systematic review (Paper I) and a qualitative needs assessment (Paper II). These studies aimed to identify gaps in the literature and to understand user needs and requirements to inform the UCD of the ResuGlove.

### 6.1.1.1 Systematic Review

In recent years, multiple reviews have assessed the effectiveness and usability of AVF feedback devices for CPR (Kirkbright et al., 2014; Miller et al., 2020; Gugelmin-Almeida et al., 2021; Lv et al., 2022). However, explicit evidence regarding the effectiveness and usability of real-time standalone AVF devices when used specifically by laypersons was lacking. This systematic review (Paper I) was therefore conducted to explicitly examine the strengths and limitations of these real-time, standalone AVF devices with respect to their effectiveness and usability for laypersons.

Although there was no consistent improvement across all compression metrics, there is substantial evidence that standalone AVF can help laypersons in delivering deeper compressions at a rate closer to the recommended range of 100-120 per minute. This finding aligns with previous systematic reviews that reported significant improvements in one or more of the evaluated chest compression metrics when AVF devices were used to guide chest compression quality during CPR (Kirkbright et al., 2014; Gugelmin-Almeida et al., 2021).

Interestingly, compression depth appears to be the parameter most positively affected when rescuers use AVF devices during CPR. Both the meta-analysis and the narrative synthesis revealed that participants guided by the feedback devices achieved significantly deeper compressions than those delivering standard CPR. This finding is important because evidence indicates that achieving an appropriate compression depth is often more difficult than maintaining the correct compression rate when inexperienced rescuers perform CPR (Lund-Kordahl et al., 2019). Lund-Kordahl et al. (2019) compared three groups of individuals with varying levels of training and found that those with advanced CPR training performed significantly deeper compressions. In contrast, the compression rate did not differ significantly across groups and remained within acceptable limits in all groups (Lund-Kordahl et al., 2019). Similarly, in many studies included in this review, participants performed compressions within the recommended range of 100–120 per minute in both groups (See Figure 4 in paper I). This indicates that, unlike compression depth, it is much easier for laypersons to adjust their compression rate to the recommended range, with or without guidance from AVF devices.

Although compression rate typically remained within the recommended range in both groups, participants who performed CPR guided by standalone AVF devices delivered fewer compressions per minute. Consistent with our findings, a previous meta-analysis of pooled data reported an average reduction of approximately 10 compressions per minute when participants used feedback devices during CPR on simulated manikins (Kirkbright et al., 2014). If the compression rate remains within the recommended range, this decrease may indirectly facilitate rescuers' delivery of deeper compressions. During standard CPR, learners tend to compress the chest more quickly than recommended, and an increase in compression rate was associated with premature fatigue, leading to shallow compression depth (Agostinucci et al., 2021; Zhang et al., 2013). Real-time AVF devices could therefore enhance the quality of chest compression depth by assisting rescuers in adjusting compression rates to reduce fatigue (Zhang et al., 2013).

This review found no conclusive evidence that real-time standalone AVF devices are superior to standard CPR in achieving complete chest release or improving correct hand position. Contrary to our findings, one systematic review reported significant improvement in the percentage of complete chest release when feedback devices guided rescuers during chest compression (Gugelmin-Almeida et al., 2021). One possible reason for the variation in the findings could be differences in the target study populations. In their review, Gugelmin-Almeida et al. (2021) included studies targeting healthcare professionals skilled in CPR. In contrast, the target population in our review were rescuers with no prior experience in actual patient resuscitation. Another possible reason could be the difference in AVF device types used in the studies included in the two systematic reviews. We included studies that used only standalone AVF devices, whereas Gugelmin-Almeida et al. (2021) included studies that evaluated both integrated and standalone AVF devices.

Three of the four studies that evaluated skill retention demonstrated a significant improvement in at least one compression metric at the second time point when laypersons used standalone AVF devices during simulated CPR (Smereka et al., 2019; Suet et al., 2020; Sevil et al., 2021). Hence, although no consistent improvement was observed across all compression metrics, the evidence indicates that standalone AVF devices were, to some extent, beneficial in enhancing skill retention. This finding aligns with previous systematic reviews reporting the benefits of AVF devices for enhancing skill acquisition and retention in CPR training (Kirkbright et al., 2014; Gugelmin-Almeida et al., 2021). It appears that CPR skills were better retained when refresher CPR training was provided at shorter intervals using standalone AVF devices, as recommended by the resuscitation guidelines (Greif et al., 2021). One study evaluated CPR skill retention after one month (Smereka et al., 2019), rather than after three months (Suet et al., 2020; Sevil et al., 2021). Unlike other studies that reported improvements in only subsets of chest

compression metrics (Suet et al., 2020; Sevil et al., 2021), Smereka et al. (2019) found significant improvements in CPR skill retention across all assessed compression parameters when rescuers were retrained at 1-month intervals using standalone AVF devices.

Five studies included in this review evaluated usability in terms of satisfaction, confidence and preference using various tools. Although participants' satisfaction, confidence, and preferences varied across studies, most favoured standalone AVF devices over the standard CPR. In line with our findings, a previous study reported that 66% of participants preferred AVF devices over instructor-guided feedback during CPR training for health professionals (Wilson et al., 2021). Effective chest compressions rely on specific compression metrics, making it challenging for teachers to subjectively and precisely identify inadequate compression depth, rate, and recoil during CPR (Wilson et al., 2021). This may explain why rescuers preferred objective feedback from AVF devices to instructor-based subjective feedback during CPR training.

Despite favouring real-time AVF devices during chest compressions, many participants reported negative experiences when using rigid, standalone AVF devices during CPR. This may degrade compression quality, leading to adverse outcomes during real-patient resuscitation. For example, in one study, approximately half (48.5%) of participants reported hand pain, 21.25% reported unstable posture, and 18.2% reported their device slipping while in use (S.-S. Park, 2014). In another study, there were reports of 8 (13%), 7 (12%), and 7 (12%) injuries (blisters) when participants used PocketCPR, CPRmeter, and smartphone, respectively, compared to a 2 (3%) injury rate in the case of Standard CPR (Zapletal et al., 2014).

In line with our findings, several previous studies also reported a high rate of hand discomfort when rescuers used the rigid standalone AVF devices during CPR. For instance, in a study by Perkins et al., 95% of rescuers experienced hand discomfort while using the CPREzy device during CPR (Perkins et al., 2005). Similarly, Hong et al., in their letter to the editor, disclosed that 38.9% of students sustained hand injuries when the CPRmeter was used as a standalone feedback device during CPR training (Hong et al., 2016). These findings suggest that, for effective chest compressions and improved outcomes in CPR, standalone AVF devices must be comfortable, as CPR itself can be exhausting for rescuers. Hence, soft, flexible wearable devices that can be placed securely and as close as possible to the compression site may have advantages over currently marketed rigid, inflexible standalone AVF devices in minimising discomfort and fatigue during CPR.

### 6.1.1.2 Qualitative Study

Understanding user needs, organisational characteristics, and the intended environment for use are the first steps in developing a safe, effective, and acceptable medical device (Tsai et al., 2023). Hence, this user-based qualitative study (Paper II) aimed to define the requirements and explore the factors affecting the acceptability of AVF devices. Ten themes were identified within the four UTAUT constructs that define user requirements and acceptability of AVF technologies. Perceived usefulness, outcome expectations, and applicability across diverse situations were identified within the performance expectancy construct. User-friendliness and complexity are two themes included under the effort expectancy construct. Organisational and social factors are the two main themes of the social influence construct. Lastly, the facilitating factors construct comprised three themes: device compatibility, perceived cost, and staff competence.

Performance expectancy is “the degree to which an individual believes that using the system will help him or her attain gains in the job”(Venkatesh et al., 2003). In the current study, the perceived usefulness of AVF devices in monitoring and guiding the quality of chest compression performance was frequently highlighted as the primary factor influencing the acceptability of AVF devices among healthcare professionals in CPR. Our results align with earlier studies that characterised technology usefulness as a crucial determinant of health device adoption (Asadi et al., 2019; Q. Yang et al., 2022).

Some participants preferred AVF devices that could detect the return of a heartbeat (pulse) and provide feedback on the quality of chest compressions. Furthermore, respondents state that AVF devices should be accurate, reliable, and capable of storing data for various purposes, including debriefing and research. They were against devices that present extraneous information, because CPR is inherently a stressful and exhausting situation (Vincent et al., 2021), and such unnecessary extraneous information may compromise the quality of CPR and potentially jeopardise positive patient outcomes.

Users can recognise medical devices as safe, convenient, and efficient if researchers and designers accurately identify user types and the contexts in which the devices will be used, thereby facilitating the diffusion of developed health technologies (Money et al., 2011; Bitkina et al., 2020). Therefore, AVF device design must align with the intended use and context to ensure smoother user acceptance (Bitkina et al., 2020), enabling institutions to avoid unnecessary investment in multiple devices. Participants from Ghana, for example, reported that AVF devices that do not account for frequent power shortages cannot be easily adopted and used in their health institutions, as has been previously reported in other African countries (Namatovu et al., 2021; Akinnuwesi et al., 2022). Some participants from Finland were also concerned about the acceptability of an AVF

device, which cannot tolerate extreme weather conditions, such as sauna temperatures and freezing temperatures of up to -40 degrees Celsius. Therefore, designers and researchers of medical devices need to consider how best to respond to the environments and contexts in which they are intended for use (Piaggio et al., 2021). For the above-mentioned reasons, involving users in the early stages of the development process helps researchers and designers to understand the usability and acceptability requirements of the medical device in the intended context (Money et al., 2011; Bitkina et al., 2020), even though achieving all requirements at one time was proven to be impossible. Although expected effectiveness is critical, it is insufficient on its own. User-friendliness also plays a key role in the acceptance and use of AVV devices.

In general, user-friendly medical technologies that are easy to operate and maintain are more likely to be widely accepted and implemented than those that are complicated to learn and challenging to operate (Metelmann et al., 2021; Wingen et al., 2024). According to the participants in this study, small, lightweight devices that combine all functions in one place would be more readily accepted and adopted than large, heavy AVF devices, which are burdensome to carry alongside other resuscitation equipment. These findings align with previous research, which has shown that users favour lightweight, easy-to-use wearable heart-monitoring technologies (Ferguson et al., 2020). The type of feedback provided by the AVF device also appears to affect its acceptability and usability. According to the participants, excessive audio feedback from an AVF device has occasionally been distracting, which could lower the quality of chest compressions during CPR. Additionally, users had difficulty reading visual feedback on small screens, which might affect CPR quality. This underscores the importance of meticulous design of AVF devices, not only to ensure their technical functionality and effectiveness but also to account for human factors to enhance usability and acceptability by end users (Guthrie et al., 2017; Kong et al., 2019).

Some participants preferred AVF devices integrated into defibrillators because they offer experienced healthcare professionals a range of options. Nevertheless, many agreed that operating the various features of more advanced devices can pose significant challenges for inexperienced health professionals and laypersons. Furthermore, devices that appear easy to use in controlled settings, such as simulation scenarios, can be more complex and confusing when used on patients in cardiac arrest, owing to the added stress of fearing further harm to the patient (Malta Hansen et al., 2017). This implies that AVF devices designed for actual patient resuscitation should be even simpler to operate than those intended for training in a controlled environment. Therefore, our findings and those of previous researchers highlight the strong need to improve the user-friendliness of existing devices to support laypeople in performing CPR (Metelmann et al., 2021), a process that

requires the involvement of health professionals and other users in the development process of health technologies (Guthrie et al., 2017). The acceptance and use of the AVF device can also be influenced by other users and by organisational decisions and recommendations.

Participants were ready to adopt and use the AVF device recommended by trusted colleagues and senior supervisors, especially after seeing it used safely and effectively. This finding aligns with previous studies, which have identified social influence as a key factor impacting the acceptance and adoption of new systems or technologies (Namatovu et al., 2021; Akinnuwesi et al., 2022). Individuals tend to accept and use new medical devices if they observe those around them using the devices with utmost safety (Akinnuwesi et al., 2022). Conversely, participants reported that insufficient support from colleagues and senior managers may negatively affect the acceptability and uptake of new health technologies.

Organisational benefits, culture, and expectations may positively or negatively influence the behavioural intention to adopt and use new technologies (Akinnuwesi et al., 2022). Organisational influence is particularly important in hierarchical healthcare settings, where decisions on procurement and implementation are often made at the management or institutional level (Venkatesh et al., 2003). Watkinson et al. observed that in some healthcare organisations, end-users were not directly involved in technology implementation, as these processes were primarily managed by information technologists and organisational change teams (Watkinson et al., 2021). Similarly, participants in the current study reported being unaware of when new medical devices were introduced, as their opinions were seldom considered in decisions to implement or adopt them. As a result, they often followed organisational recommendations and decisions rather than making independent choices about adopting and using new medical devices. Such top-down decision-making processes may encourage compliance, but do not necessarily lead to optimal use, as health professionals' perceptions of usefulness and their willingness to adopt new technology are key determinants of implementation (Borges do Nascimento et al., 2023).

Furthermore, facilitating conditions, defined as the degree to which an individual believes that an organisational and technical infrastructure exists to support the use of these AVF devices (Venkatesh et al., 2003), also mediate acceptance of these AVF devices. In this study, the three main themes identified under the facilitating conditions influencing the acceptability and adoption of AVF devices were staff competence, perceived cost, and AVF device compatibility.

Regular training for users is expected to improve the attitudes, skills, and knowledge of staff members regarding the safe and proper use of medical devices (Doyle et al., 2017; Maamri et al., 2024; Rettinger et al., 2024). In the current study, participants with extensive experience with AVF devices reported significantly

higher confidence in their knowledge and skills. In contrast, users with little or no exposure to AVF devices appeared to have lower confidence in using the device, suggesting a need for tailored training and support for users with limited experience, as noted in a previous study (Kuek & Hakkennes, 2020). Users with less experience should receive appropriate training to increase productivity and help them take full advantage of innovation, thereby enabling organisations to reap its full benefits (Han et al., 2020). Interestingly, respondents from Ghana viewed the lack of spare parts for the devices and the absence of individuals possessing the technical expertise to repair faulty devices as significant barriers to adoption. A study conducted in Uganda identified similar barriers during the implementation and adoption of e-health for women's antenatal care practices (Namatovu et al., 2021), highlighting the impact of technical expertise on the adoption of new technologies in resource-limited settings.

According to a previous systematic review, various evidence-based approaches are employed to balance the technical, financial, safety, and clinical requirements of device selection, involving a multidisciplinary team (Hinrichs-Krapels et al., 2022). According to participants in our study, regardless of the purchasing process, the cost of the AVF device and the organisation's financial strength significantly influence adoption. As Venkatesh et al. have shown, the price usually has a positive impact on the intention of using a technology if the perceived benefits of the technology outweigh the monetary cost (Venkatesh et al., 2003). This condition appears to be applicable only in Finland, where participants were more concerned with quality than with cost. In contrast, respondents in Ghana perceive cost as the primary obstacle to adopting new AVF technology. This suggests that high-quality medical devices designed for developed countries may never be accepted in countries and organisations with limited resources (Malkin, 2007; Piaggio et al., 2021). In fact, most participants advocated for devices compatible with existing technology and infrastructure, which could substantially reduce implementation and maintenance costs. This finding aligns with previous studies that have documented a positive association between technology compatibility and user acceptability (H. Yang et al., 2016; Akinuwesi et al., 2022).

In summary, the initial phase, involving a systematic review and user needs assessment, revealed important gaps and clarified essential user requirements for effective, user-friendly feedback devices. Findings from these studies laid an evidence-based, user-focused foundation for designing the ResuGlove. Building on this, the following section discusses the design and prototype development process, in which these insights were translated into tangible design solutions.

## 6.1.2 Phase II: Design and Prototype Development

The proof-of-concept study (Paper III) outlined and discussed the iterative design and development process for the ResuGlove prototype, based on requirements identified through the systematic review (Paper I) and user interviews (Paper II) in the initial phase of device development.

Setting priorities among various options and alternatives is a key step in product design and development (Berander & Andrews, 2005). As a result, the second phase of the development process commenced after multiple brainstorming sessions to define the identified gaps, needs, and requirements. After multiple brainstorming sessions, researchers agreed to focus on designing and testing a device prototype to address compression depth, compression rate, and chest recoil, as these are the most vital elements of chest compression metrics for improving CPR quality (Olasveengen et al., 2021). The ResuGlove has a feature to detect compression interruptions, but testing of this feature was deferred for future study, as the focus of this early-stage device development was on the above-mentioned chest compression metrics.

Sensor-embedded wearable devices have become popular and play a significant role in healthcare due to their benefits, including being lightweight, comfortable, flexible, and cost-effective (S. M. Ali et al., 2025). Similarly, after discussing various design options and materials to address the identified gaps, brainstorming participants proposed a textile-based, soft, flexible, hand-adaptable, portable wearable resuscitation glove featuring embedded pressure and accelerometer sensors that monitor and provide feedback on the quality of chest compressions (details are described in paper III). The flexible design is intended to minimise the possible risk of rescuers' hand discomfort associated with rigid standalone real-time AVF devices (Elding et al., 1998; Perkins et al., 2005; Buléon et al., 2013). Secure wearability and sensor placement on the palm in direct contact with the compression site are expected to prevent sensor displacement while maximising the likelihood of obtaining accurate data on compression quality. Most previously developed and tested wearable, standalone AVF devices have focused on improving compression depth and rate using accelerometer sensors (Aase & Myklebust, 2002; Dellimore et al., 2013; Hermann et al., 2021; S. Lee et al., 2021). In contrast, our design supplemented the accelerometer sensor with pressure sensors to effectively monitor chest recoil, which is a vital component of high-quality CPR (Kouwenhoven et al., 1960; Eijk et al., 2024)

The device development in this study integrated expertise from clinical research, engineering, design, and data science to develop innovative solutions that address limitations of existing real-time AVF devices. Multidisciplinary teams have the potential to develop innovative solutions that bridge traditional disciplinary boundaries, combining the knowledge and skills of multiple disciplines to produce

more effective, safe, and user-friendly devices (Mohammadiounotikandi, 2023). Multidisciplinary approaches proved to be a significant strength of this study. During development, engineers and designers initially found it challenging to grasp the clinical importance of chest compression metrics and the impact of this device design on user performance and patient outcomes. Meanwhile, clinical researchers lacked detailed knowledge of textile properties and sensor technologies. Therefore, continuous collaboration among these disciplines from the early stages of development was vital to ensure that the design's technical aspects align with clinical needs and user requirements.

The design employed rapid prototyping techniques, enabling the simultaneous identification and specification of requirements for materials, technology, wearability, and accuracy throughout the development process. The development of ResuGlove incorporated RtD framework into the design process to generate new knowledge by gathering information from the design itself (Bayazit, 2004). It emphasised the importance of using both qualitative and quantitative evaluation methods to guide decision-making at different development stages. Modern technological innovation depends on transparent knowledge transfer through open-source collaboration, which breaks traditional organisational boundaries and facilitates the free exchange of knowledge (Chen & Zhou, 2025). Once this project is complete, all necessary files and algorithms will be made publicly available to support ongoing development. Therefore, the iterative design process, guided by the principle of RtD, focused not only on creating a market-ready product but also on building prototypes and exploring opportunities beyond the immediate device (Stappers & Giaccardi, 2014). In this way, RtD is an approach in which the design process serves as an investigative method for generating knowledge (Stappers & Giaccardi, 2014; Prochner & Godin, 2022).

The proof-of-concept results showed excellent performance of the ResuGlove in monitoring the compression rate, with reasonable depth-tracking accuracy. Compared to a previous similar study that employed a bandpass method for a wrist-worn device (Hermann et al., 2021), the ResuGlove device showed greater errors, with a median absolute difference of 8.7 mm (Hermann et al = 4.5 mm) and higher variability, with an IQR of  $-25.0$  to 5.6 mm (Hermann et al = 2.3 to 7.8 mm). Three main factors negatively affected the depth accuracy of the ResuGlove prototype. The first was the use of an ultrasonic sensor in the ground-truth measurements, which yielded noisy results despite filtering. The second factor was the placement of the IMU sensor on the back of the hand, which was less accurate than the sensor placed on the palm side in direct contact with the compression site. Rescuers' hands bouncing due to the spring inside the manikin's chest was another reason for the lower accuracy. Therefore, despite relatively higher reported errors with the ResuGlove, it demonstrated reasonable accuracy, which is expected to improve

further when actors contributing to these inaccuracies are addressed in future refinements of the ResuGlove design.

The proof-of-concept small-scale user test revealed that the two-hand sensor setup increased noise, thereby raising the risk of errors. Future work integrating both pressure and IMU sensors into a single glove in direct contact with the compression site is expected to reduce errors and enhance CPR quality. Therefore, once fully developed, the ResuGlove is expected to address some of the limitations of currently available real-time AVF feedback devices. However, readers should note that this has not yet been demonstrated clinically, as no simulations or clinical studies have compared the ResuGlove prototype with standardised existing wearable or other real-time AVF devices. Conducting these comparative studies will be part of the researchers' future development plan. Thus, the early-stage development summarised in the proof-of-concept study was crucial, providing essential insights that guided ongoing prototype refinement and future research and development.

The prototype design selection focused on low-cost, accessible materials, making it suitable for use at the community level and in resource-limited settings where advanced, expensive, and complex devices are not readily available (Kalu et al., 2022). It is important to remember that resource-limited settings are not always confined within national borders, as high-income countries can also have regions and communities with limited resources (Schnaubelt et al., 2023). Therefore, the device is intended for use in regions, communities, and institutions in any country or region where the most expensive and complex devices are not readily available. Nevertheless, it is important to recognise that the device is in its early stages of development, and participants in the proof-of-concept study have already identified multiple usability issues that must be addressed during subsequent refinement and development before it becomes available for CPR training and real patient resuscitation.

Participants, for example, reported discomfort associated with device size and increased sweating during compressions. Although the sensors retained some of the material's elasticity as expected, the multilayer sensor construction limited the glove's adaptability to palm movements. The size of the sensors also affected the glove's fit on rescuers' hands and palms. As this proof of concept suggests, usability issues related to sensor size can be addressed by reducing the number and size of sensors in future refinements and developments, without compromising their ability to monitor chest compression quality. User discomfort and hygiene issues related to excessive sweating can be mitigated in future development by selecting materials that facilitate easy observation of perspiration, such as moisture-wicking fabrics (Y. Dong et al., 2015).

According to the participants, the ResuGlove could be helpful in monitoring and providing feedback during CPR training. However, during team-based real-patient

resuscitation, switching or sharing the glove between providers was seen as time-consuming and impractical, as it takes a significant amount of time to take it off and fit it to another rescuer's hand during CPR. There was also concern that if multiple devices are planned, with each user having their own disposable pair of gloves during CPR, the devices may become prohibitively expensive, particularly for resource-limited settings. Therefore, researchers and designers should consider developing a fast-donning design (Seim et al., 2022), such as the Palmar strap system, that can be easily removed and shared among rescuers without disrupting compressions during CPR.

Another usability concern raised by participants in the proof-of-concept study was the use of the device to resuscitate children and infants during CPR. Chest compressions in infants, for example, are performed either with both thumbs or with two fingers of one hand (Madar et al., 2021). Therefore, placing the pressure sensors on the palm of the right-hand glove and the IMU sensor on the dorsal side of the left-hand glove may not be practical for these age groups. Future research and design should consider a new version of the ResuGlove by positioning sensors on the fingers to enhance usability in infant resuscitation, as previously reported (Dellimore et al., 2013). The selected materials and techniques enabled the development of an affordable, readily accessible CPR tool that can be replicated without advanced textile manufacturing or laboratory facilities. Therefore, although the current prototype is designed for adult rescuers and adult cardiac arrest scenarios, it can be easily adapted to fit different hand sizes and hand positioning techniques for resuscitating children and infants.

In conclusion, the second phase of development focused on translating identified gaps and user needs into the iterative development of a novel ResuGlove to monitor chest-compression quality during CPR. In this phase, key functionality and ergonomic features were refined iteratively through a UCD approach. While the proof-of-concept study confirmed the device's feasibility and viability, its practical usefulness ultimately depends on real-world performance. Therefore, the next section discusses the effectiveness and usability of the ResuGlove, highlighting how well its design achieves its intended goals in a simulated CPR setting.

### 6.1.3 Phase III: Effectiveness and Usability Testing

#### Effectiveness evaluation

The quality of chest compressions was assessed from various perspectives (Paper IV), including the mean compression rate and depth, the proportion of adequate compression depth and chest recoil. Researchers also analysed the number (percentage) of participants who attained the recommended compression depth, rate,

and chest recoil. The study revealed that using ResuGloves with feedback mechanisms improved specific chest compression metrics compared with standard manual compressions, a finding consistent with previous reviews (Kirkbright et al., 2014; Sood et al., 2023)

Although compression with a minimum depth of 50 mm is recommended to improve patient outcomes, rescuers often struggle to achieve the minimum compression depth during standard CPR (Stiell et al., 2012; Vadeboncoeur et al., 2014). ResuGlove was effective in reducing the percentage of rescuers who delivered a compression depth less than 50 mm (37.9% in standard CPR vs. 17.2% in ResuGlove CPR). This initial finding suggests that, when fully developed, the ResuGlove is expected to help rescuers deliver deeper compressions, thereby improving patient outcomes. This is because previous studies documented a positive correlation between deeper compressions and improved patient outcomes (Stiell et al., 2012; Vadeboncoeur et al., 2014). The percentage of rescuers who delivered compressions exceeding the upper limit of 60 mm decreased from 20.7% to zero, indicating that the newly designed device could also be essential in preventing excessive deep compressions and thus reducing the risk of unintended patient injuries, such as rib fractures (Hellevuo et al., 2013). A study that investigated the possible relationship between compression depth and CPR injuries found a rise in the incidence of rib fractures and other organ damage when compression depth exceeded 60 mm (Hellevuo et al., 2013), a finding that could be addressed by this newly designed device.

Similarly, our findings aligned with another study that documented a significant increase in the number of rescuers who achieved a compression rate of 100-120 per minute when using AVF devices (Lin et al., 2020). In the previous study, compression rates exceeding the upper limit (120 per minute) were more common than those below the lower limit (100 per minute) during standard CPR, a pattern corrected by a real-time AVF device (Lin et al., 2020). This was also a key finding in our study. For example, 20.7% of the standard CPR group delivered an average compression rate above the upper limit ( $> 120$ ), which was reduced to 3.5% when participants delivered CPR guided by the ResuGlove prototype. These findings suggest that the unnecessary high compression rates observed during standard CPR decreased with the use of the AVF device, as previously reported (Lakomek et al., 2020). This is an interesting finding because a decreased compression rate has been correlated with improved compression depth (Agostinucci et al., 2021). Although this study was conducted using manikins and the results cannot be directly applied to actual patient resuscitation, ResuGlove may have the potential to enhance outcomes during real patient resuscitation, as even a small increase in compression depth directly impacts survival (Stiell et al., 2012; Vadeboncoeur et al., 2014).

Complete chest recoil is essential between compressions to enable full chest expansion and generate negative intrathoracic pressure, which draws blood back into the chest and heart (Kouwenhoven et al., 1960; Lurie et al., 2016; Eijk et al., 2024). Our systematic review found no substantial improvement in chest recoil quality when laypersons performed CPR guided by standalone AVF devices (Paper I). Interestingly, the crossover manikin-based randomised trial revealed a significant difference in chest recoil quality between the two groups, with participants monitored and guided by the ResuGlove feedback showing a greater degree of complete chest release between compressions. This initial finding is promising, as the newly designed ResuGlove appears to outperform other standalone AVF devices in detecting leaning during the decompression phase, an important compression component often overlooked in many recently designed wearable devices (S. Lee et al., 2021; Musiari et al., 2021; Xie & Wu, 2023; LaPrad et al., 2024). Pressure-sensor input was used alongside accelerometers during ResuGlove development to enhance the accuracy of chest recoil detection. This may explain why the study of the ResuGlove has revealed promising findings in identifying leaning and in guiding rescuers to optimise chest recoil.

### Usability Evaluation

Usability of the ResuGlove was evaluated using a quantitative method, employing the SUS questionnaire (Bangor et al., 2008). The SUS usability score of 70.4 indicates that the newly developed ResuGlove is acceptable. However, it falls at the lower end of the range, suggesting that further ergonomic improvements and feedback enhancements during subsequent development could elevate usability to an excellent level. Our findings align with previous studies, which have demonstrated that the use of real-time, wearable AVF devices to monitor the quality of chest compressions was within an acceptable range (Ahn et al., 2021; Xie & Wu, 2023). This implies that wearable technology might be a sensible and practical substitute for the stiff, detachable real-time AVF devices (Perkins et al., 2005; Zapletal et al., 2014).

Statements regarding learnability and usability were the two most highly rated aspects among participants in this study, indicating that ResuGlove could be convenient for inexperienced rescuers. This is an important finding because evidence suggests that user-friendly wearable medical devices are readily adopted and accepted by users (Yin et al., 2022). Similarly, participants rated the ResuGlove as comfortable to use, suggesting it may reduce rescuers' hand discomfort associated with existing rigid, standalone AVF devices (Perkins et al., 2005; Hong et al., 2016). This is a promising finding, as the main purpose of the study was to demonstrate a multidisciplinary approach to developing a soft, flexible, standalone AVF feedback

device that is comfortable for both rescuers and patients. However, this study was conducted in a controlled simulation environment with a small sample size using manikins. Hence, further research with a larger sample size on patients experiencing actual cardiac arrest is necessary to verify whether the promising findings from simulation can be replicated in real-world settings.

Nevertheless, items regarding the need for technical support and device inconsistency received the lowest scores. Many participants reported needing technical support to use the device and rated it as having some inconsistencies. Several factors may have led some participants to rate the SUS statements lower, resulting in a SUS Score at the lower end of the acceptable range. It was observed that even after participants adjusted the compression metrics to the normal range, the device continued to send corrective feedback for a few seconds before recognising that the error had been corrected. This inconsistency may have contributed to the low usability score. This limitation of the ResuGlove needs to be addressed in later stages of development, as it may frustrate users by making them feel they are not performing well.

In this study, only one ResuGlove size was available, with some flexibility to accommodate different hand sizes. As a result, some rescuers might find the device uncomfortable due to excessive tightness, leading to sweating, which could impact the usability score. The ResuGlove prototype was designed assuming that the right hand is placed directly on the patient's chest. Therefore, all participants were asked to place their right hand on the manikin's chest in indirect contact with the compression site, although some preferred to place their hand at the bottom. This could also lower the SUS usability rating for some items, affecting the overall usability score.

The findings of this study highlight the potential and feasibility of a user-centred, wearable AVF device for improving CPR performance, while also revealing important challenges in design, accuracy, and usability. While the discussion of the results provides valuable insights, it warrants interpretation in the context of methodological rigour, which addresses the strengths and limitations of the studies at different stages of development.

## 6.2 Strengths and Limitations of the Study

In research, rigour encompasses the entire research process, from start to finish, ensuring the integrity and quality of the final research outcomes (Laher, 2016; Cypress, 2017; Shaheen et al., 2023). It refers to the extent to which the researcher strives to reduce bias and enhance quality to ensure the reliability of findings (Alele & Malau-Aduli, 2023). Methodological soundness, the accuracy of the results, and the integrity of the assumptions are considered when evaluating research rigour (Liu,

2017). Flaws in approach, design, execution, analysis, interpretation, and reporting indicate that a study was conducted with insufficient rigour (Sansbury et al., 2022). Researchers disagree on the terminology used to evaluate rigour in research (Cypress, 2017; Liu, 2017). According to the positivist approach, rigour in quantitative research is characterised by high reliability and validity (Liu, 2017; I. M. Ali, 2024). In contrast, according to the interpretive approach, the rigour of qualitative research is characterised by credibility (internal validity), transferability (external validity), dependability (reliability), and confirmability (Guba & Lincoln, 1994; Liu, 2017). The aim of the study always guides the choice of research approach. This study, therefore, employed a sequential design, involving researchers from diverse backgrounds and utilising mixed research methods, thereby increasing internal consistency, methodological rigour, and real-world applicability.

### 6.2.1 Systematic Review (Paper I)

To ensure rigour in a systematic review, researchers must clearly define the research question, develop a coherent and well-structured protocol, conduct comprehensive literature searches, maintain transparency in data extraction, critically assess the included studies, and adhere to reporting guidelines and checklists (Batten & Brackett, 2021; Brackett & Batten, 2022).

Similarly, to enhance the rigour of this systematic review (Paper I), the research question was clearly defined using the standard PICO format, accurately reflecting the inclusion criteria and aligning well with the objectives of the review (Aromataris et al., 2015; Brackett & Batten, 2022). A comprehensive protocol detailing the research question, review process, and research outcomes was developed and registered in PROSPERO (reg. CRD42020205754) prior to the initial search, as recommended by the “Cochrane Handbook for Systematic Reviews of Interventions” (Higgins, 2020). Registering the review protocol in public registration databases enhanced transparency and methodological rigour (Brackett & Batten, 2022).

A comprehensive search of five databases was conducted to identify published articles without language restrictions, to minimise bias (Appendix 1). Multiple database searches guarantee a thorough search that encompasses a range of perspectives and disciplines relevant to the research question (Gusenbauer, 2022). Information specialists assisted in developing search strings for the five databases, and an experienced researcher in database searching conducted electronic searches to enhance accuracy and minimise errors (Shaheen et al., 2023). The systematic search did not include grey literature such as dissertations, conference papers, and ongoing studies, which could have further enhanced the rigour of this systematic review (Paez, 2017). Additionally, only randomised trials were included in the

systematic review. This omission is an important limitation that readers should bear in mind when interpreting the findings of the systematic review.

Data extraction and quality assessment of the individual studies were performed using the standardised Cochrane extraction template and RoB 2.0 for randomised trials, respectively, to increase the reliability of the extracted data (Higgins, 2020). Two independent reviewers conducted the data extraction and quality assessment to minimise errors, as recommended by the Cochrane Handbook for Systematic Reviews of Interventions (Higgins, 2020). However, the studies included in this review were conducted in only a few Asian and European countries, which may compromise their generalisability across other regions (ecological validity) (Shadish et al., 2002; Laher, 2016). Most participants in the included study were young university students enrolled in health sciences. This profile is different from that of the community-level rescuers who are most likely to witness cardiac arrest and initiate CPR. As a result, the findings of this review may not accurately reflect laypeople's performance in CPR in the general population (population validity) (Shadish et al., 2002; Laher, 2016).

There was considerable variation among the included studies regarding data analysis, devices used, and sample sizes. As a result, conducting a meta-analysis for all outcomes was not possible. Even the studies included in the meta-analysis showed moderate heterogeneity, which should be considered when interpreting the conclusions of this systematic review and meta-analysis. To enhance the validity of the findings, researchers employed narrative synthesis alongside meta-analysis. Moreover, the Prisma reporting checklist was followed to ensure transparent, comprehensive, and accurate reporting of the results (Page et al., 2021).

### 6.2.2 Qualitative Study (Paper II)

The degree of confidence or trust that readers have in the qualitative findings is usually referred to as trustworthiness (Schmidt & Brown, 2021). The quality, genuineness, and precision of qualitative research findings are all factors that contribute to their trustworthiness (Cypress, 2017). Hence, trustworthiness is the central concept in frameworks aimed at appraising the rigour of a qualitative study (Cypress, 2017), which is evaluated using four criteria models: credibility, transferability, dependability, and confirmability (Guba & Lincoln, 1994; Liu, 2017; Sansbury et al., 2022). Various methods and actions were employed to strengthen the rigour of this qualitative study.

## Credibility

Credibility is related to the “true value obtained from the discovery of human experiences as they are lived and perceived by participants” (Liu, 2017). Credibility can be achieved through various methods, including but not limited to prolonged engagement at a site, peer debriefing, triangulation, and member checks (Liu, 2017).

In this study, researchers conducted extended interviews with participants, allowing sufficient time to understand the phenomenon under study, thereby enhancing the credibility of the findings (Liu, 2017). The researchers conducting the interviews were familiar with the situation and the participants, which may help to build trust and minimise misunderstandings. However, researchers' familiarity with the situation may also lead to social desirability bias, in which the researcher's characteristics influence participants' responses (Bispo, 2022).

Peer review was achieved by sharing the research process and findings with peers for feedback and critique, facilitated through several meetings and discussions with experienced qualitative researchers. Triangulation was achieved by collecting data through focus groups, dyadic, and individual interviews, all of which revealed similar themes, thereby reinforcing the credibility of the findings. A member check involves sharing findings with participants to ensure that their views and experiences were appropriately taken into account (Liu, 2017; Cypress, 2017; Johnson et al., 2020; Sansbury et al., 2022). Member check was not performed, which is a limitation of the study. However, given the researchers' experience in qualitative research, we believe that the participants' views and experiences have been accurately reflected in the data analysis.

## Transferability

“Transferability refers to the applicability of a study's findings to other similar contexts or situations” (Liu, 2017). Transferability can be achieved by employing purposive sampling and providing a detailed description of the data that enables others to compare it with similar contexts (Liu, 2017; Sansbury et al., 2022). To enhance rigour, purposive sampling was used in this study to explore the issue from participants with diverse professional backgrounds and geographical locations (Liu, 2017; Sansbury et al., 2022). To ensure a broader range of perspectives and gather a diverse selection of data and experiences, the maximum variation sampling method was employed (Kuper et al., 2008). Transferability was further enhanced by providing a detailed description that included a wide range of information (Johnson et al., 2020; Sansbury et al., 2022), such as the data collection process, the number and characteristics of participants, the study's geographical location, and the timeframe for data collection and analysis.

Sampling was stopped once a thorough understanding of the topic was reached, a process often known as saturation (Kuper et al., 2008). Researchers consider sampling saturation as having been reached when additional interviews no longer yield new concepts, categories, or themes (Elo & Kyngäs, 2008; Kuper et al., 2008). During the analysis, every effort was made to document the findings as transparently as possible to ensure that the report is accurate and reliable. Moreover, the interview questions and data analysis were guided by a widely used theoretical framework (UTAUT), thereby enhancing the accuracy and transferability of the findings.

### Dependability

Dependability in qualitative research refers to the consistency of findings over time (Ahmed, 2024). The results can be replicated by other researchers when studying similar subjects in comparable contexts (Liu, 2017). The dependability of the qualitative study was established through transparent and thorough descriptions and documentation of the methods, data collection procedures, and analysis. The first author primarily conducted the data analysis but consistently consulted with experienced co-authors to ensure the trustworthiness of the results. There is a risk that the researchers' experience with device use and resuscitation may have influenced the interviews and data analysis, potentially leading to social desirability bias, a common limitation of qualitative research (Bispo, 2022). However, to minimise this social desirability bias, the study process, analysis, and findings were reviewed and commented by external reviewers, allowing other researchers to reproduce the results (Ahmed, 2024).

### Confirmability

Confirmability (neutrality) refers to the degree to which a qualitative research finding is derived from participants' narratives and viewpoints, rather than being heavily influenced by the investigator's subjective assumptions and biases (Liu, 2017; Kakar et al., 2023; Ahmed, 2024). In this study, confirmability was established by documenting the process, which showed how the codes, themes, and sub-themes emerged from participants' perspectives and narratives, enabling readers to follow the reasoning behind the study's findings and conclusions. Confirmability of the qualitative study was further strengthened by including direct quotes (Tables 3 to 6) from participants to ensure the investigators' neutrality in reporting the findings (Kakar et al., 2023). To avoid the bias and subjectivity inherent in a single researcher, the process of collecting, analysing, and interpreting the data was conducted in consultation with experienced coauthors. Additionally, the final report underwent

peer review and was published in an open-access journal, making it publicly accessible (Paper II).

### 6.2.3 Proof-of-Concept Study (Paper III)

The proof-of-concept study outlined the development process for the ResuGlove prototype, including brainstorming sessions, sensor selection, textile glove design, and sensor integration. It also summarised the in-house feasibility and viability testing of its use for monitoring chest compression quality during CPR, involving both CPR experts and laypersons. The rigour of this proof-of-concept study was ensured by adhering to the RtD framework and by involving interdisciplinary experts, including health professionals, engineers, designers, and data scientists, to enhance methodological consistency and transparency. Incorporating professionals from various fields, including health researchers, enhances the product's quality by blending diverse knowledge and experience and providing thorough insights into real needs, practical challenges, and the requirements of medical devices (Ushimaru et al., 2025). This approach supports the dissemination of new knowledge via scientific publications. For instance, one study highlighted the significant advantage in knowledge dissemination when academicians participated in medical device production, as most publications were mainly authored by healthcare professionals (Ushimaru et al., 2025).

The prototype design was guided by gaps identified through a systematic review (Paper I) and a user needs analysis (Paper II), thereby enhancing the relevance and acceptability of the designed device. In addition, the methods and steps for sensor selection and integration are clearly described to ensure technical reproducibility and transferability (Paper III). The validity of the ResuGlove was addressed by aligning it with the ERC guidelines and measuring key chest compression performance metrics (Olasveengen et al., 2021). Validity was further enhanced through user-prototype in house testing to assess feasibility and viability, thereby enhancing its clinical relevance.

Some estimates of compression parameters showed significant variability, which could affect the accuracy of the resuscitation glove. The implications of these limitations, along with potential future solutions, are critically discussed in the discussion section to ensure transparency and transferability (Paper III). The transparency and reproducibility of the study were further improved by the researchers' decision to publish the proof-of-concept study as open access and their commitment to open-source dissemination of designs and algorithms. However, the small sample sizes in the prototype's preliminary feasibility testing may limit the reproducibility and generalisability of the findings across populations.

Our experience shows that multidisciplinary innovation and research also face significant challenges that must be addressed in the early development phase to avoid delays and potential misunderstandings among participants. For example, a significant challenge was the misalignment of priorities: engineers and designers focused on technical feasibility, whereas clinical researchers emphasised usability and safety. There was also a challenge related to domain-specific knowledge and basic understanding of the scientific language used in each profession, which affected the project's progress. These challenges could be addressed by 1) training engineers and designers in clinical courses, and 2) educating healthcare professionals in the fundamentals of design and biomedical engineering (Chandra, 2013). Furthermore, coordinating a project involving a cross-professional team with distinct workflows, work cultures, and schedules was challenging. Therefore, it is essential to establish a clear roadmap and foster trust among the multiprofessional teams from the outset of the collaboration, as individuals tend to trust professionals from the same domain more than those from other professions (M. Nguyen & Mougnot, 2022).

#### 6.2.4 Effectiveness and Usability (Paper IV)

The rigorous randomised crossover design of this study is a key strength because it reduces inter-individual variability and enhances internal validity (Lim & In, 2021). Each subject served as their own control, which minimises the effect of confounding factors due to participants' demographic characteristics (Dickerson, 2014), improving the precision of measurements between the ResuGlove and the standard CPR groups. It also minimises the allocation imbalance commonly observed in parallel designs, thereby reducing bias and increasing the likelihood that the observed differences are due to the treatment under study rather than to pre-existing differences between groups (Madurasinghe, 2017; Lim & In, 2021).

The data were analysed using a suitable statistical technique for a crossover design, including period, carryover, and treatment-effect testing. The potential carryover and period effects, which are common concerns in crossover designs (Lim & In, 2021), were carefully assessed, and no statistically significant evidence of bias was observed. An adequate sample size was estimated for this study based on a minimum mean difference, the within-subject standard deviation, and a significance level of 0.05 (two-sided) with a power of 0.8 (details in Paper IV). Although this sample size was sufficient for early-stage prototype testing, future studies should include a larger sample to increase statistical power and enhance the reliability of the findings (Kemal, 2020).

Another key strength of the study was the use of validated instruments to assess both chest compression performance and the usability of the ResuGlove. We used

the Laerdal Resusci Anne Q CPR manikin with the Laerdal Q CPR feedback app to objectively measure and record chest compression performance (Laerdal, n.d.). This manikin is widely used as a standardised tool in training and research, thereby enhancing the reliability of findings. Similarly, the SUS questionnaire is a reliable and popular tool for assessing the usability of various innovations and technologies (Bangor et al., 2008; Weenk et al., 2020).

Furthermore, the study protocol has been registered on ClinicalTrials.gov under NCT05695469 to enhance transparency and minimise unnecessary duplication of research. Furthermore, researchers adhered to the CONSORT reporting checklist to ensure clear and transparent reporting of the findings. This report checklist helps researchers present the research question, methodology details, results, discussion, and conclusion more clearly and transparently (Dwan et al., 2019).

Despite its strengths, the study had some limitations which should be considered when interpreting the results. The study was conducted in a controlled simulation environment using a manikin, which is often appropriate for testing prototypes and assessing training quality. This differs considerably from the high-pressure context of real patient resuscitation, which limits the ecological validity and real-world applicability of the findings (Andrade, 2018). Additionally, the study involved a homogeneous group of young, healthy nursing students who received basic life support training. Recruiting such participants may limit the generalizability of the findings to other populations, including older adults, untrained laypersons, and rescuers with existing medical conditions. Furthermore, double blinding of participants and researchers was not feasible given the nature of the AVF device's use in the experimental group. This could introduce bias and potentially compromise the study's credibility (Madurasinghe, 2017).

Participants performed chest compressions for only two minutes, whereas actual patient resuscitation often continues for a significantly longer period. Therefore, participants may not have experienced discomfort and fatigue to the same extent as they would during longer CPR durations. In addition, at this stage, the ResuGlove provides audio feedback, and the feedback algorithm is designed to prioritise a single error at a time (e.g., compression depth). As a result, the device's current sequence error-correction model does not adequately address multiple compression errors that may occur during CPR training or patient resuscitation.

In summary, interpreting the results alongside a thorough discussion of methodological rigour provides a balanced understanding of the study's contributions and limitations. These insights not only contextualise the findings but also highlight remaining gaps and unresolved challenges. Accordingly, the next section outlines suggestions for future research and design to address these limitations and further enhance the development and real-world application of the ResuGlove.

## 6.3 Suggestions for Future Design and Research

Building on the discussion of the findings and the interpretation of the strengths and limitations above, multiple opportunities emerged to inform future design and research aimed at further developing the ResuGlove. While the current work provides initial evidence of the ResuGlove's feasibility and potential value as a feedback device, important gaps remain in usability, real-world applicability, and long-term effectiveness. The following design and research suggestions aim to inform the next phase of development and investigation, with a focus on optimising performance, acceptability, and impact across diverse resuscitation contexts.

### 6.3.1 Suggestions for Future Design

The preliminary feasibility test revealed that the two-hand sensor setup increased noise and raised the risk of errors. Therefore, future designs should consider integrating both resistive pressure and IMU sensors into a single glove, which is expected to reduce errors and potentially cause less interference with high-quality CPR performance. A single size of the ResuGlove prototype was created specifically for people who prefer to keep their right hand on the bottom during compressions. As a result, it was uncomfortable for those who prefer to keep their hands on the bottom during compression. Additionally, although it was made from a flexible material to accommodate different hand sizes, it was prone to breakage when worn on large hands. Therefore, future work should focus on modifying the device to accommodate all hand sizes and on making it available to both right- and left-handed rescuers.

The wearability of the ResuGlove should be carefully considered in future refinement, as some participants reported excessive sweating, which may compromise hygiene, and expressed concern about the time required to exchange it with another rescuer if one becomes exhausted during real patient resuscitation. There were also concerns about its final cost if it were made disposable, as it would likely be more expensive than many marketed devices, making it unsuitable for resource-limited settings. Future designs should address these wearability and usability issues to ensure the device is accessible, comfortable, and affordable, thereby promoting its acceptability, equity, and sustainability.

In the current prototype, ResuGlove incorporates an audio feedback system that prioritises feedback based on predetermined criteria, as it is not possible to provide audio feedback for multiple compression errors simultaneously. Future work should consider incorporating additional feedback systems, such as visual feedback or a combination of audio and visual cues, to ensure that all compression errors are identified and corrected simultaneously. Moreover, when a standalone real-time AVF device is designed, the feedback system is typically embedded within the

device, eliminating the need to connect it to external, more expensive feedback sources, such as laptops and smartphones. The current ResuGlove prototype, however, remains connected to a laptop and relies on an external device for audio feedback. Therefore, the device should be refined to operate autonomously, generating internal feedback to improve portability, affordability, and accessibility.

### 6.3.2 Suggestions for Future Research

The ResuGlove device developed in this research was compared with standard CPR only. Therefore, it should be validated against an equivalent, previously validated standalone AVF device used in training and actual patient resuscitation. In accordance with ERC Resuscitation guidelines, all communities, including school-age children, should be taught and regularly practice CPR to improve the chances of a positive patient outcome. Therefore, the device's feasibility should be tested with a diverse group of users, including laypeople without CPR training, to assess its suitability for use in a community setting by non-certified individuals.

Only nursing students from Finland participated in testing the ResuGlove prototype to assess its effectiveness and usability. In the future, users from resource-limited settings and countries, such as those in sub-Saharan Africa, as well as healthcare professionals from other disciplines, including medical doctors, paramedics, and pharmacists, should be included to evaluate the feasibility, viability, and acceptance of this device in these regions and institutions.

In addition, rather than relying solely on quantitative or qualitative usability testing, a mixed-methods approach should be used to comprehensively assess the usability of the ResuGlove. Moreover, because the ResuGlove is still in early development, only simulation-based usability tests have been conducted to date. Therefore, future research should consider evaluating the effectiveness, safety, and usability of the ResuGlove using a larger sample in real patient resuscitation scenarios.

## 6.4 Implications to Clinical Practice and Research

- The findings of this study will remind device manufacturers, researchers, educators and clinicians that soft, flexible, wearable, real-time, standalone AVF devices could be the best options for reducing the pain and discomfort experienced by rescuers when using rigid, inflexible AVF devices during CPR.
- Furthermore, ResuGlove is a wearable device with sensors securely positioned on the rescuer's palm to guarantee direct contact with the compression site. This is expected to reduce the risk of sensor

displacement and improve measurement accuracy during compression, which needs to be verified in later development steps of the device.

- Although much work is still needed, once fully developed, ResuGlove can be used for both training and real patient resuscitation situations, creating a smooth transition from classroom training to real patient resuscitation, where rescuers are trained and practising with the same device, improving performance when using familiar devices in a stressful situation.
- Most standalone AVF devices focus solely on monitoring compression depth and rate, with insufficient attention to chest recoil. In contrast, the ResuGlove device features an interface that is expected to reliably provide feedback on the quality of full chest recoil, an essential component of chest compression during CPR.
- This collaborative research and design may promote future multidisciplinary cooperation among academics, engineers, and designers. Academicians ensure that the device is based on scientific evidence, sound methodology, and clinical guidelines; engineers focus on technical robustness and reproducibility; and designers emphasise ergonomics and user interaction.
- The outcome of this study is also expected to stimulate and encourage further research and device development, leading to more cost-effective, comfortable wearable AVF feedback devices with additional features and better user interfaces to improve the quality of chest compressions during CPR.

## 7 Conclusions

The study investigated the limitations of current AVF devices for CPR through a systematic literature review; explored user requirements and acceptability factors through end-user interviews; conceptualised and developed a soft and flexible wearable AVF prototype to address the identified gaps; and evaluated its effectiveness and usability in a controlled, simulation-based environment.

Results of the systematic review showed that the standalone AVF device significantly improved specific chest-compression parameters. However, there was insufficient evidence to conclude that standalone AVF devices improve complete chest recoil and correct hand positioning during CPR. Moreover, many participants reported increased discomfort in their hands during chest compressions when they used rigid, standalone real-time AVF devices compared to standard CPR. The semi-structured user interview reveals that a complex interplay among functional performance, user confidence, design factors, and contextual usability shapes the requirements and acceptability of AVF devices, indicating that multi-professional teams and user involvement are needed to address these challenges. The findings from these two studies guided the design of the wearable ResuGlove AVF device during the subsequent development phase.

The proof-of-concept study described the conceptual and iterative design of the ResuGlove prototype. The proof-of-concept study revealed promising results, indicating that the ResuGlove device under development is feasible and potentially viable for monitoring and guiding chest compression quality during CPR. The preliminary findings of the effectiveness and usability test following the proof-of-concept study further indicated that the device could improve specific chest-compression metrics compared with standard CPR. Furthermore, Participants rated the designed ResuGlove prototype as comfortable and easy to learn, with an acceptable overall usability score. However, the usability score fell at the lower end of the acceptable range, indicating the need for further refinement.

Overall, this work addressed a crucial gap in CPR feedback devices by designing and testing a new soft, flexible wearable AVF device that monitors and guides chest compression quality during CPR. Across a series of complementary studies, the work demonstrated the feasibility of soft, wearable, real-time feedback technology and

provided initial evidence that this approach can support the development of an accurate, user-friendly device to enhance CPR quality. The results indicate that the designed ResuGlove may enhance rescuer comfort, minimise device displacement, and improve key CPR metrics, particularly by guiding rescuers to avoid leaning during chest compressions, a feature overlooked in most other standalone wearable AVF devices.

While still in early-stage development and subject to methodological and developmental limitations that require several rounds of refinement and further research, this work marks an important step towards the design and evaluation of next-generation wearable CPR feedback systems. Furthermore, it advances the field by integrating UCD, resuscitation science, and wearable sensing technology, thereby laying the groundwork for future research and clinical innovations to improve CPR quality and patient outcomes.

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# References

- Aase, S. O., & Myklebust, H. (2002). Compression depth estimation for CPR quality assessment using DSP on accelerometer signals. *IEEE Transactions on Biomedical Engineering*, 49(3), 263–268. <https://doi.org/10.1109/10.983461>
- Abella, B. S., Alvarado, J. P., Myklebust, H., Edelson, D. P., Barry, A., O’Hearn, N., Vanden Hoek, T. L., & Becker, L. B. (2005). Quality of Cardiopulmonary Resuscitation During In-Hospital Cardiac Arrest. *JAMA*, 293(3), 305–310. <https://doi.org/10.1001/jama.293.3.305>
- Abella, B. S., Sandbo, N., Vassilatos, P., Alvarado, J. P., O’Hearn, N., Wigder, H. N., Hoffman, P., Tynus, K., Vanden Hoek, T. L., & Becker, L. B. (2005). Chest compression rates during cardiopulmonary resuscitation are suboptimal: A prospective study during in-hospital cardiac arrest. *Circulation*, 111(4), 428–434. <https://doi.org/10.1161/01.CIR.0000153811.84257.59>
- Agostinucci, J.-M., Weislinger, L., Marzouk, N., Zouaghi, H., Ekpe, K., Genthillomme, A., Adnet, F., Guenin, A., Reuter, P.-G., & Lapostolle, F. (2021). Relation between chest compression rate and depth: The ENFONCE Study. *European Journal of Emergency Medicine*, 28(5), 352–354. <https://doi.org/10.1097/MEJ.0000000000000802>
- Ahluwalia, A., Maria, C. D., & Lantada, A. D. (2018). The Kahawa Declaration: A manifesto for the democratization of medical technology. *Global Health Innovation*, 1(1), 1–4. <https://doi.org/10.15641/ghi.v1i1.507>
- Ahmed, S. K. (2024). The pillars of trustworthiness in qualitative research. *Journal of Medicine, Surgery, and Public Health*, 2, 100051. <https://doi.org/10.1016/j.glmedi.2024.100051>
- Ahn, C., Lee, J., Oh, J., Song, Y., Chee, Y., Lim, T. H., Kang, H., & Shin, H. (2017). Effectiveness of feedback with a smartwatch for high-quality chest compressions during adult cardiac arrest: A randomized controlled simulation study. *PLOS ONE*, 12(4), e0169046. <https://doi.org/10.1371/journal.pone.0169046>
- Ahn, C., Lee, S., Lee, J., Oh, J., Song, Y., Kim, I. Y., & Kang, H. (2021). Impact of a Smart-Ring-Based Feedback System on the Quality of Chest Compressions in Adult Cardiac Arrest: A Randomized Preliminary Study. *International Journal of Environmental Research and Public Health*, 18(10), 5408. <https://doi.org/10.3390/ijerph18105408>
- Akinuwaesi, B. A., Uzoka, F.-M. E., Fashoto, S. G., Mbunge, E., Odumabo, A., Amusa, O. O., Okpeku, M., & Owolabi, O. (2022). A modified UTAUT model for the acceptance and use of digital technology for tackling COVID-19. *Sustainable Operations and Computers*, 3, 118–135. <https://doi.org/10.1016/j.susoc.2021.12.001>
- Albert, M., Herlitz, J., Rawshani, A., Forsberg, S., Ringh, M., Hollenberg, J., Claesson, A., Thuccani, M., Lundgren, P., Jonsson, M., & Nordberg, P. (2023). Aetiology and outcome in hospitalized cardiac arrest patients. *European Heart Journal Open*, 3(4), oead066. <https://doi.org/10.1093/ehjopen/oead066>
- Alele, F., & Malau-Aduli, B. (2023). *An Introduction to Research Methods for Undergraduate Health Profession Students*. James Cook University. <https://doi.org/10.25120/fh2z-yva8>
- Ali, I. M. (2024). A Guide for Positivist Research Paradigm: From Philosophy to Methodology. *Ideology Journal*, 9(2), 187–196. <https://doi.org/10.24191/ideology.v9i2.596>

- Ali, S. M., Noghianian, S., Khan, Z. U., Alzahrani, S., Alharbi, S., Alhartomi, M., & Alsulami, R. (2025). Wearable and Flexible Sensor Devices: Recent Advances in Designs, Fabrication Methods, and Applications. *Sensors*, *25*(5), 1377. <https://doi.org/10.3390/s25051377>
- Allencherril, J., Lee, P. Y. K., Khan, K., Loya, A., & Pally, A. (2022). Etiologies of In-hospital cardiac arrest: A systematic review and meta-analysis. *Resuscitation*, *175*, 88–95. <https://doi.org/10.1016/j.resuscitation.2022.03.005>
- American Heart Association. (2000). Part 1: Introduction to the International Guidelines 2000 for CPR and ECC. *Circulation*, *102*(suppl\_1), I–1. [https://doi.org/10.1161/circ.102.suppl\\_1.1](https://doi.org/10.1161/circ.102.suppl_1.1)
- An, M., Kim, Y., & Cho, W.-K. (2019). Effect of smart devices on the quality of CPR training: A systematic review. *Resuscitation*, *144*, 145–156. <https://doi.org/10.1016/j.resuscitation.2019.07.011>
- 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. <https://doi.org/10.1001/jama.2019.1696>
- Andersson, A., Arctadius, I., Cronberg, T., Levin, H., Nielsen, N., Friberg, H., & Lybeck, A. (2022). In-hospital versus out-of-hospital cardiac arrest: Characteristics and outcomes in patients admitted to intensive care after return of spontaneous circulation. *Resuscitation*, *176*, 1–8. <https://doi.org/10.1016/j.resuscitation.2022.04.023>
- Andrade, C. (2018). Internal, External, and Ecological Validity in Research Design, Conduct, and Evaluation. *Indian Journal of Psychological Medicine*, *40*(5), 498–499. [https://doi.org/10.4103/IJPSYM.IJPSYM\\_334\\_18](https://doi.org/10.4103/IJPSYM.IJPSYM_334_18)
- Arasaratnam, A., & Humphreys, G. (2013). Emerging economies drive frugal innovation. *Bulletin of the World Health Organization*, *91*(1), 6–7. <https://doi.org/10.2471/BLT.13.020113>
- Aromataris, E., Fernandez, R., Godfrey, C. M., Holly, C., Khalil, H., & Tungpunkom, P. (2015). Summarizing systematic reviews: Methodological development, conduct and reporting of an umbrella review approach. *JBI Evidence Implementation*, *13*(3), 132–140. <https://doi.org/10.1097/XEB.0000000000000055>
- Asadi, S., Abdullah, R., Safaei, M., & Nazir, S. (2019). An Integrated SEM-Neural Network Approach for Predicting Determinants of Adoption of Wearable Healthcare Devices. *Mobile Information Systems*, *2019*(1), 8026042. <https://doi.org/10.1155/2019/8026042>
- Babbs, C. F., Kemeny, A. E., Quan, W., & Freeman, G. (2008). A new paradigm for human resuscitation research using intelligent devices. *Resuscitation*, *77*(3), 306–315. <https://doi.org/10.1016/j.resuscitation.2007.12.018>
- Babbs, C. F., Weaver, J. C., Ralston, S. H., & Geddes, L. A. (1984). Cardiac, thoracic, and abdominal pump mechanisms in cardiopulmonary resuscitation: Studies in an electrical model of the circulation. *The American Journal of Emergency Medicine*, *2*(4), 299–308. [https://doi.org/10.1016/0735-6757\(84\)90124-4](https://doi.org/10.1016/0735-6757(84)90124-4)
- Bangor, A., Kortum, P., & Miller, J. (2009). Determining what individual SUS scores mean: Adding an adjective rating scale. *J. Usability Studies*, *4*(3), 114–123.
- Bangor, A., Kortum, Philip T., & and Miller, J. T. (2008). An Empirical Evaluation of the System Usability Scale. *International Journal of Human-Computer Interaction*, *24*(6), 574–594. <https://doi.org/10.1080/10447310802205776>
- Batten, J., & Brackett, A. (2021). Ensuring the rigor in systematic reviews: Part 3, the value of the search. *Heart & Lung*, *50*(2), 220–222. <https://doi.org/10.1016/j.hrtlng.2020.08.005>
- Bayazit, N. (2004). Investigating Design: A Review of Forty Years of Design Research. *Design Issues*, *20*(1), 16–29. <https://doi.org/10.1162/074793604772933739>
- Beck, B., Bray, J., Cameron, P., Smith, K., Walker, T., Grantham, H., Hein, C., Thorrowgood, M., Smith, A., Inoue, M., Smith, T., Dicker, B., Swain, A., Bosley, E., Pemberton, K., McKay, M., Johnston-Leek, M., Perkins, G. D., Nichol, G., & Finn, J. (2018). Regional variation in the characteristics, incidence and outcomes of out-of-hospital cardiac arrest in Australia and New Zealand: Results from the Aus-ROC Epistry. *Resuscitation*, *126*, 49–57. <https://doi.org/10.1016/j.resuscitation.2018.02.029>

- Berander, P., & Andrews, A. (2005). Requirements Prioritization. In A. Aurum & C. Wohlin (Eds), *Engineering and Managing Software Requirements* (pp. 69–94). Springer. [https://doi.org/10.1007/3-540-28244-0\\_4](https://doi.org/10.1007/3-540-28244-0_4)
- Bispo, J. P. (2022). Social desirability bias in qualitative health research. *Revista de Saúde Pública*, *56*, 101. <https://doi.org/10.11606/s1518-8787.2022056004164>
- Bitkina, O. V., Kim, H. K., & Park, J. (2020). Usability and user experience of medical devices: An overview of the current state, analysis methodologies, and future challenges. *International Journal of Industrial Ergonomics*, *76*, 102932. <https://doi.org/10.1016/j.ergon.2020.102932>
- Borges do Nascimento, I. J., Abdulazeem, H., Vasanthan, L. T., Martinez, E. Z., Zucoloto, M. L., Østengaard, L., Azzopardi-Muscat, N., Zapata, T., & Novillo-Ortiz, D. (2023). Barriers and facilitators to utilizing digital health technologies by healthcare professionals. *NPJ Digital Medicine*, *6*, 161. <https://doi.org/10.1038/s41746-023-00899-4>
- Botelho, R. M. de O., Campanharo, C. R. V., Lopes, M. C. B. T., Okuno, M. F. P., de Góis, A. F. T., & Batista, R. E. A. (2016). The use of a metronome during cardiopulmonary resuscitation in the emergency room of a university hospital. *Revista Latino-Americana de Enfermagem*, *24*, e2829. <https://doi.org/10.1590/1518-8345.1294.2829>
- Brackett, A., & Batten, J. (2022). Ensuring rigor in systematic reviews: Part 7, critical appraisal of systematic review quality. *Heart & Lung*, *53*, 32–35. <https://doi.org/10.1016/j.hrtlng.2022.01.008>
- Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. <https://doi.org/10.1191/1478088706qp063oa>
- Brooke, J. (1996). SUS: A ‘Quick and Dirty’ Usability Scale. In *Usability Evaluation In Industry*. CRC Press. <https://doi.org/https://doi.org/10.1201/9781498710411>
- Brouwer, T. F., Walker, R. G., Chapman, F. W., & Koster, R. W. (2015). Association Between Chest Compression Interruptions and Clinical Outcomes of Ventricular Fibrillation Out-of-Hospital Cardiac Arrest. *Circulation*, *132*(11), 1030–1037. <https://doi.org/10.1161/CIRCULATIONAHA.115.014016>
- Buléon, C., Parienti, J.-J., Halbout, L., Arrot, X., De Facq Régent, H., Chelarescu, D., Fellahi, J.-L., Gérard, J.-L., & Hanouz, J.-L. (2013). Improvement in chest compression quality using a feedback device (CPRmeter): A simulation randomized crossover study. *The American Journal of Emergency Medicine*, *31*(10), 1457–1461. <https://doi.org/10.1016/j.ajem.2013.07.029>
- Cabrini, L., Beccaria, P., Landoni, G., Biondi-Zoccai, G. G. L., Sheiban, I., Cristofolini, M., Fochi, O., Maj, G., & Zangrillo, A. (2008). Impact of impedance threshold devices on cardiopulmonary resuscitation: A systematic review and meta-analysis of randomized controlled studies. *Critical Care Medicine*, *36*(5), 1625–1632. <https://doi.org/10.1097/CCM.0b013e318170ba80>
- Cha, K. C., Kim, H. J., Shin, H. J., Kim, H., Lee, K. H., & Hwang, S. O. (2013). Hemodynamic Effect of External Chest Compressions at the Lower End of the Sternum in Cardiac Arrest Patients. *The Journal of Emergency Medicine*, *44*(3), 691–697. <https://doi.org/10.1016/j.jemermed.2012.09.026>
- Chalkias, A., Arnaoutoglou, E., & Xanthos, T. (2019). Personalized physiology-guided resuscitation in highly monitored patients with cardiac arrest—The PERSEUS resuscitation protocol. *Heart Failure Reviews*, *24*(4), 473–480. <https://doi.org/10.1007/s10741-019-09772-7>
- Chandra, A. (2013). Multidisciplinary collaboration as a sustainable research model for device development. *Journal of Vascular Surgery*, *57*(2), 576–582. <https://doi.org/10.1016/j.jvs.2012.07.048>
- Chen, X., & Zhou, Y. (2025). Open-Source Collaboration and Technological Innovation in the Industrial Software Industry: A Multi-Case Study. *Systems*, *13*(6), 433. <https://doi.org/10.3390/systems13060433>
- Chikatimalla, R., Trivedi, Y. V., Chigurupati, H. D., Faheem, M. S. B., Naveed, M. A., Sattar, Y., Rana, J. S., & Neppala, S. (2025). From prediction to precision: Artificial intelligence and emerging technologies in cardiopulmonary resuscitation. *Progress in Cardiovascular Diseases*, 97–107. <https://doi.org/10.1016/j.pcad.2025.09.004>

- Cho, G. C. (2009). Skin and soft tissue damage caused by use of feedback-sensor during chest compressions. *Resuscitation*, *80*(5), 600. <https://doi.org/10.1016/j.resuscitation.2009.02.014>
- Cipani, S., Bartolozzi, C., Ballo, P., & Sarti, A. (2019). Blood flow maintenance by cardiac massage during cardiopulmonary resuscitation: Classical theories, newer hypotheses, and clinical utility of mechanical devices. *Journal of the Intensive Care Society*, *20*(1), 2–10. <https://doi.org/10.1177/1751143718778486>
- Citolino Filho, C. M., Santos, E. S., Silva, R. de C. G. e., & Nogueira, L. de S. (2015). Factors affecting the quality of cardiopulmonary resuscitation in inpatient units: Perception of nurses. *Revista Da Escola de Enfermagem Da USP*, *49*, 907–913. <https://doi.org/https://doi.org/10.1590/S0080-623420150000600005>
- Connolly, M. S., Goldstein, P. J., Currie, M., Carter, A. J. E., Doucette, S. P., Giddens, K., Allan, K. S., Travers, A. H., Ahrens, B., Rainham, D., & Sapp, J. L. (2021). Urban-Rural Differences in Cardiac Arrest Outcomes: A Retrospective Population-Based Cohort Study. *CJC Open*, *4*(4), 383–389. <https://doi.org/10.1016/j.cjco.2021.12.010>
- Considine, J., Gazmuri, R. J., Perkins, G. D., Kudenchuk, P. J., Olasveengen, T. M., Vaillancourt, C., Nishiyama, C., Hatanaka, T., Mancini, M. E., Chung, S. P., Escalante-Kanashiro, R., & Morley, P. (2020). Chest compression components (rate, depth, chest wall recoil and leaning): A scoping review. *Resuscitation*, *146*, 188–202. <https://doi.org/10.1016/j.resuscitation.2019.08.042>
- Crowley, C. P., Wan, E. S., Saliccioli, J. D., & Kim, E. (2020). The Use of Mechanical Cardiopulmonary Resuscitation May Be Associated With Improved Outcomes Over Manual Cardiopulmonary Resuscitation During Inhospital Cardiac Arrests. *Critical Care Explorations*, *2*(11), e0261. <https://doi.org/10.1097/CCE.0000000000000261>
- Cummins, R. O., Chamberlain, D. A., Abramson, N. S., Allen, M., Baskett, P. J., Becker, L., Bossaert, L., Deloof, H. H., Dick, W. F., & Eisenberg, M. S. (1991). Recommended guidelines for uniform reporting of data from out-of-hospital cardiac arrest: The Utstein Style. A statement for health professionals from a task force of the American Heart Association, the European Resuscitation Council, the Heart and Stroke Foundation of Canada, and the Australian Resuscitation Council. *Circulation*, *84*(2), 960–975. <https://doi.org/10.1161/01.CIR.84.2.960>
- Cummins, R. O., & Hazinski, M. F. (2000). The Most Important Changes in the International ECC and CPR Guidelines 2000. *Circulation*, *102*(suppl\_1), I-371–I-376. [https://doi.org/10.1161/circ.102.suppl\\_1.I-371](https://doi.org/10.1161/circ.102.suppl_1.I-371)
- Cypress, B. S. (2017). Rigor or Reliability and Validity in Qualitative Research: Perspectives, Strategies, Reconceptualization, and Recommendations. *Dimensions of Critical Care Nursing*, *36*(4), 253–263. <https://doi.org/10.1097/DCC.0000000000000253>
- Dainty, K. N., Colquitt, B., Bhanji, F., Hunt, E. A., Jenkins, T., Leary, M., Ornato, J. P., Swor, R. A., Panchal, A., & on behalf of the Science Subcommittee of the American Heart Association Emergency Cardiovascular Care Committee. (2022). Understanding the Importance of the Lay Responder Experience in Out-of-Hospital Cardiac Arrest: A Scientific Statement From the American Heart Association. *Circulation*, *145*(17), e852–e867. <https://doi.org/10.1161/CIR.0000000000001054>
- De Maria, C., Díaz Lantada, A., Di Pietro, L., Ravizza, A., & Ahluwalia, A. (2022). Open-Source Medical Devices: Concept, Trends, and Challenges Toward Equitable Healthcare Technology. In A. Ahluwalia, C. De Maria, & A. Díaz Lantada (Eds), *Engineering Open-Source Medical Devices: A Reliable Approach for Safe, Sustainable and Accessible Healthcare* (pp. 1–19). Springer International Publishing. [https://doi.org/10.1007/978-3-030-79363-0\\_1](https://doi.org/10.1007/978-3-030-79363-0_1)
- DeBard, M. L. (1980). The history of cardiopulmonary resuscitation. *Annals of Emergency Medicine*, *9*(5), 273–275. [https://doi.org/10.1016/S0196-0644\(80\)80389-1](https://doi.org/10.1016/S0196-0644(80)80389-1)
- Dellimore, K., Heunis, S., Gohier, F., Archer, E., de Villiers, A., Smith, J., & Scheffer, C. (2013). Development of a diagnostic glove for unobtrusive measurement of chest compression force and depth during neonatal CPR. *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 350–353. <https://doi.org/10.1109/EMBC.2013.6609509>

- Dettoni, J. R., Norvell, D. C., & Chapman, J. R. (2022). Fixed-Effect vs Random-Effects Models for Meta-Analysis: 3 Points to Consider. *Global Spine Journal, 12*(7), 1624–1626. <https://doi.org/10.1177/21925682221110527>
- Dewolf, P., Wauters, L., Clarebout, G., Van Den Bempt, S., Uten, T., Desruelles, D., & Verelst, S. (2021). Assessment of chest compression interruptions during advanced cardiac life support. *Resuscitation, 165*, 140–147. <https://doi.org/10.1016/j.resuscitation.2021.06.022>
- Dickerson, D. (2014). Randomized Allocation to Treatment Groups and the Importance of Adjusting for Covariates. *Journal of the Advanced Practitioner in Oncology, 5*(1), 61–63. <https://doi.org/10.6004/jadpro.2014.5.1.3>
- Dong, X., Zhang, L., Myklebust, H., Birkenes, T. S., & Zheng, Z.-J. (2020). Effect of a real-time feedback smartphone application (TCPRLink) on the quality of telephone-assisted CPR performed by trained laypeople in China: A manikin-based randomised controlled study. *BMJ Open, 10*(10), e038813. <https://doi.org/10.1136/bmjopen-2020-038813>
- Dong, Y., Kong, J., Mu, C., Zhao, C., Thomas, N., & Lu, X. (2015). *Materials design towards sport textiles with low-friction and moisture-wicking dual functions.* 82–87. <https://doi.org/10.1016/j.matdes.2015.08.107>
- Doyle, P. A., Gurses, A. P., & Pronovost, P. J. (2017). Mastering Medical Devices for Safe Use: Policy, Purchasing, and Training. *Quality Assurance and Utilization Review, 32*(1), 100–102. <https://doi.org/10.1177/1062860616645857>
- Dwan, K., Li, T., Altman, D. G., & Elbourne, D. (2019). CONSORT 2010 statement: Extension to randomised crossover trials. *BMJ, 366*, 14378. <https://doi.org/10.1136/bmj.14378>
- Eijk, J. A. van, Doeleman, L. C., Loer, S. A., Koster, R. W., Schuppen, H. van, & Schober, P. (2024). Ventilation during cardiopulmonary resuscitation: A narrative review. *Resuscitation, 203*. <https://doi.org/10.1016/j.resuscitation.2024.110366>
- Elding, C., Baskett, P., & Hughes, A. (1998). The study of the effectiveness of chest compressions using the CPR-plus. *Resuscitation, 36*(3), 169–173. [https://doi.org/10.1016/s0300-9572\(98\)00016-1](https://doi.org/10.1016/s0300-9572(98)00016-1)
- Elo, S., & Kyngäs, H. (2008). The qualitative content analysis process. *Journal of Advanced Nursing, 62*(1), 107–115. <https://doi.org/10.1111/j.1365-2648.2007.04569.x>
- Ewy, G. A. (2018). The mechanism of blood flow during chest compressions for cardiac arrest is probably influenced by the patient's chest configuration. *Acute Medicine & Surgery, 5*(3), 236–240. <https://doi.org/10.1002/ams2.336>
- Ferguson, C., Inglis, S. C., Breen, P. P., Gargiulo, G. D., Byiers, V., Macdonald, P. S., & Hickman, L. D. (2020). Clinician Perspectives on the Design and Application of Wearable Cardiac Technologies for Older Adults: Qualitative Study. *JMIR Aging, 3*(1), e17299. <https://doi.org/10.2196/17299>
- Field, J. M., Hazinski, M. F., Sayre, M. R., Chameides, L., Schexnayder, S. M., Hemphill, R., Samson, R. A., Kattwinkel, J., Berg, R. A., Bhanji, F., Cave, D. M., Jauch, E. C., Kudenchuk, P. J., Neumar, R. W., Peberdy, M. A., Perlman, J. M., Sinz, E., Travers, A. H., Berg, M. D., ... Vanden Hoek, T. L. (2010). Part 1: Executive Summary: 2010 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care. *Circulation, 122*(18\_suppl\_3), S640–S656. <https://doi.org/10.1161/CIRCULATIONAHA.110.970889>
- FINNISH NATIONAL BOARD ON. (2019). *The ethical principles of research with human participants and ethical review in the human sciences in Finland.* <https://tenk.fi/en/advice-and-materials/guidelines-ethical-review-human-sciences>
- Gambolò, L., Di Fronzo, P., Ristagno, G., Biserni, S., Milazzo, M., Socaci, D. M., Sarli, L., Artioli, G., Bonacaro, A., & Stirparo, G. (2024). The Role of Different Feedback Devices in the Survival of Patients in Cardiac Arrest: Systematic Review with Meta-Analysis. *Journal of Clinical Medicine, 13*(19), 5989. <https://doi.org/10.3390/jcm13195989>

- Gauna, S. R. de, González-Otero, D. M., Ruiz, J., & Russell, J. K. (2016). Feedback on the Rate and Depth of Chest Compressions during Cardiopulmonary Resuscitation Using Only Accelerometers. *PLOS ONE*, *11*(3), e0150139. <https://doi.org/10.1371/journal.pone.0150139>
- Girotra, S., van Diepen, S., Nallamothu, B. K., Carrel, M., Vellano, K., Anderson, M. L., McNally, B., Abella, B. S., Sasson, C., Chan, P. S., & in collaboration with CARES Surveillance Group and the HeartRescue Project. (2016). Regional Variation in Out-of-Hospital Cardiac Arrest Survival in the United States. *Circulation*, *133*(22), 2159–2168. <https://doi.org/10.1161/CIRCULATIONAHA.115.018175>
- Goldenberg, S. J., & Gravagna, J. (2017). A real-world perspective: Building and executing an integrated customer engagement roadmap that bridges the gaps in traditional medical device development processes. *Journal of Medical Marketing*, *16*(2), 41–49. <https://doi.org/10.1177/1745790418770598>
- González-Otero, D. M., Gauna, S. R. de, Ruiz, J. M., Gutiérrez, J. J., Saiz, P., Leturiondo, M., González-Otero, D. M., Gauna, S. R. de, Ruiz, J. M., Gutiérrez, J. J., Saiz, P., & Leturiondo, M. (2017). Audiovisual Feedback Devices for Chest Compression Quality during CPR. In *Resuscitation Aspects*. IntechOpen. <https://doi.org/10.5772/intechopen.70742>
- Gowens, P., Smith, K., Clegg, G., Williams, B., & Nehme, Z. (2022). Global variation in the incidence and outcome of emergency medical services witnessed out-of-hospital cardiac arrest: A systematic review and meta-analysis. *Resuscitation*, *175*, 120–132. <https://doi.org/10.1016/j.resuscitation.2022.03.026>
- Goyal, D., Patra, S., Sapre, A., Kaur, M., & Ramgir, N. S. (2024). Design and Development of Arduino-Based Four-Channel Data Acquisition System with Digital Temperature Control for Chemiresistive Sensors. *Sensing and Imaging*, *25*(1), 30. <https://doi.org/10.1007/s11220-024-00477-2>
- Grasner, J.-T., Bray, J. E., Nolan, J. P., Iwami, T., Ong, M. E. H., Finn, J., McNally, B., Nehme, Z., Sasson, C., Tijssen, J., Lim, S. L., Tjelmeland, I., Wnent, J., Dicker, B., Nishiyama, C., Doherty, Z., Welsford, M., & Perkins, G. D. (2024). Cardiac arrest and cardiopulmonary resuscitation outcome reports: 2024 update of the Utstein Out-of-Hospital Cardiac Arrest Registry template. *Resuscitation*, *201*. <https://doi.org/10.1016/j.resuscitation.2024.110288>
- Gräsner, J.-T., Herlitz, J., Tjelmeland, I. B. M., Wnent, J., Masterson, S., Lilja, G., Bein, B., Böttiger, B. W., Rosell-Ortiz, F., Nolan, J. P., Bossaert, L., & Perkins, G. D. (2021). European Resuscitation Council Guidelines 2021: Epidemiology of cardiac arrest in Europe. *Resuscitation*, *161*, 61–79. <https://doi.org/10.1016/j.resuscitation.2021.02.007>
- Gräsner, J.-T., Wnent, J., Herlitz, J., Perkins, G. D., Lefering, R., Tjelmeland, I., Koster, R. W., Masterson, S., Rossell-Ortiz, F., Maurer, H., Böttiger, B. W., Moertl, M., Mols, P., Alihodžić, H., Hadžibegović, I., Ioannides, M., Truhlar, A., Wissenberg, M., Salo, A., ... Bossaert, L. (2020). Survival after out-of-hospital cardiac arrest in Europe—Results of the EuReCa TWO study. *Resuscitation*, *148*, 218–226. <https://doi.org/10.1016/j.resuscitation.2019.12.042>
- Green, D. P., & Lindley, J. (2021). Design Research and Ambiguity. *Blucher Design Proceedings*, 291–297. <https://doi.org/10.5151/ead2021-172>
- Greif, R., Lockey, A., Breckwoldt, J., Carmona, F., Conaghan, P., Kuzovlev, A., Pflanzl-Knizacek, L., Sari, F., Shammet, S., Scapiagliati, A., Turner, N., Yeung, J., & Monsieus, K. G. (2021). European Resuscitation Council Guidelines 2021: Education for resuscitation. *Resuscitation*, *161*, 388–407. <https://doi.org/10.1016/j.resuscitation.2021.02.016>
- Gruber, J., Stumpf, D., Zapletal, B., Neuhold, S., & Fischer, H. (2012). Real-time feedback systems in CPR. *Trends in Anaesthesia and Critical Care*, *2*(6), 287–294. <https://doi.org/10.1016/j.tacc.2012.09.004>
- Gruenerbl, A., Javaheri, H., Monger, E., Gobbi, M., & Lukowicz, P. (2018). Training CPR with a wearable real time feedback system. *Proceedings of the 2018 ACM International Symposium on Wearable Computers*, 44–47. <https://doi.org/10.1145/3267242.3267277>
- Guba, E. G., & Lincoln, Y. A. S. (1994). *Competing Paradigms in Qualitative Research*.

- 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. <https://doi.org/10.1016/j.resplu.2021.100108>
- Gusenbauer, M. (2022). Search where you will find most: Comparing the disciplinary coverage of 56 bibliographic databases. *Scientometrics*, 127(5), 2683–2745. <https://doi.org/10.1007/s11192-022-04289-7>
- Guthrie, K. M., Rosen, R. K., Vargas, S. E., Guillen, M., Steger, A. L., Getz, M. L., Smith, K. A., Ramirez, J. J., & Kojic, E. M. (2017). User input in iterative design for prevention product development: Leveraging interdisciplinary methods to optimize effectiveness. *Drug Delivery and Translational Research*, 7(5), 761–770. <https://doi.org/10.1007/s13346-017-0397-0>
- Han, L., Liu, J., Evans, R., Song, Y., & Ma, J. (2020). Factors Influencing the Adoption of Health Information Standards in Health Care Organizations: A Systematic Review Based on Best Fit Framework Synthesis. *JMIR Medical Informatics*, 8(5), e17334. <https://doi.org/10.2196/17334>
- Hanisch, J. R., Counts, C. R., Latimer, A. J., Rea, T. D., Yin, L., & Sayre, M. R. (2020). Causes of Chest Compression Interruptions During Out-of-Hospital Cardiac Arrest Resuscitation. *Journal of the American Heart Association: Cardiovascular and Cerebrovascular Disease*, 9(6), e015599. <https://doi.org/10.1161/JAHA.119.015599>
- Harris, A. W., & Kudenchuk, P. J. (2018). Cardiopulmonary resuscitation: The science behind the hands. *Heart*, 104(13), 1056. <https://doi.org/10.1136/heartjnl-2017-312696>
- Harte, R., Glynn, L., Rodríguez-Molinero, A., Baker, P. M., Scharf, T., Quinlan, L. R., & ÓLaighin, G. (2017). A Human-Centered Design Methodology to Enhance the Usability, Human Factors, and User Experience of Connected Health Systems: A Three-Phase Methodology. *JMIR Human Factors*, 4(1), e5443. <https://doi.org/10.2196/humanfactors.5443>
- Hasselqvist-Ax, I., Riva, G., Herlitz, J., Rosenqvist, M., Hollenberg, J., Nordberg, P., Ringh, M., Jonsson, M., Axelsson, C., Lindqvist, J., Karlsson, T., & Svensson, L. (2015). Early Cardiopulmonary Resuscitation in Out-of-Hospital Cardiac Arrest. *New England Journal of Medicine*, 372(24), 2307–2315. <https://doi.org/10.1056/NEJMoal405796>
- Hellevo, H., Sainio, M., Nevalainen, R., Huhtala, H., Olkkola, K. T., Tenhunen, J., & Hoppu, S. (2013). Deeper chest compression – More complications for cardiac arrest patients? *Resuscitation*, 84(6), 760–765. <https://doi.org/10.1016/j.resuscitation.2013.02.015>
- Herlitz, J., Svensson, L., Holmberg, S., Ängquist, K.-A., & Young, M. (2005). Efficacy of bystander CPR: Intervention by lay people and by health care professionals. *Resuscitation*, 66(3), 291–295. <https://doi.org/10.1016/j.resuscitation.2005.04.003>
- Hermann, S., Breitling, P., Röddiger, T., & Beigl, M. (2021). Cardiopulmonary Resuscitation Support: Comparison of Wrist-, Chest-, and Ear-Worn Devices and Estimation Algorithms. *2021 International Symposium on Wearable Computers*, 28–32. <https://doi.org/10.1145/3460421.3478820>
- Higgins, J. P. T. (Ed.). (2020). *Cochrane handbook for systematic reviews of interventions* (Second edition). Wiley-Blackwell.
- Higgins, J. P. T., Thompson, S. G., Deeks, J. J., & Altman, D. G. (2003). *Measuring inconsistency in meta-analyses*. 557–560. <https://doi.org/10.1136/bmj.327.7414.557>
- Hinrichs-Krapels, S., Ditewig, B., Boulding, H., Chalkidou, A., Erskine, J., & Shokraneh, F. (2022). Purchasing high-cost medical devices and equipment in hospitals: A systematic review. *BMJ Open*, 12(9), e057516. <https://doi.org/10.1136/bmjopen-2021-057516>
- Hong, J. Y., Oh, J. H., Kim, C. W., & Lee, D. H. (2016). Hand injuries caused by feedback device usage during cardiopulmonary resuscitation training. *Resuscitation*, 107, e3–e4. <https://doi.org/10.1016/j.resuscitation.2016.08.001>
- Høybye, M., Stankovic, N., Holmberg, M., Christensen, H. C., Granfeldt, A., & Andersen, L. W. (2021). In-Hospital vs. Out-of-Hospital Cardiac Arrest: Patient Characteristics and Survival. *Resuscitation*, 158, 157–165. <https://doi.org/10.1016/j.resuscitation.2020.11.016>

- Idris, A. H., Guffey, D., Pepe, P. E., Brown, S. P., Brooks, S. C., Callaway, C. W., Christenson, J., Davis, D. P., Daya, M. R., Gray, R., Kudenchuk, P. J., Larsen, J., Lin, S., Menegazzi, J. J., Sheehan, K., Sopko, G., Stiell, I., Nichol, G., Aufderheide, T. P., & Investigators, for T. R. O. C. (2015). Chest Compression Rates and Survival Following Out-of-Hospital Cardiac Arrest\*. *Critical Care Medicine*, 43(4), 840–848. <https://doi.org/10.1097/CCM.0000000000000824>
- Jian, S. (2017). Research-led design practice: A new approach of research through design. *Proceedings of the 2nd Arts & Humanities Conference, Florence*, 14–25.
- Johnson, J. L., Adkins, D., & Chauvin, S. (2020). A Review of the Quality Indicators of Rigor in Qualitative Research. *American Journal of Pharmaceutical Education*, 84(1), 7120. <https://doi.org/10.5688/ajpe7120>
- Jolliffe, I. T., & Cadima, J. (2016). Principal component analysis: A review and recent developments. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, 374(2065), 20150202. <https://doi.org/10.1098/rsta.2015.0202>
- Jones, J. C., & Thornley, D. G. (1963). Conference on Design Methods. *Materials Relating to the 1962 Design Methods Conference*. [https://dl.designresearchsociety.org/design\\_methods\\_conference\\_1962/1](https://dl.designresearchsociety.org/design_methods_conference_1962/1)
- Junli, A., Isa, S. N. I., & Ibrahim, F. S. (2023). Factors of cardiopulmonary resuscitation skills retention among healthcare providers: A scoping review. *Nurse Education in Practice*, 69, 103617. <https://doi.org/10.1016/j.nepr.2023.103617>
- Kakar, Z. U. H., Rasheed, R., Rashid, A., & Akhter, S. (2023). CRITERIA FOR ASSESSING AND ENSURING THE TRUSTWORTHINESS IN QUALITATIVE RESEARCH. *International Journal of Business Reflections*, 4(2), 150–173. <https://doi.org/10.56249/ijbr.03.01.44>
- Kemal, Ö. (2020). Power Analysis and Sample Size, When and Why? *Turkish Archives of Otorhinolaryngology*, 58(1), 3–4. <https://doi.org/10.5152/tao.2020.0330>
- Kern, K. B. (2000). Coronary perfusion pressure during cardiopulmonary resuscitation. *Best Practice & Research Clinical Anaesthesiology*, 14(3), 591–609. <https://doi.org/10.1053/bean.2000.0109>
- Kern, K. B., Sanders, A. B., Raife, J., Milander, M. M., Otto, C. W., & Ewy, G. A. (1992). A Study of Chest Compression Rates During Cardiopulmonary Resuscitation in Humans: The Importance of Rate-Directed Chest Compressions. *Archives of Internal Medicine*, 152(1), 145–149. <https://doi.org/10.1001/archinte.1992.00400130153020>
- Kim, T., & Xiong, S. (2022). Effectiveness and Usability of a Novel Kinect-Based Tailored Interactive Fall Intervention System for Fall Prevention in Older People: A Preliminary Study. *Frontiers in Public Health*, 10, 884551. <https://doi.org/10.3389/fpubh.2022.884551>
- Kip, H., Jong, N. B., Gemert-Pijnen, L. J. E. W. C. van, & Kelders, S. M. (2025). The CeHRes Roadmap 2.0: Update of a Holistic Framework for Development, Implementation, and Evaluation of eHealth Technologies. *Journal of Medical Internet Research*, 27(1), e59601. <https://doi.org/10.2196/59601>
- Kirkbright, S., Finn, J., Tohira, H., Bremner, A., Jacobs, I., & Celenza, A. (2014). Audiovisual feedback device use by health care professionals during CPR: A systematic review and meta-analysis of randomised and non-randomised trials. *Resuscitation*, 85(4), 460–471. <https://doi.org/10.1016/j.resuscitation.2013.12.012>
- Kleinman, M. E., Brennan, E. E., Goldberger, Z. D., Swor, R. A., Terry, M., Bobrow, B. J., Gazmuri, R. J., Travers, A. H., & Rea, T. (2015). Part 5: Adult Basic Life Support and Cardiopulmonary Resuscitation Quality: 2015 American Heart Association Guidelines Update for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care. *Circulation*, 132(18\_suppl\_2), S414–S435. <https://doi.org/10.1161/CIR.0000000000000259>
- Kłosiwicz, T., Puślecki, M., Zalewski, R., Sip, M., & Perek, B. (2020). Assessment of Chest Compression Quality—A systematic review. *Disaster and Emergency Medicine Journal*, 5(1), 49–56. <https://doi.org/10.5603/DEMJ.a2020.0010>
- Ko, P. C.-I., Chen, W.-J., Lin, C.-H., Ma, M. H.-M., & Lin, F.-Y. (2005). Evaluating the quality of prehospital cardiopulmonary resuscitation by reviewing automated external defibrillator records

- and survival for out-of-hospital witnessed arrests. *Resuscitation*, 64(2), 163–169. <https://doi.org/10.1016/j.resuscitation.2004.08.013>
- Kong, X. T. R., Luo, H., Huang, G. Q., & Yang, X. (2019). Industrial wearable system: The human-centric empowering technology in Industry 4.0. *Journal of Intelligent Manufacturing*, 30(8), 2853–2869. <https://doi.org/10.1007/s10845-018-1416-9>
- Koster, R. W., Baubin, M. A., Bossaert, L. L., Caballero, A., Cassan, P., Castrén, M., Granja, C., Handley, A. J., Monsieurs, K. G., Perkins, G. D., Raffay, V., & Sandroni, C. (2010). European Resuscitation Council Guidelines for Resuscitation 2010 Section 2. Adult basic life support and use of automated external defibrillators. *Resuscitation*, 81(10), 1277–1292. <https://doi.org/10.1016/j.resuscitation.2010.08.009>
- Kouwenhoven, W. B., Jude, J. R., & Knickerbocker, G. G. (1960). CLOSED-CHEST CARDIAC MASSAGE. *JAMA*, 173(10), 1064–1067. <https://doi.org/10.1001/jama.1960.03020280004002>
- Kuek, A., & Hakkennes, S. (2020). Healthcare staff digital literacy levels and their attitudes towards information systems. *Health Informatics Journal*, 26(1), 592–612. <https://doi.org/10.1177/1460458219839613>
- Kühn, C., Juchems, R., & Frese, W. (1991). Evidence for the ‘cardiac pump theory’ in cardiopulmonary resuscitation in man by transesophageal echocardiography. *Resuscitation*, 22(3), 275–282. [https://doi.org/10.1016/0300-9572\(91\)90035-w](https://doi.org/10.1016/0300-9572(91)90035-w)
- Kuper, A., Lingard, L., & Levinson, W. (2008). Critically appraising qualitative research. *BMJ*, 337. <https://doi.org/10.1136/bmj.a1035>
- Laerdal. (n.d.). *Resusci Anne QCPR | Laerdal Medical*. Retrieved 11 August 2024, from <https://laerdal.com/gb/products/simulation-training/resuscitation-training/resusci-anne-qcpr/>
- Laher, S. (2016). Ostinato rigore: Establishing methodological rigour in quantitative research. *South African Journal of Psychology*, 46(3), 316–327. <https://doi.org/10.1177/0081246316649121>
- Lakomek, F., Lukas, R.-P., Brinkrolf, P., Mennewisch, A., Steinsiek, N., Gutendorf, P., Sudowe, H., Heller, M., Kwiecien, R., Zarbock, A., & Bohn, A. (2020). Real-time feedback improves chest compression quality in out-of-hospital cardiac arrest: A prospective cohort study. *PLoS ONE*, 15(2), e0229431. <https://doi.org/10.1371/journal.pone.0229431>
- LaPrad, A. S., Joseph, B., Chokshi, S., Aldrich, K., Kessler, D., & Oppenheimer, B. W. (2024). A smartwatch-based CPR feedback device improves chest compression quality among health care professionals and lay rescuers. *Cardiovascular Digital Health Journal*, 5(3), 122–131. <https://doi.org/10.1016/j.cvdhj.2024.03.006>
- Lauridsen, K. G., Morgan, R. W., Berg, R. A., Niles, D. E., Kleinman, M. E., Zhang, X., Griffis, H., Del Castillo, J., Skellett, S., Lasa, J. J., Raymond, T. T., Sutton, R. M., Nadkarni, V. M., & for the pediRES-Q Investigators. (2024). Association Between Chest Compression Pause Duration and Survival After Pediatric In-Hospital Cardiac Arrest. *Circulation*, 149(19), 1493–1500. <https://doi.org/10.1161/CIRCULATIONAHA.123.066882>
- Lee, J., Song, Y., Oh, J., Chee, Y., Ahn, C., Shin, H., Kang, H., & Lim, T. H. (2019). Smartwatch feedback device for high-quality chest compressions by a single rescuer during infant cardiac arrest: A randomized, controlled simulation study. *European Journal of Emergency Medicine*, 26(4), 266–271. <https://doi.org/10.1097/MEJ.0000000000000537>
- Lee, S., Song, Y., Lee, J., Oh, J., Lim, T. H., Ahn, C., & Kim, I. Y. (2021). Development of Smart-Ring-Based Chest Compression Depth Feedback Device for High Quality Chest Compressions: A Proof-of-Concept Study. *Biosensors*, 11(2), 35. <https://doi.org/10.3390/bios11020035>
- Levitt, C. V., Boone, K., Tran, Q. K., & Pourmand, A. (2023). Application of Technology in Cardiopulmonary Resuscitation, a Narrative Review. *Journal of Clinical Medicine*, 12(23), 7383. <https://doi.org/10.3390/jcm12237383>
- Li, S., Dong, K., Li, R., Huang, X., Chen, T., & Xiao, X. (2020). Capacitive pressure sensor inlaid a porous dielectric layer of superelastic polydimethylsiloxane in conductive fabrics for detection of human motions. *Sensors and Actuators A: Physical*, 312, 112106. <https://doi.org/10.1016/j.sna.2020.112106>

- Lim, C.-Y., & In, J. (2021). Considerations for crossover design in clinical study. *Korean Journal of Anesthesiology*, 74(4), 293–299. <https://doi.org/10.4097/kja.21165>
- Lin, C.-Y., Hsia, S.-H., Lee, E.-P., Chan, O.-W., Lin, J.-J., & Wu, H.-P. (2020). Effect of Audiovisual Cardiopulmonary Resuscitation Feedback Device on Improving Chest Compression Quality. *Scientific Reports*, 10, 398. <https://doi.org/10.1038/s41598-019-57320-y>
- Liu, X. (2017). Rigor. In *The SAGE Encyclopedia of Communication Research Methods* (pp. 1512–1514). SAGE Publications, Inc. <https://doi.org/10.4135/9781483381411>
- Lobe, B., Morgan, D. L., & Hoffman, K. (2022). A Systematic Comparison of In-Person and Video-Based Online Interviewing. *International Journal of Qualitative Methods*, 21, 1–12. <https://doi.org/10.1177/16094069221127068>
- Lu, T.-C., Chen, Y., Ho, T.-W., Chang, Y.-T., Lee, Y.-T., Wang, Y.-S., Chen, Y.-P., Fu, C.-M., Chiang, W.-C., Ma, M. H.-M., Fang, C.-C., Lai, F., & Turner, A. M. (2018). A novel depth estimation algorithm of chest compression for feedback of high-quality cardiopulmonary resuscitation based on a smartwatch. *Journal of Biomedical Informatics*, 87, 60–65. <https://doi.org/10.1016/j.jbi.2018.09.014>
- Lund-Kordahl, I., Mathiassen, M., Melau, J., Olasveengen, T. M., Sunde, K., & Fredriksen, K. (2019). Relationship between level of CPR training, self-reported skills, and actual manikin test performance—An observational study. *International Journal of Emergency Medicine*, 12(1), 2. <https://doi.org/10.1186/s12245-018-0220-9>
- Lurie, K. G., Nemergut, E. C., Yannopoulos, D., & Sweeney, M. (2016). The Physiology of Cardiopulmonary Resuscitation. *Anesthesia & Analgesia*, 122(3), 767–783. <https://doi.org/10.1213/ANE.0000000000000926>
- Lv, G. W., Hu, Q. C., Zhang, M., Feng, S. Y., Li, Y., Zhang, Y., Zhang, Y. Y., & Wang, W. J. (2022). Effect of real-time feedback on patient's outcomes and survival after cardiac arrest: A systematic review and meta-analysis. *Medicine*, 101(37), e30438. <https://doi.org/10.1097/MD.00000000000030438>
- Lyngby, R. (2022). *Cardio-pulmonary-resuscitation quality in out-of-hospital cardiac arrest: Real-time feedback and post-event debriefing* [Doctoral thesis, Kingston University]. <https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.877958>
- Lyngby, R. M., Händel, M. N., Christensen, A. M., Nikoietou, D., Folke, F., Christensen, H. C., Barfod, C., & Quinn, T. (2021). Effect of real-time and post-event feedback in out-of-hospital cardiac arrest attended by EMS — A systematic review and meta-analysis. *Resuscitation Plus*, 6, 100101. <https://doi.org/10.1016/j.resplu.2021.100101>
- Ma, W., Liu, E., Xiao, L., Song, Y., Zhou, L., Zhang, C., & Deng, H. (2025). The development and accuracy assessment of a wearable cardiopulmonary resuscitation real-time audio-visual feedback device. *Resuscitation*, 211, 110602. <https://doi.org/10.1016/j.resuscitation.2025.110602>
- Maamri, H., Ben Ayed, H., Ben Hmida, M., Trigui, M., Baklouti, M., Ben Jemaa, M., Ketata, N., Kassiss, M., Yaich, S., & Damak, J. (2024). Effectiveness of a training program on health-care professionals' knowledge and practices regarding thermo-sensitive reusable medical devices disinfection: A quasi-experimental study. *Infection, Disease & Health*, 29(1), 1–7. <https://doi.org/10.1016/j.idh.2023.07.004>
- Madar, J., Roehr, C. C., Ainsworth, S., Ersdal, H., Morley, C., Rüdiger, M., Skåre, C., Szczapa, T., te Pas, A., Trevisanuto, D., Urlesberger, B., Wilkinson, D., & Wyllie, J. P. (2021). European Resuscitation Council Guidelines 2021: Newborn resuscitation and support of transition of infants at birth. *Resuscitation, European Resuscitation Council Guidelines for Resuscitation 2021*, 161, 291–326. <https://doi.org/10.1016/j.resuscitation.2021.02.014>
- Madurasinghe, V. W. (2017). Sequence balance minimisation: Minimising with unequal treatment allocations. *Trials*, 18(1), 207. <https://doi.org/10.1186/s13063-017-1942-3>
- Makobore, P. N., Díaz Lantada, A., Di Pietro, L., De Maria, C., & Ahluwalia, A. (2022). Getting Started with an Open-Source Medical Device Project: Systematic Needs Identification Techniques for Bottom-Up Strategies. In A. Ahluwalia, C. De Maria, & A. Díaz Lantada (Eds), *Engineering Open-*

- Source Medical Devices: A Reliable Approach for Safe, Sustainable and Accessible Healthcare* (pp. 39–57). Springer International Publishing. [https://doi.org/10.1007/978-3-030-79363-0\\_3](https://doi.org/10.1007/978-3-030-79363-0_3)
- Malkin, R. A. (2007). Barriers for medical devices for the developing world. *Expert Review of Medical Devices*, 4(6), 759–763. <https://doi.org/10.1586/17434440.4.6.759>
- Malta Hansen, C., Rosenkranz, S. M., Folke, F., Zinckernagel, L., Tjørnhøj-Thomsen, T., Torp-Pedersen, C., Sondergaard, K. B., Nichol, G., & Hulvej Rod, M. (2017). Lay Bystanders' Perspectives on What Facilitates Cardiopulmonary Resuscitation and Use of Automated External Defibrillators in Real Cardiac Arrests. *Journal of the American Heart Association: Cardiovascular and Cerebrovascular Disease*, 6(3), e004572. <https://doi.org/10.1161/JAHA.116.004572>
- Marešová, P., Klímová, B., Honegr, J., Kuča, K., Ibrahim, W. N. H., & Selamat, A. (2020). Medical Device Development Process, and Associated Risks and Legislative Aspects–Systematic Review. *Frontiers in Public Health*, 8, 308. <https://doi.org/10.3389/fpubh.2020.00308>
- Markiewicz, K., Til, J. A. van, & IJerman, M. J. (2014). MEDICAL DEVICES EARLY ASSESSMENT METHODS: SYSTEMATIC LITERATURE REVIEW. *International Journal of Technology Assessment in Health Care*, 30(2), 137–146. <https://doi.org/10.1017/S0266462314000026>
- Mays, N., & Pope, C. (2000). Assessing quality in qualitative research. *BMJ*, 320(7226), 50–52. <https://doi.org/10.1136/bmj.320.7226.50>
- McBride, O., Poel, A., Counts, C. R., Parayil, M., Osborne, C., Drucker, C., Eisenberg, M., Murphy, D., Kudenchuk, P., Sayre, M., & Rea, T. (2025). Temporal Patterns in Out-of-Hospital Cardiac Arrest Incidence and Outcome. *JAMA Cardiology*, 10(9), 922–931. <https://doi.org/10.1001/jamacardio.2025.2247>
- Meaney, P. A., Bobrow, B. J., Mancini, M. E., Christenson, J., de Caen, A. R., Bhanji, F., Abella, B. S., Kleinman, M. E., Edelson, D. P., Berg, R. A., Aufderheide, T. P., Menon, V., & Leary, M. (2013). Cardiopulmonary Resuscitation Quality: Improving Cardiac Resuscitation Outcomes Both Inside and Outside the Hospital. *Circulation*, 128(4), 417–435. <https://doi.org/10.1161/CIR.0b013e31829d8654>
- Medina, L. A., Kremer, Gül E. Okudan, & Wysk, R. A. (2013). Supporting medical device development: A standard product design process model. *Journal of Engineering Design*, 24(2), 83–119. <https://doi.org/10.1080/09544828.2012.676635>
- Merchant, R. M., Topjian, A. A., Panchal, A. R., Cheng, A., Aziz, K., Berg, K. M., Lavonas, E. J., Magid, D. J., & On behalf of the 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. <https://doi.org/10.1161/CIR.0000000000000918>
- Metelmann, C., Metelmann, B., Schuffert, L., Hahnenkamp, K., Vollmer, M., & Brinkrolf, P. (2021). Smartphone apps to support laypersons in bystander CPR are of ambivalent benefit: A controlled trial using medical simulation. *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine*, 29(1), 76. <https://doi.org/10.1186/s13049-021-00893-3>
- Miller, A. C., Scissum, K., McConnell, L., East, N., Vahedian-Azimi, A., Sewell, K. A., & Zehtabchi, S. (2020). Real-time audio-visual feedback with handheld nonautomated external defibrillator devices during cardiopulmonary resuscitation for in-hospital cardiac arrest: A meta-analysis. *International Journal of Critical Illness and Injury Science*, 10(3), 109–122. [https://doi.org/10.4103/IJCIIS.IJCIIS\\_155\\_20](https://doi.org/10.4103/IJCIIS.IJCIIS_155_20)
- Mohammadiounotikandi, A. (2023). A Multidisciplinary approach to innovations in biomedical engineering for improved patient care and well-being. *Archive of Biomedical Science and Engineering*, 9(1), 001–009. <https://doi.org/10.17352/abse.000029>
- Money, A. G., Barnett, J., Kuljis, J., Craven, M. P., Martin, J. L., & Young, T. (2011). The role of the user within the medical device design and development process: Medical device manufacturers'

- perspectives. *BMC Medical Informatics and Decision Making*, *11*(1), 15. <https://doi.org/10.1186/1472-6947-11-15>
- Morgan, D. L., Ataie, J., Carder, P., & Hoffman, K. (2013). Introducing Dyadic Interviews as a Method for Collecting Qualitative Data. *Qualitative Health Research*, *23*(9), 1276–1284. <https://doi.org/10.1177/1049732313501889>
- Musiari, M., Saporito, A., Ceruti, S., Biggiogero, M., Iattoni, M., Glotta, A., Cantini, L., Capdevila, X., & Cassina, T. (2021). Can a Glove-Coach Technology Significantly Increase the Efficacy of Cardiopulmonary Resuscitation on Non-healthcare Professionals? A Controlled Trial. *Frontiers in Cardiovascular Medicine*, *8*. <https://doi.org/10.3389/fcvm.2021.685988>
- Naim, M. Y., Burke, R. V., McNally, B. F., Song, L., Griffis, H. M., Berg, R. A., Vellano, K., Markenson, D., Bradley, R. N., & Rossano, J. W. (2017). Association of Bystander Cardiopulmonary Resuscitation With Overall and Neurologically Favorable Survival After Pediatric Out-of-Hospital Cardiac Arrest in the United States: A Report From the Cardiac Arrest Registry to Enhance Survival Surveillance Registry. *JAMA Pediatrics*, *171*(2), 133–141. <https://doi.org/10.1001/jamapediatrics.2016.3643>
- Namatovu, H. K., Oyana, T. J., & Sol, H. G. (2021). Barriers to eHealth adoption in routine antenatal care practices: Perspectives of expectant mothers in Uganda – A qualitative study using the unified theory of acceptance and use of technology model. *Digital Health*, *7*, 20552076211064406. <https://doi.org/10.1177/20552076211064406>
- Nguyen, D. D., Spertus, J. A., Kennedy, K. F., Gupta, K., Uzendu, A. I., McNally, B. F., & Chan, P. S. (2024). Association Between Delays in Time to Bystander CPR and Survival for Witnessed Cardiac Arrest in the United States. *Circulation. Cardiovascular Quality and Outcomes*, *17*(2), e010116. <https://doi.org/10.1161/CIRCOUTCOMES.123.010116>
- Nguyen, M., & Mougenot, C. (2022). A systematic review of empirical studies on multidisciplinary design collaboration: Findings, methods, and challenges. *Design Studies*, *81*, 101120. <https://doi.org/10.1016/j.destud.2022.101120>
- Olasveengen, T. M., Mancini, M. E., Perkins, G. D., Avis, S., Brooks, S., Castrén, M., Chung, S. P., Considine, J., Couper, K., Escalante, R., Hatanaka, T., Hung, K. K. C., Kudenchuk, P., Lim, S. H., Nishiyama, C., Ristagno, G., Semeraro, F., Smith, C. M., Smyth, M. A., ... on behalf of the Adult Basic Life Support Collaborators. (2020). Adult Basic Life Support: 2020 International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science With Treatment Recommendations. *Circulation*, *142*(16\_suppl\_1), S41–S91. <https://doi.org/10.1161/CIR.0000000000000892>
- Olasveengen, T. M., Semeraro, F., Ristagno, G., Castren, M., Handley, A., Kuzovlev, A., Monsieurs, K. G., Raffay, V., Smyth, M., Soar, J., Svavarsdottir, H., & Perkins, G. D. (2021). European Resuscitation Council Guidelines 2021: Basic Life Support. *Resuscitation*, *161*, 98–114. <https://doi.org/10.1016/j.resuscitation.2021.02.009>
- Orlowski, J. P. (1986). Optimum position for external cardiac compression in infants and young children. *Annals of Emergency Medicine*, *15*(6), 667–673. [https://doi.org/10.1016/S0196-0644\(86\)80423-1](https://doi.org/10.1016/S0196-0644(86)80423-1)
- Otto, Q., Nolan, J. P., Chamberlain, D. A., Cummins, R. O., & Soar, J. (2021). Utstein Style for emergency care—The first 30 years. *Resuscitation*, *163*, 16–25. <https://doi.org/10.1016/j.resuscitation.2021.03.022>
- Ouzzani, M., Hammady, H., Fedorowicz, Z., & Elmagarmid, A. (2016). *Rayyan—A web and mobile app for systematic reviews*. <https://doi.org/10.1186/s13643-016-0384-4>
- Paez, A. (2017). Gray literature: An important resource in systematic reviews. *Journal of Evidence-Based Medicine*, *10*(3), 233–240. <https://doi.org/10.1111/jebm.12266>
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... Moher,

- D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *Systematic Reviews*, *10*(1), 89. <https://doi.org/10.1186/s13643-021-01626-4>
- Panchal, A. R., Bartos, J. A., Cabañas, J. G., Donnino, M. W., Drennan, I. R., Hirsch, K. G., Kudenchuk, P. J., Kurz, M. C., Lavonas, E. J., Morley, P. T., O'Neil, B. J., Peberdy, M. A., Rittenberger, J. C., Rodriguez, A. J., Sawyer, K. N., Berg, K. M., & On behalf of the Adult Basic and Advanced Life Support Writing Group. (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. <https://doi.org/10.1161/CIR.0000000000000916>
- Paratz, E. D., Rowsell, L., Zentner, D., Parsons, S., Morgan, N., Thompson, T., James, P., Pflaumer, A., Semsarian, C., Smith, K., Stub, D., & Gerche, A. L. (2020). Cardiac arrest and sudden cardiac death registries: A systematic review of global coverage. *Open Heart*, *7*(1), e001195. <https://doi.org/10.1136/openhrt-2019-001195>
- Park, H. J., Jeong, W. J., Moon, H. J., Kim, G. W., Cho, J. S., Lee, K. M., Choi, H. J., Park, Y. J., & Lee, C. A. (2020). Factors Associated with High-Quality Cardiopulmonary Resuscitation Performed by Bystander. *Emergency Medicine International*, *2020*, 8356201. <https://doi.org/10.1155/2020/8356201>
- Park, J., Lim, T., Lee, Y., Kim, W., Cho, Y., & Kang, H. (2016). Assessment of chest compression depth obtained using the PocketCPR as an educational tool according to smartphone attachment site. *The American Journal of Emergency Medicine*, *34*(11), 2243–2246. <https://doi.org/10.1016/j.ajem.2016.08.066>
- Park, S.-S. (2014). Comparison of chest compression quality between the modified chest compression method with the use of smartphone application and the standardized traditional chest compression method during CPR. *Technology and Health Care*, *22*(3), 351–358. <https://doi.org/10.3233/THC-140791>
- Patel, K., & Hipskind, J. E. (2025). Cardiac Arrest. In *StatPearls*. StatPearls Publishing. <http://www.ncbi.nlm.nih.gov/books/NBK534866/>
- Pei-Chuan Huang, E., Chiang, W.-C., Lu, T.-C., Wang, C.-H., Sun, J.-T., Hsieh, M.-J., Wang, H.-C., Yang, C.-W., Lin, C.-H., Lin, J.-J., Yang, M.-C., & Huei-Ming Ma, M. (2021). Barriers to bystanders defibrillation: A national survey on public awareness and willingness of bystanders defibrillation☆. *Journal of the Formosan Medical Association*, *120*(3), 974–982. <https://doi.org/10.1016/j.jfma.2020.10.020>
- Perkins, G. D., Augré, C., Rogers, H., Allan, M., & Thickett, D. R. (2005). CPREzy™: An evaluation during simulated cardiac arrest on a hospital bed. *Resuscitation*, *64*(1), 103–108. <https://doi.org/10.1016/j.resuscitation.2004.08.011>
- Perkins, G. D., Gräsner, J.-T., Semeraro, F., Olasveengen, T., Soar, J., Lott, C., Van de Voorde, P., Madar, J., Zideman, D., Mentzelopoulos, S., Bossaert, L., Greif, R., Monsieurs, K., Svavarsdóttir, H., Nolan, J. P., Ainsworth, S., Akin, S., Alfonso, A., Andres, J., ... Zideman, D. A. (2021). European Resuscitation Council Guidelines 2021: Executive summary. *Resuscitation*, *161*, 1–60. <https://doi.org/10.1016/j.resuscitation.2021.02.003>
- Perkins, G. D., Jacobs, I. G., Nadkarni, V. M., Berg, R. A., Bhanji, F., Biarent, D., Bossaert, L. L., Brett, S. J., Chamberlain, D., de Caen, A. R., Deakin, C. D., Finn, J. C., Gräsner, J.-T., Hazinski, M. F., Iwami, T., Koster, R. W., Lim, S. H., Ma, M. H.-M., McNally, B. F., ... Nolan, J. P. (2015). Cardiac Arrest and Cardiopulmonary Resuscitation Outcome Reports: Update of the Utstein Resuscitation Registry Templates for Out-of-Hospital Cardiac Arrest: A Statement for Healthcare Professionals From a Task Force of the International Liaison Committee on Resuscitation (American Heart Association, European Resuscitation Council, Australian and New Zealand Council on Resuscitation, Heart and Stroke Foundation of Canada, InterAmerican Heart Foundation, Resuscitation Council of Southern Africa, Resuscitation Council of Asia); and the American Heart Association Emergency Cardiovascular Care Committee and the Council on Cardiopulmonary, Critical Care, Perioperative and Resuscitation. *Resuscitation*, *96*, 328–340. <https://doi.org/10.1016/j.resuscitation.2014.11.002>

- Perkins, G. D., Travers, A. H., Berg, R. A., Castren, M., Considine, J., Escalante, R., Gazmuri, R. J., Koster, R. W., Lim, S. H., Nation, K. J., Olasveengen, T. M., Sakamoto, T., Sayre, M. R., Sierra, A., Smyth, M. A., Stanton, D., Vaillancourt, C., Bierens, J. J. L. M., Bourdon, E., ... Yeung, J. (2015). European Resuscitation Council Guidelines for Resuscitation 2015. *Resuscitation, European Resuscitation Council Guidelines for Resuscitation 2015*, 95, e43–e69. <https://doi.org/10.1016/j.resuscitation.2015.07.041>
- Piaggio, D., Castaldo, R., Cinelli, M., Cinelli, S., Maccaro, A., & Pecchia, L. (2021). A framework for designing medical devices resilient to low-resource settings. *Globalization and Health*, 17(1), 64. <https://doi.org/10.1186/s12992-021-00718-z>
- Pietzsch, J. B., Shluzas, L. A., Paté-Cornell, M. E., Yock, P. G., & Linehan, J. H. (2009). Stage-Gate Process for the Development of Medical Devices. *Journal of Medical Devices*, 3(2), 021004. <https://doi.org/10.1115/1.3148836>
- Plata, C., Nowack, M., Loeser, J., Drinhaus, H., Steinhäuser, S., Hinkelbein, J., Wetsch, W. A., Böttiger, B. W., & Spelten, O. (2021). Verbal Motivation vs. Digital Real-Time Feedback during Cardiopulmonary Resuscitation: Comparing Bystander CPR Quality in a Randomized and Controlled Manikin Study of Simulated Cardiac Arrest. *Prehospital Emergency Care: Official Journal of the National Association of EMS Physicians and the National Association of State EMS Directors*, 25(3), 377–387. <https://doi.org/10.1080/10903127.2020.1757181>
- Plata, C., Stolz, M., Warnecke, T., Steinhäuser, S., Hinkelbein, J., Wetsch, W. A., Böttiger, B. W., & Spelten, O. (2019). Using a smartphone application (PocketCPR) to determine CPR quality in a bystander CPR scenario—A manikin trial. *Resuscitation*, 137, 87–93. <https://doi.org/10.1016/j.resuscitation.2019.01.039>
- Prabowo, N. K., Paristiowati, M., & Irwanto, I. (2024). Arduino-based real-time data acquisition systems: Boosting STEM career interest. *International Journal of Evaluation and Research in Education (IJERE)*, 13(4), 2316–2325. <https://doi.org/10.11591/ijere.v13i4.27001>
- Prochner, I., & Godin, D. (2022). Quality in research through design projects: Recommendations for evaluation and enhancement. *Design Studies*, 78, 101061. <https://doi.org/10.1016/j.destud.2021.101061>
- Qvigstad, E., Kramer-Johansen, J., Tømte, Ø., Skålhegg, T., Sørensen, Ø., Sunde, K., & Olasveengen, T. M. (2013). Clinical pilot study of different hand positions during manual chest compressions monitored with capnography. *Resuscitation*, 84(9), 1203–1207. <https://doi.org/10.1016/j.resuscitation.2013.03.010>
- Redberg, R. F., Tucker, K. J., Cohen, T. J., Dutton, J. P., Callahan, M. L., & Schiller, N. B. (1993). Physiology of blood flow during cardiopulmonary resuscitation. A transesophageal echocardiographic study. *Circulation*, 88(2), 534–542. <https://doi.org/10.1161/01.cir.88.2.534>
- Rettinger, M., Steinhäuser, J., Hackenberg, A., Lehr, L., Neugebauer, P., Müller, N., Rigoll, G., & Schmaderer, C. (2024). Optimizing Medical Device Training: The Role of Multi-User VR and Expert Guidance. *Companion Publication of the 2024 Conference on Computer-Supported Cooperative Work and Social Computing, CSCW Companion '24*, 403–409. <https://doi.org/10.1145/3678884.3681883>
- Reynolds, J. C., Salcido, D. D., & Menegazzi, J. J. (2010). Coronary perfusion pressure and return of spontaneous circulation after prolonged cardiac arrest. *Prehospital Emergency Care*, 14(1), 78–84. <https://doi.org/10.3109/10903120903349796>
- Riley, L. E., Mehta, H. J., & Lascano, J. (2020). Single-center In-hospital Cardiac Arrest Outcomes. *Indian Journal of Critical Care Medicine: Peer-Reviewed, Official Publication of Indian Society of Critical Care Medicine*, 24(1), 44–48. <https://doi.org/10.5005/jp-journals-10071-23327>
- Ristagno, G., Tang, W., & Weil, M. H. (2009). Cardiopulmonary Resuscitation: From the Beginning to the Present Day. *Critical Care Clinics*, 25(1), 133–151. <https://doi.org/10.1016/j.ccc.2008.10.004>
- Riyapan, S., Naulnark, T., Ruangsomboon, O., Chaisirin, W., Limsuwat, C., Prapruetkit, N., Chakorn, T., & Monsomboon, A. (2019). Improving quality of chest compression in thai emergency

- department by using real-time audio-visual feedback cardio-pulmonary resuscitation monitoring. *Journal of the Medical Association of Thailand*, 102(3), 245–251.
- Rodriguez, N. M., Burseson, G., Linnes, J. C., & Sienko, K. H. (2023). Thinking Beyond the Device: An Overview of Human- and Equity-Centered Approaches for Health Technology Design. *Annual Review of Biomedical Engineering*, 25(Volume 25, 2023), 257–280. <https://doi.org/10.1146/annurev-bioeng-081922-024834>
- Roth, G. A., Mensah, G. A., Johnson, C. O., Addolorato, G., Ammirati, E., Baddour, L. M., Barengo, N. C., Beaton, A. Z., Benjamin, E. J., Benziger, C. P., Bonny, A., Brauer, M., Brodmann, M., Cahill, T. J., Carapetis, J., Catapano, A. L., Chugh, S. S., Cooper, L. T., Coresh, J., ... Fuster, V. (2020). Global Burden of Cardiovascular Diseases and Risk Factors, 1990–2019: Update From the GBD 2019 Study. *Journal of the American College of Cardiology*, 76(25), 2982–3021. <https://doi.org/10.1016/j.jacc.2020.11.010>
- Rudikoff, M. T., Maughan, W. L., Effron, M., Freund, P., & Weisfeldt, M. L. (1980). Mechanisms of blood flow during cardiopulmonary resuscitation. *Circulation*, 61(2), 345–352. <https://doi.org/10.1161/01.CIR.61.2.345>
- Sandroni, C., Cronberg, T., & Sekhon, M. (2021). Brain injury after cardiac arrest: Pathophysiology, treatment, and prognosis. *Intensive Care Medicine*, 47(12), 1393–1414. <https://doi.org/10.1007/s00134-021-06548-2>
- Sansbury, B. E., Nystoriak, M. A., Uchida, S., Wysoczynski, M., & Moore, J. B. (2022). Rigor Me This: What Are the Basic Criteria for a Rigorous, Transparent, and Reproducible Scientific Study? *Frontiers in Cardiovascular Medicine*, 9. <https://doi.org/10.3389/fcvm.2022.913612>
- Schmidt, N. A., & Brown, J. M. (2021). *Evidence-Based Practice for Nurses: Appraisal and Application of Research*. Jones & Bartlett Learning.
- Seim, C. E., Ritter, B., Starner, T. E., Flavin, K., Lansberg, M. G., & Okamura, A. M. (2022). Design of a Wearable Vibrotactile Stimulation Device for Individuals With Upper-Limb Hemiparesis and Spasticity. *IEEE Transactions on Neural Systems and Rehabilitation Engineering: A Publication of the IEEE Engineering in Medicine and Biology Society*, 30, 1277–1287. <https://doi.org/10.1109/TNSRE.2022.3174808>
- Sevil, H., Bastan, V., Gültürk, E., El Majzoub, I., & Göksu, E. (2021). Effect of smartphone applications on cardiopulmonary resuscitation quality metrics in a mannequin study: A randomized trial. *Turkish Journal of Emergency Medicine*, 21(2), 56–61. <https://doi.org/10.4103/2452-2473.313333>
- Shadish, W. R., Cook, T. D., & Campbell, D. T. (2002). Experimental and Quasi-Experimental Designs for Generalized Causal Inference. *Social Service Review*, 76(3), 510–514. <https://doi.org/10.1086/345281>
- Shah, S. G. S., & Robinson, I. (2006). User involvement in healthcare technology development and assessment: Structured literature review. *International Journal of Health Care Quality Assurance*, 19(6), 500–515. <https://doi.org/10.1108/09526860610687619>
- Shah, S. G. S., & Robinson, I. (2007). Benefits of and barriers to involving users in medical device technology development and evaluation. *International Journal of Technology Assessment in Health Care*, 23(1), 131–137. <https://doi.org/10.1017/S0266462307051677>
- Shah, S. G. S., Robinson, I., & AlShawi, S. (2009). Developing medical device technologies from users' perspectives: A theoretical framework for involving users in the development process. *International Journal of Technology Assessment in Health Care*, 25(4), 514–521. <https://doi.org/10.1017/S0266462309990328>
- Shaheen, N., Shaheen, A., Ramadan, A., Hefhawy, M. T., Ramadan, A., Ibrahim, I. A., Hassanein, M. E., Ashour, M. E., & Flouty, O. (2023). Appraising systematic reviews: A comprehensive guide to ensuring validity and reliability. *Frontiers in Research Metrics and Analytics*, 8. <https://doi.org/10.3389/frma.2023.1268045>
- Slabe, D., Metelko, Ž., & Šparovec, E. D. (2024). The impact on users of an unfamiliar AED following a recent training experience: A randomized cross over simulation study. *Resuscitation Plus*, 20, 100758. <https://doi.org/10.1016/j.resplu.2024.100758>

- Smereka, J., Bielski, K., Ladny, J. R., Ruetzler, K., & Szarpak, L. (2017). Evaluation of a newly developed infant chest compression technique: A randomized crossover manikin trial. *Medicine*, *96*(14), 1–6. CINAHL. <https://doi.org/10.1097/MD.00000000000005915>
- Smereka, J., Szarpak, L., Czekajlo, M., Abelson, A., Zwolinski, P., Plusa, T., Dunder, D., Dabrowski, M., Wiesniewska, Z., Robak, O., Frass, M., Sivrikaya G., U., & Ruetzler, K. (2019). The TrueCPR device in the process of teaching cardiopulmonary resuscitation. *Medicine*, *98*(27), e15995. <https://doi.org/10.1097/MD.00000000000015995>
- Smith, V., Warty, R., Nair, A., Krishnan, S., Sursas, J. A., da Silva Costa, F., Vollenhoven, B., & Wallace, E. M. (2019). Defining the clinician's role in early health technology assessment during medical device innovation – a systematic review. *BMC Health Services Research*, *19*(1), 514. <https://doi.org/10.1186/s12913-019-4305-9>
- Soenksen, L. R., & Yazdi, Y. (2017). Stage-gate process for life sciences and medical innovation investment. *Technovation*, *62–63*, 14–21. <https://doi.org/10.1016/j.technovation.2017.03.003>
- Song, Y., Chee, Y., Oh, J., Ahn, C., & Lim, T. H. (2016). Smartwatches as chest compression feedback devices: A feasibility study. *Resuscitation*, *103*, 20–23. <https://doi.org/10.1016/j.resuscitation.2016.03.014>
- Sood, N., Sangari, A., Goyal, A., Sun, C., Horinek, M., Hauger, J. A., & Perry, L. (2023). Do cardiopulmonary resuscitation real-time audiovisual feedback devices improve patient outcomes? A systematic review and meta-analysis. *World Journal of Cardiology*, *15*(10), 531–541. <https://doi.org/10.4330/wjc.v15.i10.531>
- Souchtchenko, S. S., Benner, J. P., Allen, J. L., & Brady, W. J. (2013). A Review of Chest Compression Interruptions During Out-of-Hospital Cardiac Arrest and Strategies for the Future. *The Journal of Emergency Medicine*, *45*(3), 458–466. <https://doi.org/10.1016/j.jemermed.2013.01.023>
- Standards for CPR and ECC. (1986). Standards and Guidelines for Cardiopulmonary Resuscitation (CPR) and Emergency Cardiac Care (ECC). *JAMA: The Journal of the American Medical Association*, *255*(21), 2905–2989. <https://doi.org/10.1001/jama.1986.03370210073024>
- Stappers, P., & Giaccardi, E. (2014). Research through Design. In *The Encyclopedia of Human-Computer Interaction* (2nd Ed). <https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/research-through-design>
- Stassen, W., Wylie, C., Djärv, T., & Wallis, L. A. (2021). Out-of-hospital cardiac arrests in the city of Cape Town, South Africa: A retrospective, descriptive analysis of prehospital patient records. *BMJ Open*, *11*(8), e049141. <https://doi.org/10.1136/bmjopen-2021-049141>
- Stiell, I. G., Brown, S. P., Christenson, J., Cheskes, S., Nichol, G., Powell, J., Bigham, B., Morrison, L. J., Larsen, J., Hess, E., Vaillancourt, C., Davis, D. P., & Callaway, C. W. (2012). What is the Role of Chest Compression Depth during Out-of-Hospital Cardiac Arrest Resuscitation? *Critical Care Medicine*, *40*(4), 1192–1198. <https://doi.org/10.1097/CCM.0b013e31823bc8bb>
- Stiell, I. G., Brown, S. P., Nichol, G., Cheskes, S., Vaillancourt, C., Callaway, C. W., Morrison, L. J., Christenson, J., Aufderheide, T. P., Davis, D. P., Free, C., Hostler, D., Stouffer, J. A., Idris, A. H., & the Resuscitation Outcomes Consortium Investigators. (2014). What Is the Optimal Chest Compression Depth During Out-of-Hospital Cardiac Arrest Resuscitation of Adult Patients? *Circulation*, *130*(22), 1962–1970. <https://doi.org/10.1161/CIRCULATIONAHA.114.008671>
- Suet, G., Blanie, A., de Montblanc, J., Roulleau, P., & Benhamou, D. (2020). External Cardiac Massage Training of Medical Students: A Randomized Comparison of Two Feedback Methods to Standard Training. *The Journal of Emergency Medicine*, *59*(2), 270–277. <https://doi.org/10.1016/j.jemermed.2020.04.058>
- Sumera, K., Ilczak, T., Bakkerud, M., Lane, J. D., Pallas, J., Martorell, S. O., Sumera, A., Webster, C. A., Quinn, T., Sandars, J., & Niroshan Siriwardena, A. (2024). CPR Quality Officer role to improve CPR quality: A multi-centred international simulation randomised control trial. *Resuscitation Plus*, *17*, 100537. <https://doi.org/10.1016/j.resplu.2023.100537>
- Thibodeau, J., Werner, K., Wallis, L. A., & Stassen, W. (2022). Out-of-hospital cardiac arrest in Africa: A scoping review. *BMJ Open*, *12*(3), e055008. <https://doi.org/10.1136/bmjopen-2021-055008>

- Townsend, R. C., Karttunen, A. J., Karppinen, M., & Mikkonen, J. (2017). The Cross-section of a Multi-disciplinary Project in View of Smart Textile Design Practice. *Journal of Textile Design Research and Practice*, 5(2), 175–207. <https://doi.org/10.1080/20511787.2018.1449076>
- Travers, A. H., Perkins, G. D., Berg, R. A., Castren, M., Considine, J., Escalante, R., Gazmuri, R. J., Koster, R. W., Lim, S. H., Nation, K. J., Olasveengen, T. M., Sakamoto, T., Sayre, M. R., Sierra, A., Smyth, M. A., Stanton, D., & Vaillancourt, C. (2015). Part 3: Adult Basic Life Support and Automated External Defibrillation: 2015 International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science with Treatment Recommendations. *Circulation*, 132(16\_suppl\_1), S51–S83. <https://doi.org/10.1161/CIR.0000000000000272>
- Tsai, I.-C., Wang, C.-D., & Chen, P.-T. (2023). Strategies for Medical Device Development: User and Stakeholder Perceptions. *Journal of Healthcare Engineering*, 2023(1), 6724656. <https://doi.org/10.1155/2023/6724656>
- Tse, M. M. Y., Tang, A., Budnick, A., Ng, S. S. M., & Yeung, S. S. Y. (2017). Pain and Pain Management Among University Students: Online Survey and Web-Based Education. *Cyberpsychology, Behavior and Social Networking*, 20(5), 305–313. <https://doi.org/10.1089/cyber.2016.0580>
- Tseklevs, E., Cooper, R., Jacobs, N., & Cureton, P. (2025). Designing the future of healthcare: The role of design research in shaping digital twin technologies. *Design for Health*, 9(1), 121–131. <https://doi.org/10.1080/24735132.2025.2483479>
- Urbaniak, G. C., & Plous, S. (2013). *Research Randomizer (Version 4.0) [Computer software]*. <https://www.randomizer.org/>
- Ushimaru, Y., Katoh, T., Sasaki, M., Hata, T., Hosaka, M., Eguchi, H., Doki, Y., & Nakajima, K. (2025). Development of medical devices driven by academia-industry collaboration: An internal audit. *Surgery*, 181, 109289. <https://doi.org/10.1016/j.surg.2025.109289>
- Vadeboncoeur, T., Stolz, U., Panchal, A., Silver, A., Venuti, M., Tobin, J., Smith, G., Nunez, M., Karamooz, M., Spaite, D., & Bobrow, B. (2014). Chest compression depth and survival in out-of-hospital cardiac arrest. *Resuscitation*, 85(2), 182–188. <https://doi.org/10.1016/j.resuscitation.2013.10.002>
- Vaisson, G., Provencher, T., Dugas, M., Trottier, M.-È., Chipenda Dansokho, S., Colquhoun, H., Fagerlin, A., Giguere, A. M. C., Hakim, H., Haslett, L., Hoffman, A. S., Ivers, N. M., Julien, A.-S., Légaré, F., Renaud, J.-S., Stacey, D., Volk, R. J., & Witteman, H. O. (2021). User Involvement in the Design and Development of Patient Decision Aids and Other Personal Health Tools: A Systematic Review. *Medical Decision Making*, 41(3), 261–274. <https://doi.org/10.1177/0272989X20984134>
- van der Bijl-Brouwer, M., & Dorst, K. (2017). Advancing the strategic impact of human-centred design. *Design Studies*, 53, 1–23. <https://doi.org/10.1016/j.destud.2017.06.003>
- Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User Acceptance of Information Technology: Toward a Unified View. *MIS Quarterly*, 27(3), 425–478. <https://doi.org/10.2307/30036540>
- Vincent, A., Semmer, N. K., Becker, C., Beck, K., Tschan, F., Bobst, C., Schuetz, P., Marsch, S., & Hunziker, S. (2021). Does stress influence the performance of cardiopulmonary resuscitation? A narrative review of the literature. *Journal of Critical Care*, 63, 223–230. <https://doi.org/10.1016/j.jcrc.2020.09.020>
- Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson, J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., ... SciPy 1.0 Contributors. (2020). SciPy 1.0: Fundamental algorithms for scientific computing in Python. *Nature Methods*, 17(3), 261–272. <https://doi.org/10.1038/s41592-019-0686-2>
- Visocky O’Grady, J., & Visocky O’Grady, K. (2017). *A designer’s research manual: Succeed in design by knowing your clients + understanding what they really need* (Second edition, updated + expanded). Rockport, an imprint of The Quarto Group.

- Wang, S.-A., Su, C.-P., Fan, H.-Y., Hou, W.-H., & Chen, Y.-C. (2020). Effects of real-time feedback on cardiopulmonary resuscitation quality on outcomes in adult patients with cardiac arrest: A systematic review and meta-analysis. *Resuscitation*, *155*, 82–90. <https://doi.org/10.1016/j.resuscitation.2020.07.024>
- Wang, Y., Ma, S., Chen, Z., Fan, B., & Hou, S. (2023). Feedback Devices for Cardiopulmonary Resuscitation: A Narrative Review. *Applied Sciences*, *13*(18), 10222. <https://doi.org/10.3390/app131810222>
- Ward, S. R., Scott, B. C., Rubin, D. M., & Pantanowitz, A. (2019). Development of a novel cardiopulmonary resuscitation measurement tool using real-time feedback from wearable wireless instrumentation. *Resuscitation*, *137*, 183–189. <https://doi.org/10.1016/j.resuscitation.2019.02.019>
- Watkinson, F., Dharmayat, K. I., & Mastellos, N. (2021). A mixed-method service evaluation of health information exchange in England: Technology acceptance and barriers and facilitators to adoption. *BMC Health Services Research*, *21*(1), 737. <https://doi.org/10.1186/s12913-021-06771-z>
- Weenk, M., Bredie, S. J., Koeneman, M., Hesselink, G., Goor, H. van, & Belt, T. H. van de. (2020). Continuous Monitoring of Vital Signs in the General Ward Using Wearable Devices: Randomized Controlled Trial. *Journal of Medical Internet Research*, *22*(6), e15471. <https://doi.org/10.2196/15471>
- Wik, L., Steen, P. A., & Bircher, N. G. (1994). Quality of bystander cardiopulmonary resuscitation influences outcome after prehospital cardiac arrest. *Resuscitation*, *28*(3), 195–203. [https://doi.org/10.1016/0300-9572\(94\)90064-7](https://doi.org/10.1016/0300-9572(94)90064-7)
- Wilson, C., Furness, E., Proctor, L., Sweetman, G., & Hird, K. (2021). A randomised trial of the effectiveness of instructor versus automated manikin feedback for training junior doctors in life support skills. *Perspectives on Medical Education*, *10*(2), 95–100. <https://doi.org/10.1007/s40037-020-00631-y>
- Wingen, S., Großfeld, N., Adams, N.-B., Streit, A., Stock, J., Böttiger, B. W., & Wetsch, W. A. (2024). Do laypersons need App-linked real-time feedback devices for effective resuscitation? – Results of a prospective, randomised simulation trial. *Resuscitation Plus*, *18*, 100631. <https://doi.org/10.1016/j.resplu.2024.100631>
- World Medical Association. (2004). *WMA - The World Medical Association-WMA Declaration of Helsinki – Ethical Principles for Medical Research Involving Human Participants*. <https://www.wma.net/policies-post/wma-declaration-of-helsinki/>
- Wutzler, A., von Ulmenstein, S., Bannehr, M., Völk, K., Förster, J., Storm, C., & Haverkamp, W. (2018). Improvement of lay rescuer chest compressions with a novel audiovisual feedback device: A randomized trial. *Medizinische Klinik, Intensivmedizin Und Notfallmedizin*, *113*(2), 124–130. (CN-01944687). <https://doi.org/10.1007/s00063-017-0278-9>
- Wyckoff, M. H., Greif, R., Morley, P. T., Ng, K.-C., Olasveengen, T. M., Singletary, E. M., Soar, J., Cheng, A., Drennan, I. R., Liley, H. G., Scholefield, B. R., Smyth, M. A., Welsford, M., Zideman, D. A., Acworth, J., Aickin, R., Andersen, L. W., Atkins, D., Berry, D. C., ... Collaborators. (2022). 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*, *146*(25), e483–e557. <https://doi.org/10.1161/CIR.0000000000001095>
- Xie, J., & Wu, Q. (2023). Design and Evaluation of CPR Emergency Equipment for Non-Professionals. *Sensors*, *23*(13), 5948. <https://doi.org/10.3390/s23135948>
- Yan, S., Gan, Y., Jiang, N., Wang, R., Chen, Y., Luo, Z., Zong, Q., Chen, S., & Lv, C. (2020). The global survival rate among adult out-of-hospital cardiac arrest patients who received cardiopulmonary resuscitation: A systematic review and meta-analysis. *Critical Care (London, England)*, *24*(1), 61. <https://doi.org/10.1186/s13054-020-2773-2>

- Yang, H., Yu, J., Zo, H., & Choi, M. (2016). User acceptance of wearable devices: An extended perspective of perceived value. *Telematics and Informatics*, 33(2), 256–269. <https://doi.org/10.1016/j.tele.2015.08.007>
- Yang, Q., Mamun, A. A., Hayat, N., Salleh, M. F. M., Jingzu, G., & Zainol, N. R. (2022). Modelling the mass adoption potential of wearable medical devices. *PLOS ONE*, 17(6), e0269256. <https://doi.org/10.1371/journal.pone.0269256>
- 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. <https://doi.org/10.1016/j.resuscitation.2009.04.012>
- Yin, Z., Yan, J., Fang, S., Wang, D., & Han, D. (2022). User acceptance of wearable intelligent medical devices through a modified unified theory of acceptance and use of technology. *Annals of Translational Medicine*, 10(11), 629. <https://doi.org/10.21037/atm-21-5510>
- Yow, A. G., Rajasurya, V., Ahmed, I., & Sharma, S. (2024). Sudden Cardiac Death. In *StatPearls*. StatPearls Publishing. <http://www.ncbi.nlm.nih.gov/books/NBK507854/>
- Zapletal, B., Greif, R., Stumpf, D., Nierscher, F. J., Frantal, S., Haugk, M., Ruetzler, K., Schlimp, C., & Fischer, H. (2014). Comparing three CPR feedback devices and standard BLS in a single rescuer scenario: A randomised simulation study. *Resuscitation*, 85(4), 560–566. <https://doi.org/10.1016/j.resuscitation.2013.10.028>
- Zhang, F., Yan, L., Huang, S., & Bai, X. (2013). Correlations between quality indexes of chest compression. *World Journal of Emergency Medicine*, 4(1), 54–58. <https://doi.org/10.5847/wjem.j.issn.1920-8642.2013.01.010>
- Zimmerman, D. S., & Tan, H. L. (2021). Epidemiology and risk factors of sudden cardiac arrest. *Current Opinion in Critical Care*, 27(6), 613–616. <https://doi.org/10.1097/MCC.0000000000000896>
- Zimmerman, J., & Forlizzi, J. (2014). Research Through Design in HCI. In J. S. Olson & W. A. Kellogg (Eds), *Ways of Knowing in HCI* (pp. 167–189). Springer. [https://doi.org/10.1007/978-1-4939-0378-8\\_8](https://doi.org/10.1007/978-1-4939-0378-8_8)

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# Appendices

**Appendix 1.** Details Database Search Strategy. Modified from Supplementary data S1, Paper 1

DATABASES	SEARCH STRING
<b>PUBMED</b>	("Audiovisual feedback*" [tiab] OR Audiovisual* [tiab] OR Audio-visual* [tiab] OR "feed-back" [tiab] OR "feedback system*" [tiab] OR feedback* [tiab] OR feedback [MeSH] OR Realtime OR real-time [tiab] OR "feedback device*" [tiab]) AND (CPR OR Resuscitation* [tiab] OR "cardiopulmonary resuscitation" [MeSH] OR "cardiopulmonary resuscitation*" [tiab] OR "chest compression*" [tiab] OR "Advanced cardiac life support" [Mesh] OR "Advanced cardiac life support" [tiab] OR ACLS OR "Advanced Life support" OR ALS OR "Basic Life Support" [tiab] OR BLS) AND (Train* OR "Simulation Training" [Mesh] OR "Simulation Training*" [tiab] OR "Education" [Mesh] OR education* [tiab] OR "Teaching" [Mesh] OR Teach* OR Learn*) NOT ("Defibrillators" [Mesh] OR defibrillator* [tiab] OR "automated external defibrillator*" [tiab] OR AED)
<b>EMBASE</b>	("Audiovisual feedback*" OR Audiovisual* OR Audio-visual* OR "feed-back" OR "feedback system"/exp OR feedback* OR feedback* OR "CPR feedback device"/exp OR "CPR feedback device*" OR Realtime OR real-time OR "feedback device*") AND (CPR OR "resuscitation"/exp OR Resuscitation* OR "cardiopulmonary resuscitation*" OR "chest compression*" OR "advanced cardiac life support"/exp OR "advanced life support"/exp OR ALS OR "Advanced cardiac life support" OR ACLS OR "Basic Life Support" OR "basic life support"/exp OR BLS) AND ("training"/exp OR Train* OR "simulation training"/exp OR "Simulation Train*" OR "education"/exp OR education* OR "teaching"/exp OR Teach* OR "learning"/exp OR Learn*) NOT ("defibrillator"/exp OR defibrillator* OR "automated external defibrillator"/exp OR "automated external defibrillator*" OR AED)
<b>COCHRANE</b>	(Audiovisual NEXT feedback* OR Audiovisual* OR Audio-visual* OR feedback OR feedback OR feedback NEXT system* OR feedback* OR Realtime* OR feedback NEXT device*) AND (CPR OR Resuscitation* OR "cardiopulmonary resuscitation" OR "cardiopulmonary NEXT resuscitation*" OR "chest NEXT compression*" OR "Advanced cardiac life support" OR Advanced NEXT cardiac NEXT life NEXT support* OR ACLS OR "Advanced Life support" OR ALS OR Basic NEXT Life NEXT Support* OR BLS) (Audiovisual NEXT feedback* OR Audiovisual* OR Audio-visual* OR feedback OR feedback OR feedback NEXT system* OR feedback* OR Realtime* OR feedback NEXT device*) AND (CPR OR Resuscitation* OR "cardiopulmonary resuscitation" OR "cardiopulmonary NEXT resuscitation*" OR "chest NEXT compression*" OR "Advanced cardiac life support" OR Advanced NEXT cardiac NEXT life NEXT support* OR ACLS OR "Advanced Life support" OR ALS OR Basic NEXT Life NEXT Support* OR BLS)

	OR "chest NEXT compression*" OR "Advanced cardiac life support" OR Advanced NEXT cardiac NEXT life NEXT support* OR ACLS OR "Advanced Life support" OR ALS OR Basic NEXT Life NEXT Support* OR BLS) AND (Train* OR education* OR Teach* OR Learn*) NOT (defibrillator* OR AED)
<b>CINAHL</b>	("TI Audiovisual feedback*" OR AB "Audiovisual feedback*" OR TI Audiovisual* OR AB Audiovisual* OR (MH "Audiovisuals+") OR TI "Audiovisual*" OR AB "Audio-visual*" OR (MH "Feedback") OR TI "feedback*" OR AB "Feedback" OR TI "feedback system*" OR AB "feedback system*" OR TI "feedback device*" OR AB "feedback device*" OR TI "Realtime" OR AB Realtime OR TI "real-time" OR AB "real-time") AND (CPR OR (MH "Resuscitation+") OR TI "Resuscitation*" OR AB "Resuscitation" OR (MH "Resuscitation, Cardiopulmonary+") OR TI "cardiopulmonary resuscitation*" OR AB "cardiopulmonary resuscitation*" OR TI "chest compression*" OR AB "chest compression*" OR (MH "Advanced Cardiac Life Support+") OR TI "Advanced cardiac life support" OR AB "Advanced cardiac life support" OR ACLS OR TI "Advanced Life support" OR AB "Advanced Life support" OR ALS OR TI "Basic Life Support" OR AB "Basic Life Support" OR BLS) AND ( TI "Train*" OR AB "Train*" OR TI "Simulation Training" OR AB "Simulation Training" OR (MH "Education+") OR TI "education*" OR AB "education*" OR (MH "Teaching+") OR TI "Teach*" OR AB "Teach*" OR (MH "Learning+") OR TI "Learn*" OR AB "Learn*" ) NOT ((MH "Defibrillators+") OR "defibrillator*" OR (MH "Defibrillators, Automated External") OR "automated external defibrillator*" OR AED)
<b>WEB OF SCIENCE</b>	("Audiovisual feedback*" OR Audiovisual* OR Audio-visual* OR "feed-back" OR "feedback system*" OR feedback OR Realtime OR real-time OR "feedback device*") AND (CPR OR Resuscitation* OR "cardiopulmonary resuscitation" OR "cardiopulmonary resuscitation*" OR "chest compression*" OR "Advanced cardiac life support" OR "Advanced cardiac life support" OR ACLS OR "Advanced Life support" OR ALS OR "Basic Life Support" OR BLS) AND (Train* OR "Simulation Training" OR "Simulation Training*" OR "Education" OR education* OR "Teaching" OR Teach* OR Learn*) AND ("randomized controlled trial" OR "controlled trial" OR trail*) NOT (defibrillator* OR "automated external defibrillator*" OR AED)
<b>APA PSYCINFO</b>	(DE "Feedback" OR DE "Sensory Feedback" OR DE " Feedback" OR "feedback device*" OR "Realtime feedback*") AND (DE "CPR" OR "Cardiopulmonary resuscitation" OR "Chest compression" OR "cardiac massage" OR "Advanced cardiac life support" OR ALS OR "Basic Life Support" OR BLS) AND (DE "Simulation" OR DE "Computer Simulation" OR DE "Simulation-Based Assessment" OR DE "Stimulation" OR Manikin OR Mannequin OR dummy OR doll) AND (( DE "Simulation-Based Assessment" OR TI "Simulation Training" OR AB "Simulation Training" OR DE "Clinical Methods Training" OR (D "CPR Education" OR AB "simulation Education" OR TI" CPR Learning " OR AB"CPR Learning" OR AB"CPR Teach*" OR TI"CPR Teaching" OR AB"CPR Teaching") NOT ("defibrillator* OR "automated external defibrillator*" OR AED)





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