



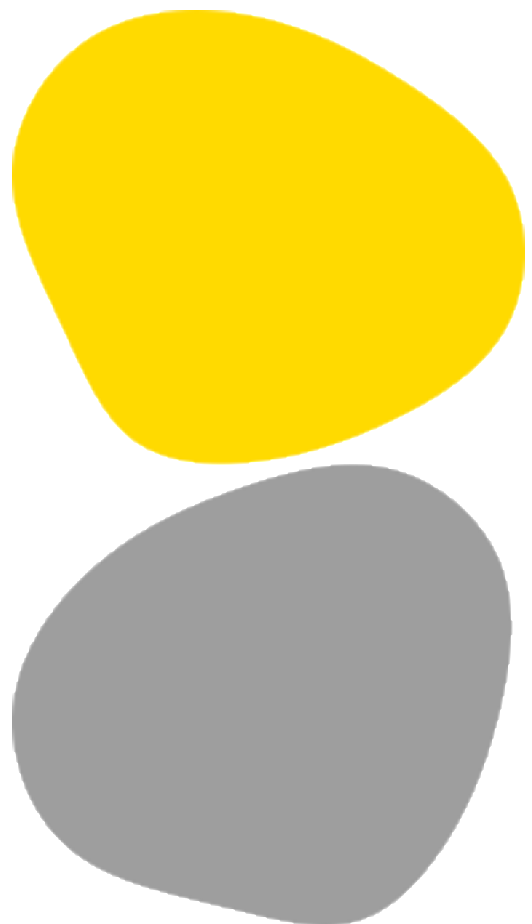
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HIGIENE E SEGURANÇA NAS ORGANIZAÇÕES

Monitoring of firefighters workload with wearable sensors: Analysing technologies, strengths, and constraints of chest-strap devices

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Resumo

Os bombeiros, no decorrer da sua atividade, estão expostos a diversos riscos. Particular atenção tem sido dada à carga de trabalho física e mental a que se encontram sujeitos. Contudo, é importante notar, que estes contribuem também para o risco de ocorrência de eventos cardiovasculares. Neste contexto, os sensores vestíveis de banda peitoral emergem como ferramentas promissoras para a monitorização em tempo real de parâmetros fisiológicos em ambientes laborais de elevada exigência. Este trabalho analisa o papel dos sensores torácicos na proteção da saúde dos profissionais de emergência, nomeadamente dos bombeiros, avaliando o estado atual desta tecnologia vestível para monitorização de variáveis cardíacas. Para isso, foi realizada uma revisão sistemática da literatura, na qual se identificam e analisam criticamente os dispositivos vestíveis de banda torácica utilizados em estudos científicos, assim como as vantagens e limitações dos mesmos.

A revisão bibliográfica foi realizada nas bases de dados PubMed, Scopus, Web of Science e Science Direct, abrangendo publicações dos últimos 10 anos. Os critérios de inclusão foram definidos utilizando a estratégia PICO, e a qualidade metodológica dos 32 estudos elegíveis foi avaliada através da ferramenta *Mixed Methods Appraisal Tool*. Os dispositivos mais frequentemente analisados foram o Polar H10 e o Zephyr BioHarness 3.0.

Estes sensores demonstraram elevada fiabilidade, com fortes correlações com a eletrocardiografia, especialmente em condições de repouso ou de atividade física ligeira a moderada. Permitem obter variáveis como variabilidade da frequência cardíaca, frequência cardíaca, intervalo R-R e análise da morfologia do traçado eletrocardiográfico. Contudo, foram identificadas várias limitações importantes: a precisão pode ser comprometida por artefactos de movimento, colocação incorreta da cinta, transpiração excessiva e deterioração da interface pele-elétrodo. Foi também observado que os sensores analisados não possuem certificação *Conformité Européenne (CE)* ou *Food and Drug Administration (FDA)* para uso clínico, sendo geralmente comercializados como dispositivos de bem-estar ou fitness. A maioria dos estudos foi realizada em ambientes laboratoriais, o que limita a generalização dos resultados para contextos do mundo real. Foram igualmente salientadas preocupações ergonómicas, como desconforto durante o uso prolongado e mobilidade restrita para certas populações. No geral, o estudo mostrou que existem no mercado disponíveis alguns dispositivos que poderão ser usados em bombeiros para determinar situações de fadiga, mas também potenciais eventos cardíacos. Contudo, algumas carecem de estudos adicionais, nomeadamente em contexto real.

Palavras-chave: sensores vestíveis; bandas torácicas; monitorização cardíaca; bombeiros; saúde ocupacional

Abstract

Firefighters, in the course of their duties, are exposed to various risks. Particular attention has been given to the physical and mental workload to which they are subjected. However, it is also important to note that these factors contribute to the risk of cardiovascular events. In this context, wearable chest-strap sensors have emerged as promising tools for real-time monitoring of physiological parameters in highly demanding work environments. This study examines the role of chest sensors in protecting the health of emergency professionals, particularly firefighters, by evaluating the current state of this wearable technology for monitoring cardiac variables.

To this end, a systematic literature review was conducted, identifying and critically analysing chest-strap wearable devices used in scientific studies, as well as their advantages and limitations. The literature review was carried out using the PubMed, Scopus, Web of Science and ScienceDirect databases, covering publications from the past 10 years. The inclusion criteria were defined using the PICO strategy, and the methodological quality of the 32 eligible studies was assessed using the Mixed Methods Appraisal Tool. The most frequently analysed devices were the Polar H10 and the Zephyr BioHarness 3.0.

These sensors demonstrated high reliability, with strong correlations with electrocardiography, particularly under resting conditions or during light to moderate physical activity. They allow for the collection of variables such as heart rate variability, heart rate, R-R interval, and analysis of the electrocardiographic waveform morphology. However, several important limitations were identified: accuracy can be compromised by motion artefacts, incorrect strap placement, excessive sweating, and deterioration of the skin-electrode interface. It was also observed that the sensors analysed do not carry *Conformité Européenne (CE)* or Food and Drug Administration (FDA) certification for clinical use, being generally marketed as wellness or fitness devices.

Most of the studies were conducted in laboratory settings, which limits the generalisation of the results to real-world contexts. Ergonomic concerns were also highlighted, such as discomfort during prolonged use and restricted mobility for certain populations. Overall, the study showed that there are devices available on the market that could be used by firefighters to detect fatigue and also potential cardiac events. However, some of them require further studies, particularly in real-world settings.

Keywords: Wearable sensors; Chest straps; Cardiac monitoring; Firefighters; Occupational health

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1. INTRODUCTION

Occupational Safety and Health (OSH) management has evolved over the years; however, accidents, injuries, and fatalities still happen across all sectors of activity and occupations, including during emergency response operations (Aksüt & Eren, 2024). In fact, first responders, in particular firefighters, are exposed to several occupational risks that can negatively impact their health and safety. Cuenca-Lozano and Ramírez-García (2023) denoted the role of mechanical, physical, chemical and psychosocial risk factors. However, in this work, particular attention will be given to the ones that can result in cognitive and physical workload (Cuenca & Ramírez, 2023). Additionally, due to the high physical and mental demands that they are exposed, another relevant occupational problem emerged, i.e., the occurrence of cardiovascular incidents (Pereira et al., 2025; Rotunda et al., 2024; Teixeira et al., 2024).

The prevention of health and safety risks associated with physically and mentally demanding tasks has driven increasing interest in wearable monitoring technologies, given their potential to measure important features in real-time during occupational activities (Taborri et al., 2021). In fact, professions such as firefighting, represent a promising field for the application of wearables in monitoring physical condition and physiological stress responses, thus helping to safeguard workers' health and safety (Bustos et al., 2023; Pereira et al., 2017). Additionally, the key to improving survival rates in the event of a cardiovascular incident lies in early detection (Sankar S et al., 2024), and wearable devices have a major impact on the real-time monitoring of vital signs (Levin et al., 2023).

The rapid evolution of wearable technology has revolutionized the collection of physiological and behavioural data, enabling continuous, non-invasive monitoring across clinical, occupational, and sporting settings (Seshadri et al., 2016; Sawka & Friedl, 2018). These devices support a range of applications, from optimizing sports performance to remote patient monitoring and enhancing OSH (Kazanskiy et al., 2024; Seshadri et al., 2016).

Wearable sensors can be positioned at different anatomical sites depending on the type of data intended to be captured (Gjoreski & Gams, 2011; Khokhlov et al., 2018). There are rings, smartwatches, smart bras, and chest straps (Angelucci et al., 2024). Wrist-worn devices, such as smartwatches, are widely used for general activity tracking but often lack the accuracy required for high-performance contexts (Martín-Escudero et al., 2023). Chest-worn band sensors, commonly known as chest straps, have gained prominence for their superior accuracy in cardiac monitoring, especially when compared to more ubiquitous wrist-worn devices (Cosoli et al.,

2020). Additionally, sensors to monitor physiological features can be integrated into firefighters' uniforms and personal protective equipment (PPE) (Aksüt & Eren, 2024). Wearable devices can monitor electrocardiogram (ECG), photoplethysmography (PPG), electroencephalogram, and electromyogram signals, and measure parameters such as heart rate (HR), blood pressure, respiratory rate, tidal volume, body temperature, and peripheral oxygen saturation (Angelucci et al., 2024).

Body-worn sensors are one sort of wearable gadget that has gotten a lot of attention for their ability to analyse a person's physical and mental state in real time. This makes them useful for everything from improving performance to keeping an eye on health (Srikrishnarka et al., 2024). The data collected by chest-strap wearables vary depending on sensors they incorporate. These devices usually have technologies like electrocardiography, accelerometry, and strain sensors that can detect things like HR, heart rate variability (HRV), respiratory effort, and body movement very accurately (Chuo et al., 2010; Dieffenderfer et al., 2015). Even if they have certain benefits, there are still problems with long-term comfort, power efficiency, and user acceptance (Umair et al., 2021). Nonetheless, as a result of their increasing use in both commercial and research settings, a large number of models with varying sensor compositions, data formats, and usability features have been produced.

Within this framework, this dissertation aims to contribute to the advancement of knowledge on the use of wearable sensors, particularly chest straps, for physiological monitoring of professionals operating in physically and mentally demanding contexts, such as firefighting. The main goal is to explore existing chest-strap devices for collecting cardiac signals, with the potential to support the assessment of physical and mental workload, as well as the detection of cardiac events. In fact, there is still a lack of systematic synthesis concerning the types of chest-strap cardiac sensors, the nature of the cardiovascular data they collect, and their respective advantages and limitations across application domains. In view of this, a systematic literature review as conducted to fill that gap.

1.1. Study motivation

This dissertation was developed within the scope of the project Safety & Incident Response for building Emergency Networks – SIREN, an international project that aims to improve disaster response through innovative solutions that integrate advanced connectivity, artificial intelligence,

and sensor technology to monitor responders in the field. At national level, the project proposes to develop an integrated system of sensors embedded in the clothing and PPE of emergency professionals, with the goal of continuously assessing their vital signs and indicators of physical and cognitive fatigue. This real-time monitoring seeks to ensure that operatives on duty possess the necessary physical and mental condition to face the high demands of operations, enabling a more efficient and safer allocation of human and material resources in high-risk scenarios.

The choice of this topic also reflects the personal motivation of the student, as a **graduate in Cardiopneumology** and a current master's student in **Occupational Safety and Hygiene at Organizations**, seeking to build a bridge between these two fields of knowledge. The student's academic and professional background has allowed to understand the relevance of monitoring physiological signals for cardiovascular health, as well as the need to integrate such monitoring into organisational strategies for OSH and well-being.

Cardiac signals play a central role in this context. The high physical and mental workload to which firefighters and other emergency professionals are exposed has been associated with a significantly increased risk of acute cardiovascular events and the development of chronic heart disease (Teixeira et al., 2024). This symbiosis between preventing cardiovascular risk and managing stress and workload in highly demanding occupational contexts lies at the heart of this dissertation, whose objective is to contribute to the protection and promotion of emergency professionals' health through the use of wearable cardiac monitoring technologies.

1.2. Thesis structure

The organisation of this dissertation was designed to interconnect its contents, providing a reading experience that fosters a thorough and coherent reflection on the topics addressed. Accordingly, it is structured into the following chapters: introduction, literature review, methodology, results and their discussion, and finally, conclusion and suggestions for future research.

The first chapter contextualises and highlights the relevance of the topic under study, as well as defining the objectives to be achieved and the methodologies chosen to accomplish them.

Chapter two presents a literature review, identifying firefighters' occupational risks, the homeostatic mechanisms, and the corresponding pathophysiological impacts of these risks. It

also addresses the current state of wearable monitoring technologies, as well as their role in workload monitoring.

Subsequently, chapter three describes the methodology applied, detailing how it supports the achievement of the proposed objectives, including the systematic review strategy and the criteria for selecting and evaluating the included studies.

Chapter four sets out the results obtained through the previously described methodology, and chapter five discusses these results in the light of the existing literature. The findings derive from the systematic review of scientific studies on chest-strap devices, highlighting their advantages, limitations, and applicability.

Finally, the most relevant conclusions and reflections on the topic are presented, followed by proposals for future research in this field.

2. LITERATURE REVIEW

This chapter begins by outlining the nature of firefighters core duties and the associated physical and mental demands. The revision then progresses to the occupational risk factors to which they are exposed, concluding with an analysis of how these risk factors may affect cardiovascular health.

2.1. Tasks and demands in disaster scenarios

Firefighters play a critical role in disaster management, facing extreme challenges to save lives and minimise damage (Lee et al., 2025). The demanding nature of their work, including fires, rescuing victims, and providing aid in scenes of widespread destruction, requires both physical and mental resilience, as they must operate for long hours, without rest (Bakirci et al., 2024; Cuenca & Ramírez, 2023).

In these circumstances, limited sleep becomes a reality (Alves et al., 2023). The fast-paced nature of emergency operations and the constant need for immediate response reduce the rest period to the minimum (Alves et al., 2023). Despite the extreme fatigue, firefighters are driven to remain on duty by a strong sense of responsibility and team spirit (Bakirci et al., 2024). Every intervention demands a high level of physical and mental effort, as any mistake could endanger not only the

lives of victims but also those of the firefighters themselves (Lee et al., 2025). Moreover, firefighters often operate in remote and difficult-to-access locations, such as dense forests, mountainous terrain, or areas devastated by earthquakes and floods (Bakirci et al., 2024; Faiz et al., 2022). Logistics present an additional challenge, as communication and supply systems are not always effective, requiring improvisation and resilience to ensure the continuity of rescue operations (Faiz et al., 2022).

Exposure to multiple risk factors is a constant during firefighters' operation (Teixeira et al., 2024). The intense heat from fires and the continuous physical exertion, both during interventions and when transporting essential equipment and heavy PPE, as well as the exposure to dangerous substances, and even the instability of collapsed buildings are threats they face on a daily basis (Aksüt & Eren, 2024; Bakirci et al., 2024; Cuenca-Lozano & Ramírez-García, 2023).

2.2. Risk factors in disaster scenarios

In the same way as other professions, firefighters are exposed to several risk factors that may result in death, accidents, or serious illnesses, making the analysis and assessment of their occupational exposure essential (Teixeira et al., 2024). Among these, they are exposed to several risk factors that contribute to high physical and mental workload, which play a critical role in these professionals' health and safety (Bustos et al., 2023). In fact, the risk of fatigue is high among these professions (Bakirci et al., 2024; Bustos et al., 2023; Li et al., 2024). This is a complex physiological and psychological state that leads to energy depletion, muscle fatigue, cognitive performance decline, emotional changes, and impairment of bodily functions: reduced neuromuscular transmission efficiency, changes in the serotonin system, decreased attention/concentration, increased reaction times, heightened interpersonal conflict, and errors in decision-making (Li et al., 2024). This state significantly impacts the efficiency, well-being, and overall health of firefighters (Li et al., 2024).

The mental capacity of firefighters can be seriously compromised during operations in disaster scenarios (Aksüt & Eren, 2024; Bakirci et al., 2024; Marks et al., 2020). Due to the nature of their work, they are constantly exposed to pressure and traumatic events such as death, which increases their psychological stress exposure (Aksüt & Eren, 2024; Marks et al., 2020). Additionally, being a firefighter is a profession/occupation that requires continuous public support and work shifts, often involving long hours working (sometimes over 24 hours) (Alves et al.,

2023). During work shifts, firefighters rest in unfamiliar environments and are frequently subjected to sudden awakenings due to unpredictable emergencies (Alves et al., 2023). Night-time calls and alerts directly affect the sleep quality of these professionals (Bakirci et al., 2024) (Marcel-Millet et al., 2021). Sleep is essential to ensure a holistic health, playing a key role in functions such as glucose metabolism (Kothari et al., 2021), cortisol regulation (Hong et al., 2025), nervous system control (Meerlo et al., 2008), and optimising immune function (Hong et al., 2025). Sleep deprivation is closely linked to an increased risk of road (Sina et al., 2025) and work accidents (Iannella et al., 2025). These professionals are the first line of disaster response and are subjected to high stress levels, which can trigger trauma-related symptoms (Bakirci et al., 2024). Occupational illnesses such as anxiety may be developed, as a result of repeated exposure to traumatic situations (Pereira et al., 2025; Rotunda et al., 2024).

Another relevant occupational risk that firefighters face is the exposure to dangerous substances, such as carbon monoxide (CO) inhalation, especially when working without respiratory protective equipment (Stec et al., 2023). This colourless and odourless gas results from the incomplete combustion of fossil fuels and/or carbon-containing substances (Du et al., 2024; Ndlovu & Nkeh-Chungag, 2024).

Firefighters are also exposed to long periods of physical exertion in hot environments, leading to increased body temperature (thermal stress) and impaired physical and mental performance (Souissi et al., 2024). In such scenarios, where oxygen demand in skeletal and cardiac muscles is high, blood flow is balanced between metabolic processes and thermoregulation: skeletal muscle activity requires increased blood supply to meet metabolic needs, while thermoregulation demands increased skin blood flow and the promotion of cutaneous vasodilation (Chou & Coyle, 2023; Souissi et al., 2024). This redistribution also involves renal and splenic recruitment, as blood supply to these organs is reduced, and visceral vasoconstriction is promoted (Chou & Coyle, 2023; Souissi et al., 2024). The metabolic process of energy production required for muscle contraction generates heat as a by-product (Souissi et al., 2024). Therefore, the type, intensity, and duration of physical exertion increase body temperature, triggering cutaneous vasodilation (Chou & Coyle, 2023; Miguel, 2012; VanPutte et al., 2016). This process, driven by sympathetic nervous system activation, results in increased plasma osmolality, blood vessel dilation, decreased peripheral vascular resistance, and consequently, increased heart rate to compensate for the elevated skin blood flow and fluctuating peripheral pressure (Chou & Coyle, 2023; Souissi et al., 2024). Continuous exposure to extreme heat can lead to hyperthermia and/or dehydration (Souissi et al.,

2024). The latter is characterised by an imbalance in the body's water levels, where fluid intake is lower than loss through urination, sweating, and pulmonary gas exchange (Miguel, 2012).

Mechanical risks are also relevant for firefighters. During disasters, many citizens may become isolated due to damaged roads or destruction of power and communication networks, making it difficult to locate and assist them (Faiz et al., 2022). In these contexts, where infrastructure is prone to failure, supporting affected populations becomes even more challenging for first responders (Faiz et al., 2022). In fact, sometimes, they need to operate in extreme physical hard conditions (Li et al., 2024). Falls, whether from heights, at ground level, or from objects, are a relevant contact-mode of injury in this occupation (Cuenca-Lozano & Ramírez-García, 2023). Working in partially or fully collapsed structures, on steep and uneven terrain, and in conditions with poor visibility and lighting is a frequent reality for firefighters (Games et al., 2020; Harbison et al., 2023). These conditions pose constant hazards that often result in trips, slips, and falls (Cuenca-Lozano & Ramírez-García, 2023; Kong et al., 2013).

Noise exposure is another relevant occupational risk for firefighters (Millet et al., 2023). Exposure to noise without the use of appropriate hearing protection can lead not only to hearing loss, as it is also directly associated with deterioration in cardiovascular health (Cuenca-Lozano & Ramírez-García, 2023; Millet et al., 2023).

2.3. Cardiovascular responses to risk factors exposure

Approximately 45% of firefighter deaths in duty are caused by cardiovascular disease, linked to their exposure to smoke, extremely hot environments, and the permanently demanding physical activity involved in their profession (Teixeira et al., 2024). These occupational stressors not only increase the risk of cardiovascular events but also disrupt the delicate physiological mechanisms that sustain cardiac function (Bustos et al., 2023; Chandola et al., 2006). In particular, the action potential of cardiac contractile cells is mediated by the presence of electrolytes such as sodium, potassium, and calcium (O'Rourke et al., 2006; Rodrigues, 2010). Depolarisation, the phase of muscle contraction, results from a massive sodium influx (O'Rourke et al., 2006; Rodrigues, 2010). Sodium affects intracardiac conduction velocity (O'Rourke et al., 2006; Rodrigues, 2010). Repolarisation, the relaxation phase allowing for cardiac filling, depends on calcium and potassium movements across the plasma membrane (O'Rourke et al., 2006; Rodrigues, 2010).

Potassium presence is evident in the QT segment and Q wave of the electrocardiogram (O'Rourke et al., 2006; Rodrigues, 2010).

2.3.1. Cardiovascular response to psychological risk

Psychosocial risks can also play a relevant role in the occurrence of these diseases (Pereira et al., 2025). Occupational stress caused by psychosocial exposure is heightened by the traumatic nature of the events experienced and the frequency with which they occur (Rotunda et al., 2024). Anxiety presents arrhythmological symptoms such as palpitations and tachycardia, which may be triggered while firefighters are on duty (Marks et al., 2020; Rotunda et al., 2024; Pereira et al., 2025).

2.3.2. Cardiovascular response to chemical risk

During firefighting, exposure to particle matter and gases such as CO is constant (Stec et al., 2023). Carbon monoxide has a high affinity for haemoglobin (250 times greater than that of O₂) a protein in red blood cells responsible for transporting gases to cells, occupying binding sites that would otherwise be for oxygen and thus reducing the blood's capacity to deliver oxygen to tissues (Du et al., 2024; Ndlovu & Nkeh-Chungag, 2024). As previously described, prolonged exercise in hot environments increases O₂ demand (Chou & Coyle, 2023). With high levels of carboxyhaemoglobin, this oxygen requirement is not met, leading to reduced oxygen delivery to skeletal and cardiac muscles, increased hypoxia, and a heightened risk of angina, arrhythmias, myocardial infarction, and death by chemical asphyxiation (Du et al., 2024; Ndlovu & Nkeh-Chungag, 2024).

CO has very specific effects on cardiac tissue (Wittenberg & Wittenberg, 1993). Like with haemoglobin, it binds with high affinity to myoglobin, leading to cardiac dysfunction (Bussienne & Betello, 2021). It inhibits oxidative phosphorylation, impairing heart function, and the continuous increase in cardiac output in response to hypoxia may eventually lead to heart failure (Bussienne & Betello, 2021). CO poisoning can also cause apoptosis in cardiac contractile cells (Du et al., 2024). The mechanisms contributing specifically to coronary artery disease include reduced O₂ supply, increased myocardial contractility, CO-induced endothelial dysfunction, and enhanced coronary vasoconstriction (Du et al., 2024).

Firefighters may also inhale oxygen free radicals generated from combustion (Ndlovu & Nkeh-Chungag, 2024). Prolonged exposure to these particles can cause oxidative stress and inflammation in the respiratory system, contributing to both respiratory and cardiovascular diseases (Ndlovu & Nkeh-Chungag, 2024). Inhaled particle matter may trigger local inflammatory responses in the alveoli and systemic effects once they cross the alveolar, capillary barrier, altering cardiovascular and neurological functions (Du et al., 2024; Ndlovu & Nkeh-Chungag, 2024). The lungs respond to oxidative stress by activating alveolar immune cells, particularly macrophages, which release inflammatory molecules, cytokines, that spread through the body, potentially affecting heart and blood vessel function (Ndlovu & Nkeh-Chungag, 2024).

2.3.3. Cardiovascular response to physical fatigue, thermoregulation and electrolytic loss

Increased heart rate and cardiac output are physiological responses to heat exposure (Miguel, 2012). The increased output aims to regulate body temperature but is also a sympathetic response to stress (VanPutte et al., 2016).

Prolonged physical activity can also lead to oxidative stress and inflammatory responses, promoting cardiovascular fatigue and manifesting in left ventricular dysfunction and increased risk of thromboembolic (Souissi et al., 2024). The continuous need to maintain elevated heart rates and the mechanical stress applied to blood vessel walls increase the production of hydrogen peroxide and endothelial superoxide (Howard et al., 1997; Souissi et al., 2024). These oxygen free radicals cause oxidative stress, decreasing cardiac myofilament sensitivity, which contributes to myocardial dysfunction (Souissi et al., 2024). Cardiovascular fatigue is also associated with increased aldosterone, thyroid hormone, and fibroblast growth factor 23 (FGF-23) (Souissi et al., 2024).

Platelet aggregation stimulates the coagulation cascade. If endothelial tissue damage and clot formation occur, the haemostatic response is triggered, involving the recruitment of collagen and platelets, increasing their blood concentration and viscosity (Sang et al., 2021). This may promote adverse thromboembolic events such as strokes, acute myocardial infarctions, cardiovascular dysfunction, and cardiac arrest (Souissi et al., 2024).

Additionally, when skin blood flow increases it leads to heat dissipation by convection, and vasodilation supports thermoregulation by facilitating the evaporation of sweat (Chou & Coyle, 2023; Souissi et al., 2024). Sweating is a homeostatic response to demanding physical activity

and to the exposure to hot environments (Sol et al., 2021; Souissi et al., 2024). This process leads to the loss of water and electrolytes, such as potassium and sodium, which are essential for cardiac muscle contraction and cardiac output volume (Seshadri et al., 2019).

Due to intense sweating, significant losses of fluids and electrolytes may occur, whereby severe depletion of NaCl resulting from this loss can lead to a marked increase in heart rate (VanPutte et al., 2016). When body weight fluid losses exceed 15%, the critical depletion of blood volume becomes potentially fatal, putting survival at risk (Miguel, 2012).

Maintaining adequate hydration is essential for replacing lost fluids, particularly during physical exertion and exposure to high temperatures (Pires da Silva et al., 2018). If the individual fails to restore fluid balance, a state of dehydration may develop (Popkin et al., 2010). In cases of severe dehydration, blood viscosity increases, which in turn raises the workload of the heart and can lead to heart failure (Souissi et al., 2024).

2.4. Wearable technologies for monitoring physical and mental workload

During wildland firefighting, where firefighters are exposed to extreme conditions, the oxygen demand for muscle effort increases significantly, pushing them quickly into anaerobic metabolism and forcing them to operate at submaximal or even maximal capacity (Teixeira et al., 2024). The resulting physical fatigue leads to reduced performance (Parekh et al., 2019). This decline, often underestimated by the individual, can be identified through physiological signs such as electrocardiogram changes, where HRV and machine learning algorithms allow for early detection (Kolodziej et al., 2020).

HRV is also used as a stress indicator (Ferreira et al., 2022). In fact, it is an excellent indicator to assess cardiovascular health, as reduced HRV is directly associated with the development of heart disease (Sankar S et al., 2024). HRV is measured by assessing the variation in R-R intervals, i.e., the time between two heartbeats, in milliseconds (ms) (Schams et al., 2022). This analysis reflects the individual's ability to adapt and respond to stress. The regulation between the sympathetic and parasympathetic systems to maintain homeostasis, with normal values generally falling between 600 and 1000 ms. (Sankar S et al., 2024; Seshadri et al., 2019).

Psychological stress and emotional changes can be assessed through electrodermal activity (Li et al., 2024), as well as methods such as pupil diameter measurement, blood pressure, body

temperature, and HRV analysis also allow for the assessment of mental stress (Pereira et al., 2017).

Fatigue resulting from work activity can be detected through electromyography by measuring the muscle activity exerted by the individual during the performance of their tasks (Li et al., 2024). Other variables relevant for predicting fatigue include respiratory rate, body temperature, oxygen consumption (VO_2 max), and the measurement of pH, metabolites, electrolytes, and biomarkers such as capillary lactate, salivary glucose, and sodium and potassium in sweat (Bustos et al., 2022; Ras et al., 2023; Seshadri et al., 2019). However, the use of these devices in real-world settings may pose practical challenges for firefighters (Pereira et al., 2017).

3. METHODOLOGY

3.1. Research question and eligibility Criteria

The research was based on the following question: Which chest-worn band sensors are available for cardiac monitoring, what types of cardiac data do they collect, and what are their key strengths and limitations in different contexts?

Eligibility criteria were defined according to PICO framework:

- **Population (P):** Studies involving individuals across clinical, sporting, or occupational settings who use chest-worn band sensors.
- **Intervention (I):** The use of chest-worn band sensors for cardiac monitoring.
- **Comparison (C):** Between chest-worn bands or a chest-worn band compared to a golden standard.
- **Outcome (O):** Measurement of cardiac physiological parameters and assessment of the advantages and limitations of chest-worn sensors in various contexts.

Studies were considered eligible for inclusion if they were original research articles, either observational or experimental, that investigated chest-worn band sensors (e.g., biometric chest straps or chest belts). Eligible studies were required to report on the types of sensors embedded in chest-strap devices and the corresponding physiological data related to cardiac monitoring, such as heart rate measured via ECG and blood pressure. Studies also qualified if they discussed

technological, clinical, or practical advantages and/or limitations associated with the use of chest-strap devices. Only publications written in English and with open access were considered. Lastly, only research released in the previous 10 years was included to guarantee currency and relevance.

Studies were excluded if they focused exclusively on wrist-worn devices, such as smartwatches or smartbands, unless chest-worn sensors were also independently assessed. Additionally, research involving non-wearable technologies or sensors located outside the chest region (e.g., head-mounted, finger-based, or implantable devices) was not considered eligible for this review.

3.2. Information Sources

Studies were initially identified through a search conducted in the following databases: PubMed, Scopus, Web of Science and Science Direct. After this initial analysis, manual methods were used to identify studies, in particular backward citation technique, where the bibliographic references of the included studies were analysed. Relevant review articles were also consulted. The search of these sources was conducted at 14 May of 2025.

3.3. Search Strategy

A comprehensive search strategy was designed for Pubmed, Scopus and Web of Science database, incorporating a combination of keywords and MeSH terms. The complete search strategy is detailed in Table 1. For the ScienceDirect database, where a maximum of eight Boolean operators is allowed, the following query was used: ("Chest Based Sensor" OR "Chest Strap" OR "Wearable") AND ("Heart Rate" OR "Heart Rate Variability" OR "Cardiac Stress" OR "Electrocardiogram"). Filters were applied to limit the search to studies published in the last ten years, in English and Portuguese and also to include only peer-reviewed articles.

3.4. Selection Process

Two reviewers independently screened all records identified in the initial search. Disagreements between the reviewers were resolved through discussion, and a third reviewer was consulted if necessary. Each study was assessed for eligibility based on the inclusion and exclusion criteria. Automated tools such as Rayyan were used to expedite the screening process and manage duplicates. The final list of eligible studies was determined after full-text review

Tabel 1: Query used in the systematic review

"Chest Strap" AND	("Chest Strap" OR "Thoracic Sensor" OR "Wearable Sensor" OR "Wearable devices" OR "Wearable" OR "Chest-worn" OR "Thoracic band" OR "Chest belt" OR "Chest monitor")
"Physiological Data"	("Physiologic* Data" OR "Heart Rate" OR "HR" OR "Biometric" OR "Heart Rate Monitoring" OR "Biometry" OR "Blood Pressure" OR "Physiologic* signals" OR "Physiological measures" OR "Physiological Parameters" OR "Physiologic* Monitoring" OR "Ambulatory Monitoring" OR "Ambulatory Blood Pressure Monitoring" OR "Ambulatory Electrocardiography" OR "ECG" OR "Ambulatory Electrocardiography Monitoring" OR "Electrocardiogram" OR "Heart Rate Variability" OR "HRV" OR "Cardiac* stress")

3.5. Data Collection Process

Data were independently extracted by two reviewers from each included study. Data extraction involved identifying the sample, the study aim, the study type, the key aspects of the chest-worn band sensors used and the comparison wearable or golden standard, the application setting, the type of cardiac parameters collected, main results and key strengths and limitations. Any discrepancies between reviewers were resolved through discussion.

3.6. Quality Assessment

This review's studies were evaluated using the Mixed Methods Appraisal Tool (MMAT) from 2018 (Hong et al., 2018). The MMAT is a recognized and validated method for appraising empirical studies with multiple methodological frameworks boundaries, it allows evaluation of qualitative, quantitative (randomized, non-randomized, and descriptive), or mixed methods studies. Each study was categorised according to its study design (SD) as follows: SD1 – Qualitative studies; SD2 – Quantitative randomised controlled trials; SD3 – Quantitative non-randomised studies; SD4 – Quantitative descriptive studies; SD5 – Mixed methods studies.

The MMAT comprises a series of standardised criteria tailored to each study design. S1 and S2, two preliminary screening questions, evaluate whether the research questions are well-articulated and whether the data gathered is sufficient to answer them. This is followed by five methodological quality criteria specific to each design. For example, when it comes to non-randomized quantitative studies (SD3), the tool looks at things like participant representativeness, measurement appropriateness, outcome data completeness, confounder control, and whether the intervention was carried out as planned. Every criterion has a rating of "Yes" (Y), "No" (N), or "Can't tell" (CT). Studies were given an overall quality rating based on the

quantity of criteria that were rated as "No" or "Can't tell": High quality – 0 or 1 response of 'No' or 'Can't tell'; Medium quality – 2 responses of 'No' or 'Can't tell'; Low quality – 3 or more responses of 'No' or 'Can't tell'. Although the MMAT authors advise against assigning overall ratings, this review reports them due to the identification of only two SD categories.

A strong interpretation of the body of evidence included in the review is supported by this systematic approach, which guarantees consistency and transparency in the evaluation of study quality.

4. RESULTS

Figure 1 presents the flow diagram of study selection for this systematic review. The search strategies were applied to four databases, from which 78 374 records were identified: 9 064 in PubMed, 13 318 in Web of Science, 21 288 in Scopus, and 34 704 in ScienceDirect. After applying filters (restrict the search to peer-reviewed articles published within the past ten years, written in either English or Portuguese), 11 875 records were obtained: 682 from PubMed, 4 298 from Web of Science, 5 926 from Scopus, and 969 from ScienceDirect. Using Rayyan, 4 517 duplicate records were removed. With the same tool, 6 940 records were excluded based on title analysis and 322 based on abstract analysis. Accordingly, 96 records were subjected to the eligibility criteria analysis. After full text screening 64 articles were excluded due to one of the following reasons:

1. Device type not aligned (not chest strap focused): Studies were excluded under this category if they did not involve or focus on chest strap-based ECG sensors. This included studies examining alternative devices such as patches, belts, wristbands, adhesive tapes, e-tattoos or general electrode-based systems, as well as those that failed to specify the ECG device model used. Moreover, research that was only dedicated to the parts of a chest strap or comparing different methods of fixing a strap without considering the strap as a system, were also excluded because they did not align with the review's emphasis on holistic ECG monitoring based on chest straps.
2. Insufficient attention to cardiac parameters: Although the studies may involve physiological monitoring, the main concern remains focused on other parameters according to the various physiological components (energy expenditure/obesity, sleep/wake classification, training adaptation or any other non-cardiac parameter).

These articles were disqualified since the focus of this review is cardiac-specific metrics (such as heart rate, heart rate variability, and arrhythmias).

3. Data availability limitations (no results presented): Some references are methodological proposals, ongoing studies, or conceptual papers that lack experimental data or validation results. Others are guidelines or overviews without original data. These do not provide empirical evidence required for evaluation of sensor accuracy or applicability.
4. Algorithm-focused without sensor validation: A few studies concentrate on algorithm development or signal processing pipelines (e.g., arrhythmia detection, classification models), without actual validation of chest strap sensor performance or without specifying the hardware used. Thus, they do not meet inclusion criteria centred on device-level evaluation.
5. Duplicated or covered in other sources: Some studies use methodologies or datasets already validated and detailed in another included article, particularly when marked as “overnight” protocols where relevant parameters were reported elsewhere.

Furthermore, many of the heart rate monitoring devices analysed were patches or adhesive devices, which were not classified as chest straps and were therefore excluded from the review.

In this way, 32 studies were included in this review. To enhance clarity and analytical depth, the results of this review are presented in two separate tables, reflecting the distinct roles that chest-worn band sensors played across the included studies. This approach allows for a more targeted synthesis of the evidence and facilitates comparison within and across application contexts.

Table 2 includes studies in which chest-worn band sensors were the primary object of research. These studies aimed to evaluate the performance of such sensors in terms of accuracy, usability, and applicability across different settings. They encompass four main types of research: (i) validation studies that assessed the sensor’s accuracy against a clinical gold standard (e.g., 12-lead ECG); (ii) comparative studies between different chest-worn sensors; (iii) application studies conducted in real-world environments (e.g., clinical, sporting, or occupational) without direct comparison; and (iv) studies focused on the technical development of new sensors or algorithms. This table highlights the key features, measured cardiac parameters, strengths, and limitations of each sensor in context.

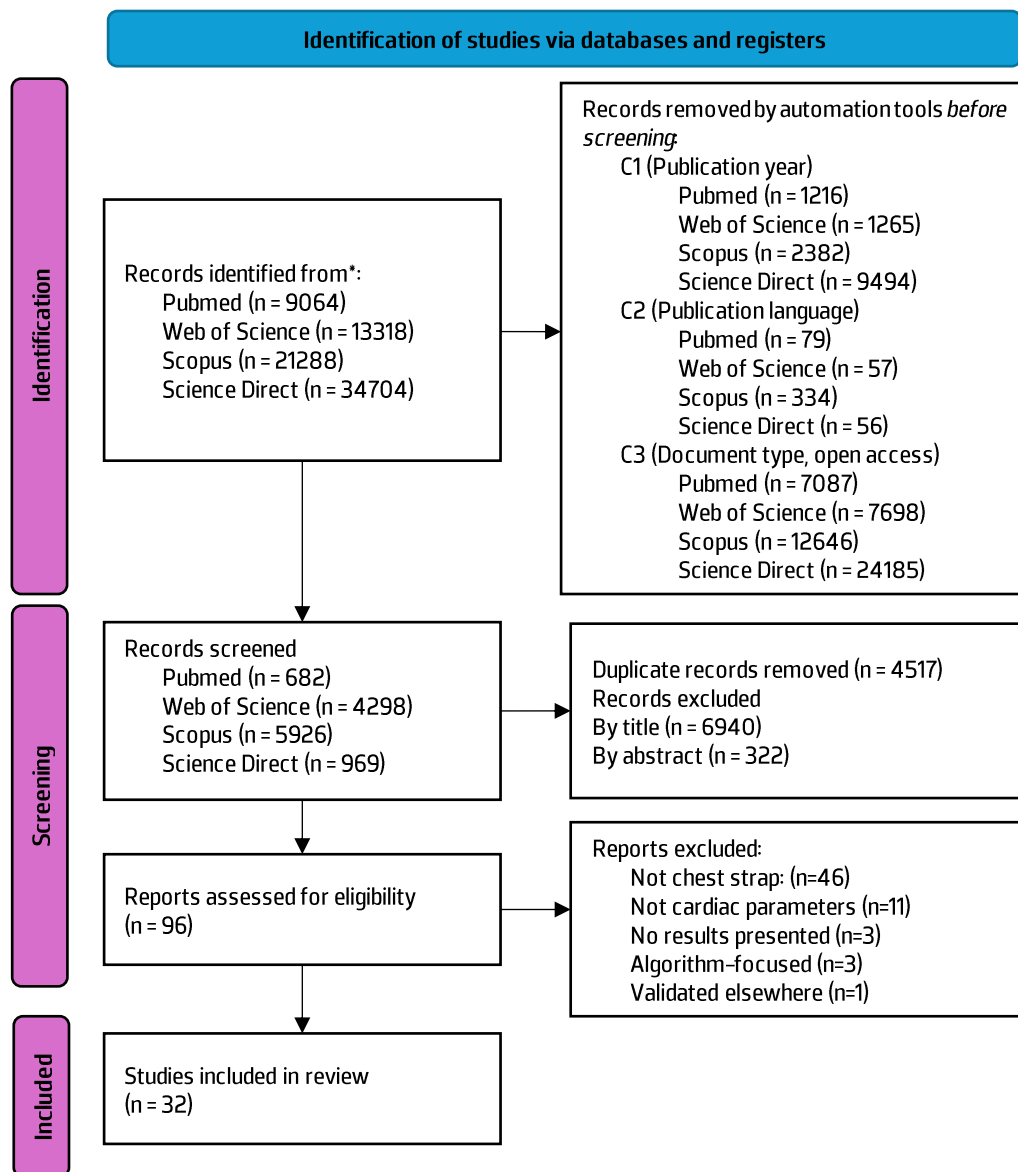


Figure 1: Flow diagram of study selection for this systematic review

Table 3, by contrast, includes studies in which chest-worn band sensors were not the primary focus but were instead used as a reference standard for validating other devices or technologies. These include smartwatches, wrist-worn PPG sensors, wearable patches, or novel data processing algorithms. In such studies, the chest-worn sensor served as the benchmark for assessing the accuracy of alternative cardiac monitoring tools. Although these studies do not evaluate the chest-worn sensors directly, their frequent use as a reference underscores their perceived reliability and methodological relevance.

By distinguishing between these two types of studies, this review aims to provide a more nuanced understanding of the role of chest-worn band sensors in cardiac monitoring. This structure also supports a more coherent discussion of their advantages, limitations, and application domains,

whether as the focus of technological assessment or as a trusted reference in the validation of emerging solutions. Additionally, the inclusion of studies conducted in different settings (sports, clinical and occupational), allow to cover the different requirements for a wearable applied to firefighters.

The analysis covered 32 articles, of which 68.75 % were conducted in laboratory environments, 21.88% in real-world environments, and 9.38 % combined both scenarios. In another analytical dimension, 6 articles focused on occupational users, 3 targeted athletes (professional or amateur), 7 were clinical (individuals with or without pathology), and 16 evaluated device performance in tasks with varying workload levels.

Table 2 shows that the most frequently used devices in scientific experimental contexts were the Zephyr BioHarness 3.0 and the Polar H10. Marzano-Felisatti et al. (2024)) used the Garmin HRM-Dual wearable in their experimental study. Di Palma et al. (2017) chose to employ the Shimmer® IFC-CNR chest strap in their feasibility study. Martín Gómez et al. (2024), Parak et al. (2021), and Rogers et al.(2022) conducted their studies using the Movesense chest strap, in the HR+, Suunto, and Medical models respectively. The Zephyr BioHarness 3.0 chest strap was the main tool used in the studies of Constantini et al. (2018), Kuo et al. (2023), Romagnoli et al. (2021), Saggu et al. (2024), Van Oost et al. (2024), and Vila et al. (2021). Montes e Navalta (2019) carried out their test-retest reliability study using the Polar T31 chest strap along with the Polar CE0537 wristband. Etiwy et al. (2019), Mishra et al. (2020), Nuske et al. (2022), and Nuske et al. (2017) used the Polar H7 chest strap in their investigations. The Polar H10 chest strap was employed in the studies by Bläsing et al. (2022), Flores et al. (2024), Gilgen-Ammann, Schweizer, e Wyss (2019) Maza, Goizueta, e Llorens (2024), Skála et al. (2022) and Speer at al. (2021).

According to Table 3, the devices most frequently employed as reference technologies in research were the Zephyr BioHarness 3.0, Polar H7, and Polar H10. The Zephyr BioHarness 3.0 was adopted by Milena et al.(2023) Kuo et al. (2015) and Romano et al. (2022) in their investigations. Higgins et al.(2018) when evaluating an earpiece heart rate monitor, used the Polar T31 chest strap with the Polar FT1 wristband. Cosoli et al. (2022), Liu et al. (2025) and Navalta et al. (2023) conducted their studies using the Polar H10 strap. In the studies by Chow e Yang(2020), Hoevenaars et al.(2022), and Navalta et al. (2020) the Polar H7 strap was used.

Table 2: Studies Evaluating Chest-straps

Reference	Population	Study Type	Aim	Sensor (Model & Technology)	Comparison/Reference device	Cardiac Parameters Measured	Application Context	Reported Results
Bläsing et al.(2022)	13 healthy participants	Comparative experimental study	To compare the usability and data quality of various consumer and professional electrocardiogram (ECG) devices in both research and leisure contexts, by developing two novel approaches: one to assess local noise and waveform disturbances, and another to verify and classify RR intervals (RRI).	Polar H10 (chest-strap, 1000Hz, Infrared) + Polar RS800 Multi (wrist/storage)	NeXus-10 MKII (chest patch electrodes, 8000Hz, Bluetooth); eMotion Faros 360°(chest patch electrodes, 1000Hz, Bluetooth); SOMNOtouch NIBP (chest patch electrodes, 512Hz, Bluetooth); Hexoskin Hx1 (Shirt, 256Hz, Bluetooth)	RRI; Heart Rate (HR)	Experimental: Treadmill and leisure scenarios	Accuracy: NR; Precision: NR; Device comparison: Polar has the highest percentage of missed beats during P3 (2-back) with 6.6% misclassification, but also the best result in P4 (0.02% misclassification). Polar scores better in phases with higher HR. had the most scores low or insufficient quality (below 99%: 7 participants), mainly attributable to the 2-backtask, but achieves very high scores during the running phase.
Constantini et al. (2018)	10 elite male distance runners	Experimental crossover study with within-subject comparison	To examine the effects of timing foot strikes to the systolic or diastolic phase of the cardiac cycle on heart rate, oxygen consumption, and ventilatory responses in elite distance runners.	Zephyr BioHarness 3.0 (chest-strap)	Unpublished values and tolerances collected previously by authors JLB and PDM	HR; ECG waveform; RRI	Sports: treadmill	Accuracy: NR; Precision: NR; Device comparison: Group mean HR was significantly lower during diastolic compared with systolic stepping ($P < 0.001$); strong correlations were observed between diastolic and systolic stepping for HR, step rate (SR), and step length ($P < 0.05$, $r = 0.95$ for all comparisons)

Reference	Population	Study Type	Aim	Sensor (Model & Technology)	Comparison/Reference device	Cardiac Parameters Measured	Application Context	Reported Results
Etiwy et al. (2019)	80 adults enrolled in a Phase II or III CR program	Cross-sectional comparative validation	To assess the accuracy of four commercially available, optically based wearable heart rate monitors in patients with cardiovascular disease attending a cardiac rehabilitation programme at a tertiary care centre.	Polar H7 (chest-strap)	Standard 12-Lead ECG (chest patch electrodes); 2 of this wristbands HR monitors: Apple Watch, Fitbit Blaze, Garmin Forerunner 235, TomTom Spark Cardio	HR; ECG waveform	Clinical: Treadmill	Accuracy: Polar chest strap (rc of 0.99). Among wrist-worn monitors, the Apple Watch performed best with rc =0.80, followed by the Fitbit Blaze (rc =0.78), TomTom Spark Cardio (rc =0.76) and Garmin Forerunner 235 (rc =0.52); Precision: NR; Device comparison: Wrist-worn HR monitors, the Apple Watch and TomTom Spark Cardio were most accurate, with no statistical difference from ECG (P=0.62 for TomTom Spark Cardio and P=0.09 for Apple Watch)
Flores et al. (2024)	15 semi-professional soccer players	cohort study	To analyse autonomic nervous system adaptations following musculoskeletal injury in athletes by measuring heart rate variability.	Polar H10 (chest-strap, Bluetooth); Polar m200 (wristband/storage, Bluetooth)	No comparison device	Heart Rate Variability (HRV); RRI	Occupational (in lab)	Accuracy: NR; Precision: NR; Device comparison: Results show differences between T1 and T2 ($p \leq 0.05$) in low-frequency power (n.u.) ($p = 0.001$) and high-frequency power (n.u.) ($p = 0.001$), in lowfrequency/high-frequency ratio ($p = 0.001$) and in high-frequency power (ms ²) ($p = 0.017$) measures.

Reference	Population	Study Type	Aim	Sensor (Model & Technology)	Comparison/Reference device	Cardiac Parameters Measured	Application Context	Reported Results
								No statistical differences were found in low-frequency power (ms2) ($p = 0.233$). The low frequency power (n.u.) was significantly lower after injury compared with LF power (n.u.) values after full return-to-play. In high frequency power there was a significant difference between both moments with high values after injury.
Gilgen-Ammann, Schweizer, e Wyss (2019)	10 healthy adults (5 male + 5 female)	Laboratory-based comparative validation study	To assess the RR interval signal quality of the medilog® AR12plus Holter monitor and the Polar H10 chest strap at rest and during exercise in healthy individuals, using visual ECG inspection as the reference.	Polar H10 (chest-strap, 1 ms)	Medilog® AR12plus Holter (3-lead ECG Holter; chest patch electrodes, 1 ms, signals recovered)	RRi; ECG waveform	Experimental (in lab): sedentary activities, walking with workload, walking and running on treadmill	Accuracy: NR; Precision: NR; Device comparison: RR interval signal qualities of 94.6% and 99.6% were demonstrated for the medilog® AR12plus and the Polar H10. During the high-intensity activities, the RR interval signal quality of the medilog® AR12plus dropped to 89.8%, whereas the Polar H10 maintained a signal quality of 99.4%. The correlation between both systems was high ($r = 0.997$, $p > 0.001$).

Reference	Population	Study Type	Aim	Sensor (Model & Technology)	Comparison/Reference device	Cardiac Parameters Measured	Application Context	Reported Results
Martín Gómez et al. (2024)	21 healthy adults	Experimental	To evaluate the validity and reliability of Movesense HR+ ECG measurements across various exercise modes and intensities, using standard three-lead ECG as the reference, and to compare the performance of the Garmin HRM-Pro against the same criterion.	Movesense HR+ (chest strap, single-channel ECG, 500 Hz, Bluetooth)	ADInstruments (chest patch electrode, standard three-lead ECG, 1000 Hz) + Garmin HRM-Pro with Garmin Fenix 3 watch (chest strap + wristband)	R-R peak; ECG; HR; HRV	Experimental (in lab): treadmill or a cycle ergometer	Accuracy: Movesense HR+ Mean absolute percentage error (MAPE)= 1%; rC (Lin)= 0,99; Garmin HRM MAPE= 13%; rC (Lin)= 0,32; Precision: Movesense HR+ = 99.6%; Garmin HRM = 87.7%; Device comparison: Bland-Altman analysis compared to the criterion indicated mean differences (SD) in RR' intervals of 0.23 (22.3) ms for Movesense HR+ at rest and 0.38 (18.7) ms during the incremental test. The mean difference for Garmin HRM-Pro at rest was -8.5 (111.5) ms and 27.7 (128.7) ms for the incremental test. The incremental test correlation was very strong (r = 0.98) between Movesense HR+ and criterion, and moderate (r = 0.66) for Garmin HRM-Pro.
Kuo et al. (2023)	213 military aircrew trainees	Observational study, G tolerance prediction	To verify participants' cardiac performance during walking using the CFI and to develop a	Zephyr BioHarness 3.0 (Chest strap)	Omron 1100U sphygmomanometer (armband)	HR	Occupational	Accuracy:NR; Precision:NR; Device comparison: Walking cardiac force index (WCFl) positively correlated with Relaxed G tolerance

Reference	Population	Study Type	Aim	Sensor (Model & Technology)	Comparison/Reference device	Cardiac Parameters Measured	Application Context	Reported Results
		model development	formula predicting individual G tolerance in centrifuge training.					(RGT) ($r=.234$; $P=.001$) and straining G tolerance (SGT) ($r=.256$; $P<.001$). $RGT = 0.066 \times \text{age} + 0.043 \times (\text{WCFI} \times 100) - 0.037 \times \text{height} + 0.015 \times \text{SBP} - 0.010 \times \text{HR} + 7.724$. $SGT = 0.103 \times (\text{WCFI} \times 100) - 0.069 \times \text{height} + 0.018 \times \text{SBP} + 15.899$.
Marzano-Felisatti et al. (2024)	30 physically active males	Experimental	To evaluate the accuracy of two chest straps and one armband during intermittent exercise in laboratory conditions, comparing their performance in effort and recovery phases to identify strengths and limitations of armband heart rate monitoring relative to chest straps.	Garmin HRM-Dual (Chest-strap, 4 Hz, ANT+); Coospo H6 (Chest-strap, 4 Hz, ANT+)	Coospo HW807 (armband, 4 Hz, ANT+)	HR	Experimental (in lab): cycle ergometer	Accuracy:NR; Precision:NR; Device comparison: The ICC (intraclass correlation coefficients) values indicate a strong agreement between the Garmin and Coospo chest straps ($ICC = 0.6-1.0$). However, lower ICC values between the Coospo Armband and both chest straps ($ICC = 0.10-0.77$) reflect the higher measurement of discrepancies, particularly during effort stages
Maza, Goizueta, e Llorens (2024)	29 healthy participants	Validation	To investigate the reliability of a widely used low-cost chest strap in detecting HRV fluctuations in response to	Polar H10 (chest strap, 1 Hz, Bluetooth)	Shimmer3 ECG (Four-lead cardiac monitor, 8 Hz, Bluetooth)	HRV	Experimental: Emotion recognition research	Accuracy: NR; Precision: NR; Device comparison: Signals recorded by both devices were highly correlated with no significant discrepancies between measures;

Reference	Population	Study Type	Aim	Sensor (Model & Technology)	Comparison/Reference device	Cardiac Parameters Measured	Application Context	Reported Results
			emotionally valenced stimuli, by assessing its similarity and agreement with a five-lead cardiac monitor under short-term and ultra-short-term conditions.					strong to excellent agreement in time-, frequency-, and nonlinear measures
Mishra et al. (2020)	27 university students	Validation and field study using commodity hardware	To evaluate the viability of using a commercially available heart rate monitor (Polar H7) to detect stress, by assessing its performance in both controlled laboratory settings and free-living conditions, as a low-cost alternative to clinical-grade sensors.	Polar H7 (chest strap; 1 Hz, Bluetooth)	Biopac MP150 (Standard ECG, chest patch electrode, signal recovered); Zephyr HXM (chest strap; 1 Hz, Bluetooth)	HR; HRV; RRI	Experimental (in lab/in loco): Laboratory stress-induction and real-life (field) monitoring	Accuracy: NR; Precision: NR; Device comparison: F1-score up to 0.87 (lab) and 0.66 (field); strong correlation with clinical ECG ($r > 0.95$ for most features)
Montes e Navalta (2019)	40 healthy young adults	Test-retest reliability study	To determine the reliability of the T31 heart rate monitor at rest and during motion-based activities, including free movement and treadmill exercise, in	Polar T31 (Chest strap) + Polar CE0537 (wrist/storage)	No direct comparison in this study	HR	Experimental (in lab); Fitness, general exercise	Accuracy: NR; Precision: NR; Device comparison: Cronbach's α from 0.90 to 0.99 across all test conditions; all $p < 0.001$; excellent reliability

Reference	Population	Study Type	Aim	Sensor (Model & Technology)	Comparison/Reference device	Cardiac Parameters Measured	Application Context	Reported Results
			both male and female participants.					
Nuske et al. (2022)	Study 1: 23 adults (typical); Study 2: 32 children with ASD and 23 typically developing children (8–12 yrs)	Two-phase feasibility and validation study (lab setting)	To evaluate the suitability, comfort, and validity of commercially available ambulatory cardiovascular monitors for measuring psychosocial stress in children with and without ASD, by first testing a validation framework in adults and then applying it to children.	Polar H7 (ECG, chest-strap, Bluetooth)	Mio Fuse (PPG, wristband, Bluetooth); PulseOn (PPG, wristband, Bluetooth); Biopac MP-150 (Standard ECG, chest patch electrode, signal recovered)	HR; HRV	Clinical: ASD stress assessment	Accuracy: NR; Precision: NR; Device comparison: HR ↑ and HRV ↓ during stress vs. rest ($p < 0.001$ for both devices); Sampling Fidelity $\geq 83\%$; Spike Rate $\leq 13\%$; $\eta^2 > 0.25$ for HR and 0.16–0.26 for HRV effects
Di Palma et al. (2017)	5 male children with High-Functioning ASD; diagnosed with ADOS-2 and WISC-IV	Feasibility study (longitudinal, 6 months)	To assess autonomic nervous system responses in children with ASD during therapeutic sessions involving interactive serious games, using wearable technologies to correlate physiological signals with engagement levels and	Shimmer® IFC-CNR wireless ECG chest-strap (Chest-strap, single lead, 200 Hz, Bluetooth)	ELA medical (Holter)	HR	Clinical: therapy with “serious games” for ASD	Accuracy: NR; Precision: NR; Device comparison: Physiological events (↑ HR, ↓ Root Mean Square of Successive Differences (RMSSD), ↓ Respiratory Sinus Arrhythmia (RSA)) correlated with sociocognitive engagement; increased “lower RSA” and “lower RMSSD” events over time; ECG well tolerated throughout

Reference	Population	Study Type	Aim	Sensor (Model & Technology)	Comparison/Reference device	Cardiac Parameters Measured	Application Context	Reported Results
			support therapy personalisation.					
Parak et al. (2021)	25 healthy adults	Validation of form factor for HR/HRV sensors	To compare the accuracy of a chest strap and a vest against a clinical ECG monitor for HR and HRV monitoring, and to analyse the impact of their accuracy on accumulated physiological metrics (Training Impulse (TRIMP), Excess Post-exercise Oxygen Consumption (EPOC), and Energy Expenditure (EE)) used in training monitoring and planning.	Suunto Movesense ECG (chest strap and sports vest, 125 Hz, Bluetooth)	Bittium Faros (3-lead Holter ECG, 256 Hz)	HR; HRV; RRI	Experimental (in lab): Sports training and performance monitoring	Accuracy: Strap= 99,24%; Vest= 84,70%; Precision:NR; Device comparison: Chest strap: HR MAPE = 0.76%, EPOC MAPE = 3.90%, TRIMP MAPE = 0.38%; Vest: HR MAPE = 3.32%, EPOC MAPE = 54.15%, TRIMP MAPE = 8.99%; chest strap more accurate across all measures
Plews et al. (2017)	26 healthy individuals (elite, well-trained and recreational athletes)	Validation study during resting breathing (1 min)	To compare the accuracy and validity of HRV recordings obtained using a PPG smartphone application (HRV4Training) and the	HRV4Training smartphone app (Photoplethysmography (PPG), video camera, 180Hz); Polar H7 (chest strap, Bluetooth)	Cosmed Quark T12x (Standard 12-lead ECG, chest patch electrode)	HRV	Sports: resting	Accuracy: NR; Precision: NR; Device comparison: All differences vs. ECG were “trivial”; technical error of estimate (TEE) coefficient variation (CV) %: PPG GB = 3.8%, Polar H7 NB = 8.6%; correlations r = 0.99–1.00; mean bias < 2.0 ms

Reference	Population	Study Type	Aim	Sensor (Model & Technology)	Comparison/Reference device	Cardiac Parameters Measured	Application Context	Reported Results
			Polar H7 chest strap against gold standard ECG.					
Rogers et al. (2022)	21 physically active adults	Cross-sectional validation study	To evaluate the agreement of the Movesense Medical chest-strap device (single-channel ECG) with a 12-channel ECG system for RR interval detection and selected HRV measures during rest, incremental cycling exercise, and post-exercise recovery.	Movesense Medical (chest-strap, single-channel ECG; 512 Hz)	CardioPart 12 Blue (Standard 12-lead ECG, 500Hz)	RRI; HRV	Experimental: rest, ramp test, recovery	Accuracy: NR; Precision: NR; Device comparison: High correlations for HRV parameters: Pearson's $r = 0.95-1.00$; small bias (e.g., meanRR PRE bias = 0.0 ms, Limits of Agreement (LOA) ± 1.9 ms); short-term scaling exponent of Detrended Fluctuation Analysis (DFA a1) agreement $r \geq 0.95$
Romagnoli et al. (2021)	51 healthy Caucasian athletes training 4 ± 1 times/week	Initial observational study for reference value development	To support large-scale prevention of sport-related sudden cardiac death by identifying electrocardiographic features that may serve as reference values in the pre-exercise phase.	Zephyr BioHarness 3.0 (chest strap, 1-lead ECG, 250Hz, Bluetooth)	Reference values from clinical 12-lead ECG	HR; HRV; ECG waveform	Sports: pre-exercise monitoring	Accuracy: NR; Precision: NR; Device comparison: Median values reported with interquartile range; significant differences found vs. clinical ECG norms (e.g. $\downarrow$ HRV, $\uparrow$ QRS duration, $\downarrow$ QT interval)

Reference	Population	Study Type	Aim	Sensor (Model & Technology)	Comparison/Reference device	Cardiac Parameters Measured	Application Context	Reported Results
Saggu et al. (2024)	34 patients [subgroup A: 20 inpatients (24 h), subgroup B: 14 ambulatory (12 weeks)]	Pilot observational feasibility study	To design and evaluate the feasibility of an investigational external cardiac monitor using a chest strap with single-lead dry electrodes for affordable long-term (3–6 months) cardiac monitoring, assessing its ECG diagnostic quality, patient comfort, and effectiveness in detecting cardiac arrhythmias compared to existing short- and long-term monitoring methods.	Zephyr BioHarness 3.0 + Reveal LINQ™ electronics (Chest strap, single lead)	DR220 Holter (chest patch electrodes)	ECG waveform; HR; Inter-beat Interval (IBI)	Clinical: short- and long-term monitoring	Accuracy: NR; Precision: NR; Device comparison: Diagnostic-quality ECG for 76.5% of monitoring; arrhythmia yield: 24% (24h) and 64% (12 weeks); comfort reported in 94.9%
Skála et al. (2022)	161 participants: Hospitalised patients (n=54), outpatients (n=53), healthy	Validation	To verify the feasibility of accurate long-term evaluation of all heartbeats on a single-lead ECG by an experienced cardiologist across patients with varying body types,	Polar H10 (Chest Strap, 1-lead ECG)	Standard 12-lead ECG (chest patch electrodes)	ECG waveform	Clinical: Hospitalised and outpatient cardiology	Accuracy: NR; Precision: NR; Device comparison: Basic rhythm reliably determined in majority of patients; 2.16% noise

Reference	Population	Study Type	Aim	Sensor (Model & Technology)	Comparison/Reference device	Cardiac Parameters Measured	Application Context	Reported Results
	controls (n=54)		rhythms, and cardiac devices, and to assess the presence of artefacts or noise that may hinder ECG evaluation in different patient groups.					
Speer et al. (2021)	146 healthy Australian preschool children (3–5 years old)	Cross-sectional study	To investigate the relationship between resting vagally-mediated heart rate variability (HRV) and body mass index (BMI) in Australian preschool children aged 3 to 5 years.	Polar H10 (Chest strap, Bluetooth 4.0)	Compared to electrocardiographic-derived recordings	HRV	Clinical: Children relationship between resting vagally-mediated HRV and BMI	Accuracy: NR; Precision: NR; Device comparison: Significant inverse relationship between RMSSD (ln) and BMI ($\beta = -0.06$; 95% CI = $-0.12 - -0.01$; $p = 0.032$)
Van Oost et al. (2024)	24 healthy young adults (students)	Validation study in controlled dynamic protocol	To validate the accuracy of commercial wearable devices, including the Zephyr BioHarness 3.0 chest-strap device and six wrist-worn wearables, for heart rate measurement and stress monitoring in road freight drivers under	Zephyr BioHarness 3.0 (Chest strap)	CAM-14 module (Standard 12-lead ECG, chest patch electrodes)	HR	Occupational: drivers (in lab)	Accuracy: NR; Precision: NR; Device comparison: Zephyr showed near-perfect accuracy (MAPE & CCC) in dynamic HR; wrist-wearables varied: Fitbits performed best, WHOOP & Withings worst; transitions (HR dynamics) caused performance drop in all devices

Reference	Population	Study Type	Aim	Sensor (Model & Technology)	Comparison/Reference device	Cardiac Parameters Measured	Application Context	Reported Results
			both transient and steady state conditions.					
Vila et al. (2021)	3 healthy male adults	Field validation and algorithm development	To develop and validate a signal quality index for data loss in IBI signals and assess the accuracy of a wrist-worn sensor against a wearable ECG in real-life conditions.	Zephyr BioHarness 3 (Chest strap, 250Hz, signal recovered)	Empatica E4 (wristband, 64 Hz, signal recovered); Pan-Tompkins ECG-derived IBI as academic reference	HR; IBI; HRV	Occupational (in loco)	Accuracy: NR; Precision: NR; Device comparison: Median error for mean HR: 3.2%; RMSSD: 62%; Low Frequency (LF): 25%; High Frequency (HF): 63%. Accuracy improved when no missing samples (0.0%, 27%, 6.4% respectively)

Note: NR: Not Reported

Table 3: Studies Using Chest-strap Device as Reference Tools

Reference	Aim	Population	Sensor (Model & Technology)	Target Device	Reported Results (Reference vs Target)	Cardiac Parameters Measured	Application Context
Chow e Yang (2020)	To compare the real-time heart rate (HR) tracking performance of two commercial fitness wearables (Photoplethysmography (PPG)-based) in younger versus older adults during moderate physical activity	20 adults aged 65 years and above (Senior) and 20 adults aged between 20 years and 26 years (Young).	Polar H7 (chest strap)	Xiaomi Mi Band 2 (Xiaomi Cooperation) and Garmin Vivosmart HR+ (Garmin International Inc)	Garmin device produced more reliable and accurate HR readings than the Xiaomi one. The accuracy levels of both devices were negatively correlated with the level of activity intensity. For both devices, the measurement accuracy deteriorated in individuals while cycling.	HR	Experimental (in lab): treadmill, upright stationary bike, and elliptical machine: aerobic training.
Cosoli et al. (2022)	To evaluate the accuracy and precision of wrist-worn (Polar Vantage V2, Garmin Venu Sq) versus chest-strap (Polar H10) HR monitors during swimming and dry-land activities in expert swimmers.	10 expert swimmers	Polar H10 (cardiac belt, 130 Hz)	Polar Vantage V2; Garmin Venu Sq	Precision and accuracy worsen in-water tests. The metrological performance in terms of accuracy of Polar Vantage V2 is better compared to Garmin Venu Sq.	HR	Occupational/Sports/Experimental: swimming in different styles (in loco); walking/running on a treadmill (in lab)
Higgins et al. (2018))	To evaluate the validity of an earpiece HR monitoring device against a previously validated chest strap HR monitoring device	15 college students	Polar T31 (Chest Strap) + Polar FT1 HR monitor (Bluetooth)	Bioconnected wireless exercise earpieces	Device Correlation: Strong overall correlation between earpiece and chest strap ($r = 0.97$); Meets validity threshold ($r \geq 0.90$) for HR monitoring devices. Measurement Accuracy: 521 ± 117 HR data points (earpiece) vs 517 ± 118 (chest strap);	HR	Experimental (in lab)

Reference	Aim	Population	Sensor (Model & Technology)	Target Device	Reported Results (Reference vs Target)	Cardiac Parameters Measured	Application Context
					Close overlap in readings for first 350 seconds of protocol. Max discrepancy: <10 beats per minute (bpm) during walk-to-jog transition. Algorithm Differences: Chest strap showed sudden HR spikes (5-sec averaging); Earpiece demonstrated gradual increases (continuous monitoring).		
Hoevenaars et al. (2022)	To assess the reliability of Fitbit Charge 2's PPG-based HR monitoring in spinal cord injuries (SCI) wheelchair users, investigating the impact of exercise intensity and neurological impairment level on measurement accuracy	48 participants (38 with SCI and 10 without)	Polar H7 HR Monitor (chest strap, Bluetooth Low Energy)	Fitbit Charge 2	Overall Accuracy (All Lesions): Mean Absolute Percentage Error (MAPE): 12.99% (outside acceptable $\pm 10\%$ range); Agreement: Moderate (CCC = 0.577). Accuracy by Lesion Level: Non-SCI: 8.09% (within acceptable range); Lesions below T5: 11.16%; Lesions T1–T5: 10.5%; Cervical Lesions (tetraplegia): 20.43% (significantly reduced accuracy); Accuracy by Activity Intensity: Rest: 6.5% (best performance); Moderate Activity: 12.97%; Strength Exercises: 14.2% (worst performance).	HR	Clinical/Experimental: rest, wheelchair activities, and a 30-minute strength exercise block

Reference	Aim	Population	Sensor (Model & Technology)	Target Device	Reported Results (Reference vs Target)	Cardiac Parameters Measured	Application Context
Kuo et al. (2015)	To assess the feasibility of using imaging PPG (IPPG) from in-vehicle face video for HR monitoring during real-world driving, compared to chest-strap measurements.	10 drivers	Zephyr Bioharness 3.0 (chest strap)	IPPG (camera-based)	48–75% accuracy in 4/10 participants	HR	Occupational (in loco): drivers
Liu et al. (2025)	To assess the validity of the Polar Verity Sense (PVS) armband versus the Polar H10 chest strap for HR monitoring during high-intensity interval training (HIIT) in adolescents.	39 students (7th grade)	Polar H10 (chest strap; Bluetooth)	PVS	Strong agreement between PVS and H10 overall ($r^* = 0.93$, Mean absolute error (MAE) = 4 bpm, 2.8% error). Slightly reduced accuracy at high intensity ($\geq 80\%$ max HR, $r^* = 0.84$). Unaffected by sex, body mass index, waist size, or fitness level. PVS is a valid, practical alternative to chest straps for HIIT monitoring in school settings.	HR	Experimental (in lab): HIIT
Milena et al. (2023)	To assess the feasibility of deriving HR variability (HRV) metrics from mechanical cardiac signals (recorded via accelerometer and gyroscope) as an alternative to conventional electrical signals (ECG)	22 healthy subjects	Zephyr Bioharness 3.0 (chest strap, 1-lead ECG, 250 Hz)	Inertial Measurement Unit (IMU) sensor (Xsens DOT)	Gyrocardiogram (GCG) in lying posture showed the highest accuracy; seismocardiogram (SCG) was less reliable than GCG, especially in seated posture.	HRV; R-R peaks	Experimental (in lab): sitting (1) and lying (2) posture
Navalta et al. (2020)	The purpose was to determine concurrent heart rate validity during trail running	21 healthy subjects	Polar H7 (chest strap, 1000Hz)	Garmin Fenix 5 wristwatch, Jabra Elite Sport earbuds, Motiv	Garmin Fenix 5 (MAPE = 13%, Bland-Altman Limits of Agreement (LOA) = -32 to 162, Lin's Concordance Coefficient (rC)	HR	Experimental (in lab): The trail runs were out-and-back with the first 1.61 km in an

Reference	Aim	Population	Sensor (Model & Technology)	Target Device	Reported Results (Reference vs Target)	Cardiac Parameters Measured	Application Context
				ring, Scosche Rhythm+ forearm band, Suunto Spartan Sport watch with accompanying chest strap	= 0.32), Jabra Elite Sport (MAPE = 23%, LOA = -464 to 503, rC = 0.38), Motiv ring (MAPE = 16%, LOA = -52 to 96, rC = 0.29), Scosche Rhythm+ (MAPE = 6%, LOA = -114 to 120, rC = 0.79), Suunto Spartan Sport (MAPE = 2%, LOA = -62 to 61, rC = 0.96).		uphill direction, and the 1.61 return being downhill in nature
Navalta et al. (2023)	To determine the validity of the PVS optical HR monitor for measuring HR and HRV during rest and exercise, using the Polar H10 chest strap as the criterion device.	17 healthy adults	Polar H10 (chest strap, 1000Hz, Bluetooth)	PVS (PPG armband)	PVS HR: r = 0.99 vs. H10; HRV: Intraclass Correlation Coefficient = 0.83, r = 0.84; mean bias: -3.3 ms; all within acceptable limits. Wearable, comfortable, good agreement with criterion device, wrist/arm placement flexibility	HR, HRV	Experimental (in lab): Exercise monitoring
Romano et al. (2022)	To compare the performance of accelerometer (ACC) and gyroscope (GYR) sensors (embedded in a single IMU) for simultaneous HR and respiratory rate (RR) monitoring while evaluating the impact of window length and posture on accuracy	18 healthy subjects	Zephyr Bioharness 3.0 (chest strap, 250 Hz)	Chest-worn IMU (Shimmer3) – Accelerometer & Gyroscope	HR: 5-second windows yielded the worst agreement with ECG, especially in the standing posture (LOA -12.5–12.8 bpm); 55-second windows showed the best agreement (LOA -3.5–3.7 bpm for SCG and GCG); Other window sizes (15–45 s) showed comparable and stable performance. MAE were similar for SCG and GCG, with SCG differing by no more than 0.53 bpm in the seated posture.	HR	Experimental (in lab)

Among the analysed devices, those showing the highest performance in terms of HR measurement accuracy and precision were the Polar chest strap models (H7, H10). For example, Etiwy et al. (2019) reported a correlation coefficient of 0.99 between Polar H7 data and reference values. Nuske et al. (2022) found the Polar H7 achieved sample fidelity rates above 80% in high physiological variability contexts. The Polar H10 demonstrated performance comparable to reference ECGs in both low- and high-intensity activities, even showing superior RR signal quality during vigorous movements (Gilgen-Ammann et al., 2019). Similarly, Bläsing et al. (2022) found that the Polar H10's signal precision was particularly relevant under high physical demand, with superior performance in phases of elevated HR.

Studies involving Movesense devices showed correlations above $r = 0.95$ in various HRV metrics (Rogers et al., 2022), absolute mean errors below 1% (MAPE) (Parak et al., 2021), and residual means under 0.5 ms (Martín Gómez et al., 2024).

In clinical practice, the Zephyr BioHarness 3.0 differentiated and detected clinically meaningful changes, such as arrhythmia and reduced HRV (Romagnoli et al., 2021; Saggu et al., 2024), and was also identified as the best device exhibiting performance while changing exertion states (Van Oost et al., 2024).

Performance metrics when using wrist-worn devices, such as the Apple Watch and TomTom Spark, generally did not represent reliable data, especially when physically intense movement or exercise occurred. Wearable devices that are used in common everyday scenarios, such as Garmin, Fitbit, or Xiaomi, used contextually varied, and therefore applicability of performance measures were mixed based on both exertion intensity and also target population. Chow e Yang (2020) reported that the Garmin Vivosmart HR+ was found to be more accurate than the Xiaomi Mi Band 2, (although both manufacturers showed reduced accuracy as exercise intensity increased). Kuo et al. (2015) and Romano et al. (2022) assessed alternate technologies of video-based PPG and Inertial Measurement Unit (IMU) sensors, but would still pose significant issues of accelerated signal precision and stability, verified by the reported limits of agreement (LOA), with findings suggesting Romano et al. (2022), produced wide LOA especially in upright postures.

Ear sensors, as analysed by Higgins et al. (2018), showed strong correlation with chest straps ($r = 0.97$), although methodological differences in heart rate calculation algorithms caused temporary discrepancies during sudden intensity changes. After analysing the studies, the technical specifications of each of the chest straps were thoroughly compiled based on information from

user manuals and official brand websites, and are presented in Table 4 (Coospo, 2024; Garmin & subsidiaries, s.d; Polar Electro, 2025; Zephyr Technology, 2012; Movesense, s.d).

In general, the devices do not include a screen or geolocation functionality, and all support real-time data transmission.

Regarding the quality assessment, two separate summary tables are presented, one for each type of included study. The methodological quality of the 22 studies listed in Table 2 is summarised in Table 5, while the 10 studies included in Table 3 are assessed in Table 6. All studies met the MMAT screening criteria concerning the clarity of research questions and the adequacy of data to address those questions. This review includes only two study types: the majority were quantitative non-randomised studies (SD3), while four were classified as quantitative descriptive studies (SD4).

Among the studies evaluating chest-strap devices, 9 were rated as medium quality, 8 as high, and 3 as low. All quantitative descriptive studies were rated high quality, although 75% of them failed to include participants representative of the target population. In the case of quantitative non-randomised studies (SD3), quality ratings were more variable. All medium and low-quality studies fell within this category, while 6 studies were classified as high quality. All SD3 studies used appropriate measurements for both outcomes and interventions. However, several studies failed to adequately describe or address key methodological aspects, resulting in "Can't tell" (CT) ratings for: participant representativeness (27%), completeness of outcome data (5%), control of confounders (50%) and intervention fidelity (11%). Furthermore, some studies were rated "No" (N) in domains they did not consider methodologically, including participant representativeness (44%), completeness of outcome data (11%) and confounder accountability (22%).

Focusing specifically on studies using chest-strap devices as reference, all demonstrated appropriate measurements for both outcome and intervention, presented complete outcome data, and clearly explained whether the intervention/exposure occurred as intended. However, 60% failed to describe or address (CT) potential confounders, and 10% did not contemplate them at all (N). In terms of participant representativeness, 50% failed to consider this factor (N), and an additional 20% did not address it (CT). These gaps in reporting and methodological consideration limited the confidence in the appraisal of certain studies.

Table 4: Chest strap devices technical specifications

Brand	Polar			Zephyr	Movesense	Garmin	Coospo	Shimmer®
Model	H7	H10	T31	Bioharness 3.0	Sensor	HRM-Dual	H6	IFC cnr
Dimension	30x20x9mm	65x34x10 mm		28x7 mm	36.6x10.6 mm	62x34x11 mm	60x33,8x12,2	50 x 25 x 23 mm
Weight	100 g	60 g		89 g	9,4 g	54,4 g	46.4 g	30 g
Performance	No recording mode	CPU velocity: 64 MHz; Memory: MB; Recording mode	Coded; No recording mode	Continuous physiological monitoring; ROG status (Red/Orange/Green) alerts; Data logging up to 500+ hours; Multiple transmission modes; Recording mode	Nordic Semiconductor nRF52832, 32-bit ARM Cortex-M4, 64kB RAM, 512kB FLASH; Recording mode	No recording mode	No recording mode	12-bit A/D resolution; 200 Hz sampling rate; Recording mode
Connectivity	Bluetooth Low Energy (BLE); Analog; Transmission rate varies with receiving device; Short transmission range (receiving device should be in front of the user fixed on a belt or pocket)	BLE; Analog; ANT 2.1; Transmission range: 9000 cm	Analog 5kHz	Bluetooth 2.1 + EDR; IEEE 802.15.4 (2.405–2.480 GHz); USB (for charging/configuration)	BLE 4.0/5.0	ANT; BLE 2	Bluetooth (10 m); ANT+ (7 m);	Chipcon CC2420 radio transceiver (2.4 GHz), Rufa™ antenna, RN-41 Bluetooth® module; Short-range transmission (up to 30 m); low-power modes for energy efficiency
Durability	-10°C to +50 °C; Water Resistant (WR)	-10°C to +50°C; WR 30 m	WR	IP55 water/dust resistant; Operating Temp: -30°C to +60°C; WR 30 m Storage Temp: -40°C to +85°C		WR 10 m	+5 °C a +40°C, <= 95% Relativity Humidity	Designed for long-term chest wear; comfortable and adaptable to body shape
Sensors	Electrodes	Electrodes; Accelerometer	Electrodes	Electrodes (250 Hz); Respiratory (25 Hz); 3-axis accelerometer (100 Hz); Posture detection; Internal temperature sensor	Accelerometer, Gyroscope, Magnetometer, Temperature, Electrodes	Electrodes	Electrodes	ECG with gain of 175; uses low-power CMOS op-amps; cable-free electrode connection
Battery	Type: CR 2025; Lifetime: 200 h; Rechargeable: No; Replaceable: yes	Duration: 165 mAh; Type: coin cell; Rechargeable: No; Replaceable: yes	Duration: 2500 h; Non replaceable.	Rechargeable Lithium-Polymer (3.7V); 12–24 hrs (transmit), 35 hrs (logging); Charging via USB: 3 hrs full, 1 hr to 90%	CR2025 type battery (lithium coin battery), duration varies depending on use, up to several months	CR2032; 3.5 y (1h a day); Replaceable: yes; Rechargeable: no	Type: CR2032; 300 h; Replaceable: yes; Rechargeable: no	3V Li-ion, 280 mAh; transmission: 60 mA; reception: 40 mA; idle: 1.4 mA; sleep: 50 µA
Extra features	Discontinued from 2020 Firmware upgradeable			ROG status logic configurable; Software Development Kit available; Data export in CSV/HEX for analysis (e.g., MATLAB)	Software controllable red LEDs, 3Mbit EEPROM for storage, API for development, OTA firmware			Includes 2 GB SD Card for onboard storage; SPI via USART1; suitable for wearable applications

Table 5: Quality assessment of studies evaluating chest-strap devices

Reference	SD	S1	S2	SD.1	SD.2	SD.3	SD.4	SD.5	Level
Bläsing et al. (2022)	3	Y	Y	N	Y	Y	CT	Y	Medium
Constantini et al. (2018)	3	Y	Y	Y	Y	Y	CT	Y	High
Etiwy et al. (2019)	4	Y	Y	Y	Y	Y	Y	Y	High
Flores et al. (2024)	3	Y	Y	N	Y	Y	N	CT	Medium
Gilgen-Ammann, Schweizer, e Wyss (2019)	4	Y	Y	Y	N	Y	Y	Y	High
Martín Gómez et al. (2024)	4	Y	Y	Y	N	Y	Y	Y	High
Kuo et al. (2023)	3	Y	Y	Y	Y	Y	Y	Y	High
Marzano-Felisatti et al. (2024)	3	Y	Y	N	Y	Y	CT	Y	Medium
Maza, Goizueta, e Llorens (2024)	3	Y	Y	N	Y	Y	CT	Y	Medium
Mishra et al. (2020)	3	Y	Y	N	Y	Y	CT	Y	Medium
Montes e Navalta (2019)	3	Y	Y	N	Y	Y	CT	Y	Medium
Nuske et al. (2022)	3	Y	Y	Y	Y	Y	Y	Y	High
Di Palma et al. (2017)	3	Y	Y	CT	Y	Y	N	Y	Medium
Parak et al. (2021)	3	Y	Y	CT	Y	Y	Y	Y	High
Plews et al. (2017)	3	Y	Y	CT	Y	Y	N	Y	Medium
Rogers et al. (2022)	3	Y	Y	CT	Y	N	N	Y	Low
Romagnoli et al. (2021)	4	Y	Y	Y	N	Y	Y	Y	High
Saggu et al. (2024)	3	Y	Y	CT	Y	N	CT	Y	Low
Skála et al. (2022)	3	Y	Y	Y	Y	Y	Y	Y	High
Speer et al. (2021)	3	Y	Y	Y	Y	Y	Y	CT	High
Van Oost et al. (2024)	3	Y	Y	N	Y	Y	CT	Y	Medium
Vila et al. (2021)	3	Y	Y	N	Y	CT	CT	Y	Low

Legend: SD: Study Design (1- Qualitative studies; 2- Quantitative randomized controlled trials; 3- Quantitative non-randomized studies; 4- Quantitative descriptive studies; 5- Mixed methods studies); S1. Are there clear research questions? S2. Do the collected data allow to address the research questions?; Questions: 3.1. Are the participants representative of the target population? 3.2. Are measurements appropriate regarding both the outcome and intervention (or exposure)? 3.3. Are there complete outcome data? 3.4. Are the confounders accounted for in the design and analysis? 3.5. During the study period, is the intervention administered (or exposure occurred) as intended? 4.1. Is the sampling strategy relevant to address the research question? 4.2. Is the sample representative of the target population? 4.3. Are the measurements appropriate? 4.4. Is the risk of nonresponse bias low? 4.5. Is the statistical analysis appropriate to answer the research question? Y- Yes; N-No; CT- Can't tell. Quality rating: High: 0 or 1 N or CT; Medium: 2 N or CT; Low: 3 or more N or CT

Table 6: Quality assessment of studies using chest-strap devices as reference

Reference	SD	S1	S2	SD.1	SD.2	SD.3	SD.4	SD.5	Level
Chow e Yang (2020)	3	Y	Y	Y	Y	Y	CT	Y	High
Cosoli et al. (2022)	3	Y	Y	N	Y	Y	CT	Y	Medium
Higgins et al. (2018)	3	Y	Y	N	Y	N	CT	Y	Low
Hoevenaars et al. (2022)	3	Y	Y	Y	Y	Y	Y	Y	High
Kuo et al. (2015)	3	Y	Y	N	Y	Y	Y	Y	High
Liu at al. (2025)	3	Y	Y	Y	Y	Y	Y	Y	High
Milena et al. (2023)	3	Y	Y	N	Y	Y	CT	Y	Medium
Navalta et al. (2020)	3	Y	Y	CT	Y	Y	N	Y	Medium
Navalta et al. (2023)	3	Y	Y	CT	Y	Y	CT	Y	Medium
Romano et al. (2022)	3	Y	Y	N	Y	Y	CT	Y	Medium

Legend: SD – Study Design (1- Qualitative studies; 2- Quantitative randomized controlled trials; 3- Quantitative non-randomized studies; 4- Quantitative descriptive studies; 5- Mixed methods studies); S1. Are there clear research questions? S2. Do the collected data allow to address the research questions?; Questions: 3.1. Are the participants representative of the target population? 3.2. Are measurements appropriate regarding both the outcome and intervention (or exposure)? 3.3. Are there complete outcome data? 3.4. Are the confounders accounted for in the design and analysis? 3.5. During the study period, is the intervention administered (or exposure occurred) as intended?; Y- Yes; N-No; CT- Can't tell.

Quality rating: High: 0 or 1 N or CT; Medium: 2 N or CT; Low: 3 or more N or CT

5. DISCUSSION

This dissertation critically examined the use of wearable sensors, focusing on chest strap devices, for monitoring workload in physically and psychologically demanding occupational contexts, such as the firefighting profession. Additionally, it was the intent to also analyse their potential to identify cardiac disorders.

5.1. Overview of Chest Strap Devices Usage

The dominance of laboratory studies present in this review foreshadows a lingering reliance on controlled environments to evaluate wearable cardiac monitoring systems for healthcare applications that may restrict validity of findings, particularly for the usage of these wearables in uncontrolled environments (Khundaqji et al., 2021). Although real-world and mixed-context studies were limited in inclusion, the need for such studies is imperative to assess device robustness when implemented in meaningful dynamic and less controlled environmental conditions. For example, a number of recent studies have emphasized the importance of generating evidence in real-world conditions, in order to address the lack of robustness. Specifically, Keersmaecker et al. (2025) developed a framework to unveil hidden implicit communication patterns that existed for smart home devices in less controlled conditions, the study found 27% more unique flows due to the less controlled testing conditions, than utilizing the traditional means; Morales Casas et al. (2024) conducted a semi-real validation of a medical device that had been installed within the information communication technology domain with emergency services, reporting a reliability outcome of 70-100% even though testing took place in difficult conditions; and Alkurdi et al. (2025) transferred existing anxiety detection models that were constructed based on controlled conditions to real-world environments and reported that feature-based models performed better than traditional machine learning based on accuracy outcomes, despite the difference in noise conditions.

Furthermore, the concentration of studies around a few specific devices, particularly the Polar H10, Zephyr BioHarness 3.0, and Polar H7, suggests a lack of diversity in technology evaluation, potentially driven by accessibility, brand trust, or legacy use (Sannomia et al., 2019; Planning et al., 2011). Notably, although Polar models often outperform others in terms of accuracy and signal stability, especially under physical strain, devices like the Zephyr offer broader contextual usability, particularly in occupational and clinical domains (Kuo et al., 2015; Kuo et al., 2023; Saggu et al., 2024; Van Oost et al., 2024; Vila et al., 2021). This distinction reinforces the importance of considering not only technical performance but also situational adaptability when selecting reference technologies (Nazari et al., 2018).

The overall analysis reveals that the most widely used devices across the different reviewed studies were the Zephyr BioHarness 3.0 and the Polar H10 chest straps. Their recurring selection as both primary tools and reference technologies suggests a level of popularity and perceived reliability that reinforces their status as gold standards in cardiac monitoring for scientific research.

The examination of the different contexts in which devices were used also demonstrate the Zephyr BioHarness 3.0's superior versatility in application compared to the Polar H10. Specifically, the Zephyr was employed in 2 sports studies (Constantini et al., 2018; Romagnoli et al., 2021), 2 experimental studies (Milena et al., 2023; Romano et al., 2022), 4 occupational studies (Kuo et al., 2015; Kuo et al., 2023; Van Oost et al., 2024; Vila et al., 2021), and 1 clinical study (Saggu et al., 2024), the results in all contexts were satisfactorily positive regarding its applicability. The Polar H10, with the majority of its 11 studies located, was primarily conducted in experimental contexts (5 studies) and had lesser amounts of utilisation in occupational (2 studies) and clinical contexts (2 studies), and was not located in the sports context the reviewed articles. Based on this evidence, the Polar H10 may be favoured in current documentation, however, the Zephyr BioHarness 3.0 will have more realistic, practical application potential in real-world, challenging contexts such as the occupation and sports contexts.

The inconsistent performance of wrist-worn and other consumer-grade devices reinforces the on-going challenge to establish medical-grade accuracy in a more pleasing or commercially viable format (Mohamoud et al., 2024; Shcherbina et al., 2017). While new methods such as video-based PPG and IMU-based systems show promise, there is a noticeable lack of validation for different postural and exertional contexts (Valenza et al., 2017, 2018). The wear-based monitoring technologies have potential, but their susceptibility to algorithmic inconsistencies, particularly upon sudden changes in activity intensity, also suggests the need for greater algorithm development (Masè et al., 2020; Stutz et al., 2024). Collectively, findings indicate the need for new validation processes centred in context, but also for incorporation of end-user scenarios in research design.

5.2. Clinical applications and constraints

Cardiac rehabilitation programmes, arrhythmia screening, and remote physiological monitoring are promising application areas for chest strap sensors (Di Palma et al., 2017; Etiwy et al., 2019; Hoevenaars et al., 2022; Saggu et al., 2024; Skála et al., 2022). In medical sciences, the 12-lead ECG remains the gold standard for detecting abnormalities (Kligfield et al., 2007). While some studies included comparisons

with ECG or Holter monitors (Di Palma et al., 2017; Etiwy et al., 2019; Gilgen-Ammann et al., 2019; Saggu et al., 2024; Skála et al., 2022), Di Palma et al. (2017) had a small sample size, limiting generalisability to clinical populations.

Clinically, HRV is an increasingly important parameter for assessing autonomic balance, recovery, and cardiovascular prognosis (Kolodziej et al., 2020; Sankar S et al., 2024). Therefore, it is relevant in clinical practice that chest strap wearables not only capture ECG waveforms (with high-quality morphology) but also HRV – something that was not achieved in any of the reviewed articles. Although non-invasive HR and HRV monitoring has shown increasing validity, reliability remains dependent on activity intensity, the technology used, study population, and application context (Gilgen-Ammann et al., 2019; Parak et al., 2021; Plews et al., 2017; Tarvainen et al., 2014). Despite advances in connectivity, some sensors do not offer access to raw data or real-time extraction of HRV or ECG morphology, reducing their value in clinical contexts where detailed cardiac pattern analysis is essential (Bläsing et al., 2022).

In clinical applications, Etiwy et al. (2019), Nuske et al. (2022), Gilgen-Ammann et al. (2019), Di Palma et al. (2017), Saggu et al. (2024), Skála et al. (2022) and Speer et al. (2021) used the Polar H7, Polar H10, and Zephyr BioHarness 3.0 sensors. However, these devices are not CE- or FDA-certified for clinical use and are usually sold as fitness wearables (Bläsing et al., 2022; Dunn et al., 2018; Iqbal & Biller-Andorno, 2022). This lack of certification raises concerns regarding their use for diagnosis or clinical decision-making (Bläsing et al., 2022).

Most validations were conducted at rest or during light exercise, which prevents extrapolation to high-intensity or high-stress scenarios (Di Palma et al., 2017; Etiwy et al., 2019; Gilgen-Ammann et al., 2019; Nuske et al., 2022). Movement artefacts or improper strap placement can compromise data reliability, particularly in patients with limited mobility or excessive sweating (Martín Gómez et al., 2024; Parak et al., 2021; Saggu et al., 2024).

5.3. Environmental and users factors

The reviewed studies showed that external factors such as body movement, perspiration, environmental noise, and humidity significantly affect HR measurement quality, especially in chest straps with electrodes. Martín Gómez et al. (2024) noted that sweat and moisture compromise the electrode-skin interface, affecting electrical conduction. Similarly, Nuske et al. (2022) and Saggu et al. (2024) reported that motion directly interferes with signal quality. Finally, Parak et al. (2021) indicated that poor strap fit can introduce significant mechanical artefacts in the signal. These findings underscore the importance of

testing devices under realistic usage conditions and considering environmental and user-related factors in sensor reliability assessments.

In occupational settings, environmental conditions can interfere with signal accuracy, in particular air pollution, environmental noise, body movement, and vibrations (Gaspar et al., 2017). In high-risk environments, sensors display slow recovery times, limiting their capacity to respond instantly (Koochi et al., *sem data*; Shakeriaski & Ghodrat, 2022; Wang & Yuan, 2010). These constraints are consistent with the limitations identified in several of the included studies (Marzano-Felisatti et al., 2024; Nuske et al., 2022; Parak et al., 2021; Vila et al., 2021).

For wearable devices to be successful in workplace applications, they have to guarantee biocompatibility and skin permeability as well as make it easy to use and remove, and monitor physically active workers during non-stop dynamic daily activities while maintaining signal quality free of errors and interference (Angelucci et al., 2024; Levin et al., 2023). However, loss of skin contact due to sweating, very physically active individuals and wearing multiple layers of clothing represent important challenges that could impede ECG signal quality in some of the articles reviewed (Martín Gómez et al., 2024; Parak et al., 2021; Saggu et al., 2024). In extreme contexts, Cosoli et al. (2022) explored devices' performance during swimming which presents an extreme challenge for physiological monitoring.

Beyond environmental and technical considerations, user discomfort over prolonged wear remains a significant limitation, often rendering continuous use impractical (Lee et al., 2025). More than half of the studies took place in laboratory environments where conditions are controlled. Therefore, considering the signal quality limitations in real-world contexts, future studies should focus on workplace applications to address real-environment biases and support the development of high-precision signal technologies.

5.4. Technical and Ergonomic Considerations and Limitations

From a technical perspective, functional robustness was highly valued, including real-time transmission (Nuske et al., 2022), both online and offline analysis (Di Palma et al., 2017), high sampling rates (Bläsing et al., 2022), and long-lasting batteries (Saggu et al., 2024). Ergonomics and user comfort were also recurrent, especially regarding ease of use and fitting (Bläsing et al., 2022; Saggu et al., 2024).

Overall, the findings from the included studies confirm the superiority of chest straps in contexts requiring high HR monitoring precision. As such, they remain the preferred choice in clinical research and applied settings where reliable physiological data is crucial.

Nonetheless, several cross-cutting limitations, including small sample sizes, experimental protocol variability, and lack of data for submaximal or maximal intensities. These shortcomings point to the need for broader, longitudinal studies with standardized methodologies.

These observations are consistent with prior systematic reviews, which also reported high sampling rates and reliable data transmission as key technical requirements in wearable HR monitors (Evenson et al., 2015; Giggins & Muggeridge, 2019). Likewise, the ergonomic concerns identified in this review echo findings from broader evaluations of wearable usability across occupational contexts (Khakurel et al., 2020; Schall et al., 2018).

5.5. Quality assessment

Regarding quantitative non-randomized studies, the predominance of medium-quality assessments highlights recurring methodological limitations—particularly concerning population representativeness and control of confounding factors. These limitations were often rated as "Can't tell" reflecting insufficient information for the evaluation. High-quality studies had no limitations for appropriate sampling strategies or analytic approaches that addressed confounding issues. Low-quality studies had poor clarity along the important domains of representativeness, confounder control and completeness of outcomes. In fact, the findings highlight how poor reporting for non-randomized studies (with a physiological measurement device) detracts from credibility and transparency. This stands in contrast to the quantitative descriptive studies, all of which achieved high overall quality scores.

These findings are consistent with previous literature, which has highlighted frequent limitations in non-randomized designs, particularly regarding inadequate control of confounding and incomplete reporting (Dhiman et al., 2020; Sterne et al., 2016).

5.6. Chest Strap Devices in Firefighting

Studies show that the high physical and mental workload to which firefighters are exposed significantly increases the risk of acute cardiovascular events as well as the development of chronic cardiovascular disease (Bustos et al., 2023; Chandola et al., 2006; Teixeira et al., 2024). This statement is supported by several studies documenting the association between fatigue, thermal stress, extreme physical exertion, and cardiovascular dysfunction (Chou & Coyle, 2023; Seshadri et al., 2019; Souissi et al., 2024).

The identified pathophysiological mechanisms include disturbances in cardiac electrical activity, increased blood viscosity, oxidative stress, inflammation, and haemodynamic changes (Ndlovu & Nkeh-Chungag, 2024; Souissi et al., 2024), which may culminate in arrhythmias, myocardial infarction, or sudden cardiac death (Du et al., 2024; Seshadri et al., 2019).

The use of wearable sensors for physiological monitoring in firefighters should take into account the extreme demands of this profession: high physical and psychological workloads, hot and humid environments, rapid and unpredictable movements, and prolonged use of PPE's (Aksüt & Eren, 2024; Bakirci et al., 2024; Vila et al., 2021). Among the devices analysed in this review, chest strap sensors stand out as the most suitable for firefighters.

The devices most commonly used in the studies were the Zephyr BioHarness 3.0 and the Polar H10, which stand out for their high accuracy, robustness, and ability to collect relevant cardiovascular variables such as HR, HRV, R-R intervals, and electrocardiographic signal quality.

The Zephyr BioHarness 3.0 exhibited high reliability in both occupational and sport contexts, including monitoring during rigorous exercise and in field contexts, where it exhibited adequate tolerance to heat and sweat and generated consistent readings gathered to users' satisfaction (Constantini et al., 2018; Kuo et al., 2023; Romagnoli et al., 2021; Saggu et al., 2024; Van Oost et al., 2024; Vila et al., 2021).

The main barriers to the use of wearables are losing attachment to the skin, monitoring participants in physically demanding tasks, and wearing multiple layers of clothing that resulted in unreadable ECG signals (Aksüt & Eren, 2024; Levin et al., 2023). Another limitation of physiological observatories such as these is the burden of monitoring, and discomfort, that may limit prolonged use (Lee et al., 2025).

The Polar H10 produced good results, with a high degree of similarity to clinical ECG standards even while engaged in high-intensity tasks and with superior signal quality (Bläsing et al., 2022; Gilgen-Ammann et al., 2019; Skála et al., 2022). His device also demonstrated that it was comfortable and tolerated during prolonged duration but is significant for firefighters working long hours under conditions of heightened demands (Maza et al., 2024; Speer et al., 2021).

Alternative devices such as smartwatches and PPG wristbands, although more popular in the consumer market, have shown lower accuracy compared to chest straps, especially in situations of intense movement or heavy sweating (Cosoli et al., 2022; Liu et al., 2025).

Considering their high reliability, accuracy, resistance to adverse conditions, and user acceptance, the Zephyr BioHarness 3.0 and Polar H10 sensors emerge as the most recommended for monitoring workload and early detection of cardiac events in firefighters.

6. CONCLUSION AND FUTURE RESEARCH

This study aimed to deepen the understanding of the role of chest-strap wearable sensors in the continuous physiological monitoring of professionals exposed to demanding working conditions, with an emphasis on firefighters. This professional group is chronically exposed to intense physical and mental demands, as well as to extreme thermal conditions, factors which significantly increase the risk of acute cardiovascular events and the progression of chronic cardiac disease. Within this context, it becomes imperative to have reliable and non-invasive technological tools that enable the early detection of physiological signs indicative of fatigue, thermal stress, or imminent cardiovascular dysfunction, in order to prevent adverse outcomes and safeguard the physical integrity of the operatives.

Results of this study demonstrated that the Polar H10 and Zephyr BioHarness 3.0 are the most frequently used devices in validation studies, showing high levels of reliability in measuring heart rate and heart rate variability, particularly under resting or light-to-moderate physical activity conditions. Their portability, ease of use, and relative accessibility make them attractive tools both for research and occupational applications. Limitations were identified, namely the presence of motion artefacts, degradation of the skin–electrode interface due to sweat or friction, discomfort caused by prolonged use, and the lack of regulatory certification (CE/FDA) for formal clinical use.

Nevertheless, it should be noted that the majority of the included studies were conducted in controlled laboratory environments, which limits the generalisability of the findings to real operational contexts, characterised by high environmental variability, intense physical effort, and multiple external interference factors. This gap underscores the need for applied research in real field scenarios, namely during operational simulations or real-time rescue missions, where the technical performance of the devices and their acceptability by operatives can be rigorously assessed. This opens a door for more validation studies, as well as to new devices, more suitable to be used by first responders, that overcome the limitations of the existing ones.

In view of the above, the following recommendations are proposed for future research:

- The development of validation studies in real-world settings, with on-duty firefighters, incorporating contextual variables such as thermal stress, high physical demands, and long time journeys;
- The ergonomic optimisation of the devices, aimed at improving comfort, skin adhesion, and signal stability, even under intense movement and the use of multiple layers of clothing;
- The development of more robust signal filtering and analysis algorithms, capable of distinguishing noise artefacts from meaningful physiological variations;
- The integration of sensors into interoperable platforms, enabling real-time visualisation by command teams and supporting informed clinical or operational decisions;
- Longitudinal studies with a preventive focus, assessing the impact of continuous monitoring on reducing cardiovascular incidents, work absenteeism, and premature mortality in professionals exposed to extreme conditions.

The results of this study are limited, as the articles identified and selected were constrained by the previously defined inclusion and exclusion criteria. Scientifically recognised databases were chosen to identify the scientific articles, however, it is possible that relevant studies were not identified. The interpretation of the conclusions presented should therefore take this limitation into account.

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