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Research paper

Towards Effective Wearable Design: 20 Key Factors for Monitoring Physiological Health in Animals

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ABSTRACT

Robust physiological biosensing in animals is valuable for improving health monitoring and advancing animal welfare. However, the design of wearable devices for this purpose faces significant challenges affecting measurement accuracy and user acceptance. These include insufficient adaptation to the specific characteristics of the animal user, limitations in measurement methods, and a lack of standardised documentation regarding usage conditions. This study presents the 20-Factors Framework, a comprehensive framework based on 20 critical factors for designing and evaluating biosensing wearables for continuous physiological monitoring in animals, with a focus on dogs and cats. Developed through a systematic literature review and real-world project participation, the framework is structured using the 5Ws+1H Method (Who, Why, What, When, Where, How), enabling the identification of design gaps and the analysis of interactions between key factors shaping both the physical and functional aspects of these systems. To validate its applicability, a case study on thermal stress monitoring in cats illustrates how these factors can be practically integrated, reinforcing the framework's relevance for research and industry applications. The findings underscore the importance of considering Animal-Computer Interaction (ACI) through Animal-Centred Design (ACD) to ensure that biosensing technologies are aligned with the needs of the animal user—maximising precision, functionality, and acceptability. This work establishes a solid foundation for future research and innovation in biosensing wearables, offering opportunities for implementation across different species and environments while promoting stricter standards in engineering applications.

1. Introduction

In most cultures, animals such as dogs and cats are predominantly regarded as family members [1–3], in addition to playing vital roles in various work-related activities [4–7]. The increasing humanisation of these animals, alongside their emotional and social value growth, has heightened owners' concern for their health and well-being. This interest aligns with the One Health concept, which emphasizes the interconnection between human, animal, and environmental health—a fundamental approach to preventing zoonotic risks and promoting ecosystem balance [8].

In line with this concept, one of the most critical aspects of human-animal interaction is the potential transmission of zoonotic diseases. Dogs and cats can act as reservoirs or vectors in transmitting pathogens to humans. Common examples include the transmission of bacterial diseases such as leptospirosis, parasitic infections like toxoplasmosis, and viral diseases such as rabies [8–10]. These risks underscore the need for effective animal health monitoring, not only to safeguard their well-being but also to prevent the transmission of diseases to humans.

Despite the significance of zoonotic risks, cohabitation with dogs and cats offers multiple health benefits to humans. The presence of dogs and cats can reduce stress levels and improve the cardiovascular health of caregivers by alleviating loneliness, promoting physical activity, and fostering a sense of purpose [11–13]. Assistance dogs further illustrate these benefits by enhancing human independence and quality of life [14–16]. Beyond this, dogs have been conceptualized as living sensors, capable of detecting changes in the environment or in the people they interact with. For instance, it has been documented that dogs can identify fluctuations in blood glucose levels, detect certain types of cancer, and alert about epileptic seizures [17–23]. This role strengthens the intimate connection between humans and animals and emphasizes the importance of continuous animal monitoring to ensure an effective

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response in such situations.

These benefits highlight the need for a comprehensive approach to health. Traditionally, animal health has been understood from a purely physical perspective, focused on preventing and treating diseases and injuries. However, this concept has evolved into a holistic framework encompassing physical, mental, emotional, and social health [24–26], all of which are key components of animal welfare [27]. The mental state of animals is assessed through indicators such as physiological responses and behavioural patterns [28–30], which are directly influenced by their physical condition [30–34]. Injuries, illnesses, or infections can cause stress, anxiety, and behavioural changes, affecting mental health, while prolonged stress can weaken the immune system and lead to physical problems such as gastric ulcers, weight loss, or cardiovascular diseases. Given this bidirectional relationship, an altered mental state can serve as a key indicator of underlying physical health issues, reinforcing the need for integrated monitoring strategies that address both aspects simultaneously.

Advances in technology offer new opportunities to monitor these interconnected health parameters more effectively. Advances in sensor technologies, miniaturisation, connectivity, and data analysis have facilitated the emergence of wearable biosensing systems capable of supporting continuous physiological monitoring [35–38]. In this context, wearables can be valuable tools for continuous, non-invasive tracking of animal physiological and behavioural parameters. By providing high-resolution temporal data, they support (i) prevention, (ii) early detection, and (iii) the management of health conditions in both clinical and field settings.

Wearable devices, or simply wearables, whether extrageneous, implantables, ingestibles, injectables, etc., contribute to health monitoring indirectly by assessing physiological and behavioural parameters linked to well-being. This is particularly evident in wearables designed for working dogs, where performance-tracking technologies also provide valuable health-related insights. These devices play a key role in evaluating the abilities of guide and herding dogs [39,40] and have also been explored as tools for improving communication between dogs trained for explosive detection and their handlers [41]. While their primary function is not health monitoring, they integrate technologies and biosensors that can be extrapolated for broader use in animal health assessment.

Beyond indirect health monitoring, wearable technology has also advanced significantly in tracking animal activity and behaviour as indicators of physiological state. These devices have become widely used due to their versatility, ease of use, and affordability. Current models can track activity levels in dogs and cats [42–44], providing key insights into movement patterns, rest cycles, and general well-being. Some wearables go a step further, offering health monitoring by measuring physiological parameters such as heart and respiratory rates [45–48], or body temperature [49]. However, despite the potential of these technologies to provide detailed health assessments, physiological biosensing remains underdeveloped and less widely adopted than activity tracking.

Although these advancements have expanded the capabilities of wearable technology, most animal physiological monitoring devices still originate from human medicine [50–53]. As a result, they are not specifically designed to meet the needs of the primary wearer and the most directly affected user—the animal user. This leads to significant limitations in animal use, such as inconclusive results and operational constraints that fail to reflect real usage conditions [29,54–56].

To ensure their effectiveness, devices must be adapted to animals' physical and behavioural characteristics, minimizing invasiveness to promote data reliability and animal welfare [57,58]. Additionally, they must consider the complexity of the environments in which they interact and the nature of animal health studies. Addressing these challenges requires a thorough understanding of the design factors influencing the development of wearable devices for animal health monitoring. In the field of animal technology design, Paci, Mancini, and Price [59] developed the Wearer-Centred Framework, a design model focused on the wearer, which systematises usability and ergonomic requirements for animal wearables, emphasising the adaptation of design to their physical, behavioural, and environmental characteristics. Complementing this approach, Webber, Cobb, and Coe [60] proposed the Welfare Through Competence Framework, based on the Five Domains Model of Animal Welfare [61] and Coe's Individual Competence Model [62]. This framework provides a structured approach to defining animal-centred objectives and refining their implementation throughout the design process, ensuring that technology is not only effective but also promotes the well-being of the animal user.

Despite these advances, the design of wearables for animals still lacks a systematic framework that fully integrates the characteristics of the animal wearer with measurement objectives, usage environments, and the technical requirements of the devices. Therefore, the primary objective of this study is to identify the factors that influence the design process of a biosensing wearable device for monitoring physiological parameters in animals. These factors are extracted and classified to provide designers, technologists, and other professionals involved in developing such devices with a structured understanding of the essential elements that must be considered from the initial stages of the design process. Additionally, this research aims to assist dog and cat caregivers in identifying the critical features to consider when acquiring a health monitoring wearable tailored to their animals. The ultimate goal is to establish a foundation for the development of more precise, ergonomic, and versatile biosensing systems for continuous physiological monitoring that generate high-quality data and align with the specific needs of owners, but—most critically—with the physical, behavioural, and contextual needs of the animal wearers.

This paper presents 20 design factors relevant to developing and evaluating physiological monitoring wearables for animals, with a particular focus on dogs and cats. We first detail the systematic review and classification framework based on the 5Ws+1H Method. Then, we introduce the identified factors, highlighting key trends in wearable design. Their interrelations and implications are examined, followed by a case study illustrating their practical application. Finally, key insights are summarized, and future research directions for advancing animal-centred biosensing technologies are proposed.

This work contributes to engineering by delivering a reproducible and structured design framework that supports developing, evaluating, and deploying wearable systems for continuous physiological biosensing in animals. By integrating technical, anatomical, and environmental variables, the framework addresses key design challenges, promoting the creation of robust, user-centred solutions that can be adapted to diverse real-world applications.

The article is structured as follows. Section 2 describes the methodology, including the review protocol and the development process of the 20-Factors Framework. Section 3 introduces the framework and its categorisation, detailing the rationale behind each dimension and their interrelationships. Section 4 provides a two-part discussion: the first analyses design trends and current challenges in animal health wearables; the second explores the framework's applicability and added value, featuring a practical case study, a comparative analysis with existing models, and an outlook on future ethical, regulatory, and cross-species applications. Finally, Section 5 outlines the main conclusions.

2. Methodology

Given the growing need for biosensing wearables that can reliably and non-invasively measure and monitor the health of dogs and cats, this publication focuses on developing a framework to identify and analyse the critical factors in the design process of these devices. The objective is to guide the design and development of more effective measurement systems tailored to the animals' needs and its context of use. This work structures and classifies different solutions and their applications while identifying current challenges in implementing wearables for the physiological monitoring of dogs and cats, all within a holistic health perspective that prioritises animal welfare.

Establishing this framework requires a structured methodology to systematically define the key design factors. To achieve this, the study applies the 5Ws+1H Method (Who, Why, What, When, Where, How); a problem-solving framework commonly applied in research [63]. This approach facilitates examining the fundamental characteristics of any event, situation, or context. The study is based on a systematic literature review of the literature, considering numerous publications on the use and design of wearables for the physiological monitoring of dogs and cats. These solutions were analysed through the lens of each category in the method, enabling the identification and extraction of key factors that define them.

The categories of the 5Ws+1H Method are adapted to encompass the following specific aspects of wearable use in animals:

- **Why**: What is the purpose of the measurement?
- **Who**: Who is being measured, and what are their characteristics?
- **What**: What parameters are being measured?
- **When**: What is the duration of the measurement?
- **Where**: What is the measurement environment?
- **How (Bio, Design)**: How is the measurement carried out from the biological perspective (measurement method) and the design perspective (physical measurement system)?

To ensure a comprehensive and unbiased review, the reference search was systematized using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology [64]. The search included portable devices for the physiological monitoring of dogs and cats, encompassing health-specific devices and those designed for other purposes but offering transferable technologies relevant to continuous biosensing.

A conceptual mind map (Fig. 1) was developed to clearly define the exploration's subject and scope and establish the resulting framework's applicability. This diagram outlines the concepts included and excluded in the literature search, providing a structured guide that facilitates the identification of relevant terms.

The study focuses on dogs and cats, excluding all other animals that do not meet these criteria (other pets, farm animals, birds, reptiles, amphibians, insects, marine animals, small rodents, etc.). Additionally, the research is limited to non-invasive, portable, and externally worn devices, thereby excluding implantable devices and ingestible devices, those requiring surgical placement (e.g., catheters), internal measurement tools (e.g., rectal and vaginal thermometers), and non-portable equipment (e.g., clinical monitors, devices relying on external camera images, and external infrared apparatus). The selected biosensing technologies target physiological parameters that can be externally measured, specifically those related to the cardiovascular system (electrical signals of the heart, heart rate, heart rate variability), the respiratory system (respiratory wave, respiratory rate, blood oxygen levels), and temperature, thereby excluding biochemical sensing and internal temperatures. While localisation and activity recognition are widely used and serve as indirect indicators of health status, they are not the primary focus of this review. Nevertheless, their integration with physiological data is considered relevant, as these multimodal approaches can enhance the overall robustness of biosensing systems. Finally, research involving measurements on animals under anaesthesia or physical restrictions that could alter their natural behaviour or physiology is also excluded.

The search was conducted using the Scopus database, focusing on journal articles, reviews, and conference papers published between 2000 and 2022 in English or Spanish, ensuring relevance to technological advancements in biosensing. In addition to the articles obtained from this search, relevant publications from external sources (Web of Science, Google Scholar, and nested references from other studies) were also available. Only publications with a Digital Object Identifier (DOI) were analysed to guarantee traceability and academic reliability.

The search strategy included a combination of terms in the title, abstract, and keywords to refine the selection:

- **In the title**: (i) The name of the animal and its variants (e.g., synonyms, plural forms, juvenile terms); (ii) a fixed exclusion condition specifying that the animals were not anesthetised, in both American and British English spellings; (iii) if applicable, any exclusion conditions specific to the animal (e.g., the term "model" was excluded, as articles referencing dogs and cats as animal models generally involved anaesthetisation or restraint).
- **Supplementing the title**: A search was conducted across titles, abstracts, or keywords incorporating (i) the word "wearable" and its synonyms, or specific biosensing devices such as Holters; (ii) the verb

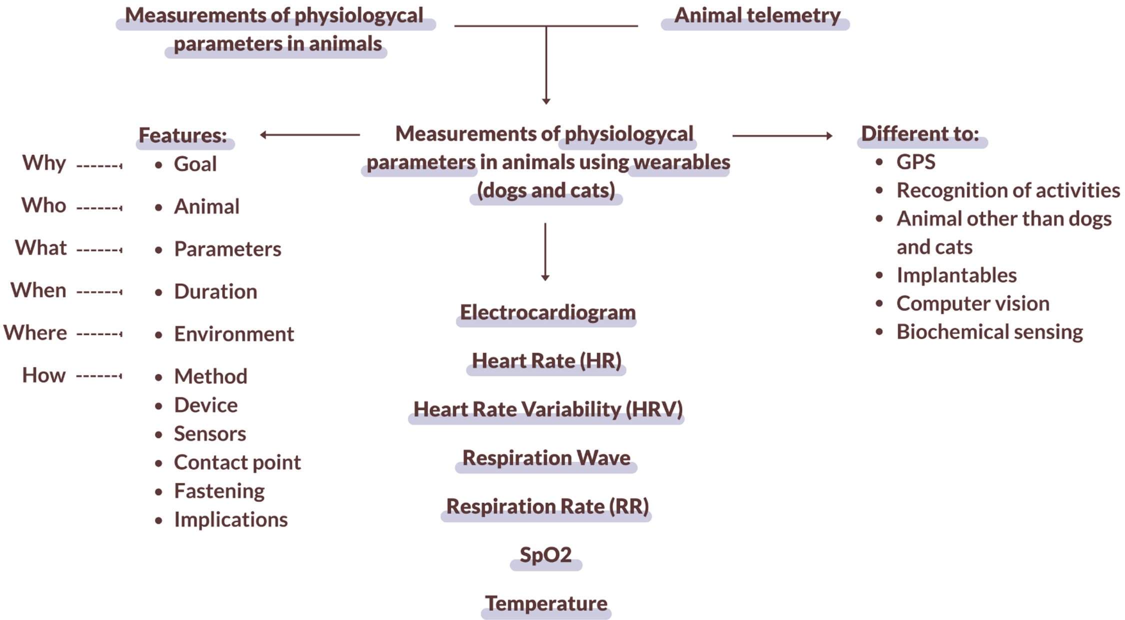

Fig. 1. Conceptual mind map of the research.

"monitor" or its root variations; (iii) the target measurement parameters and their variants.

- **Final refinements**: The remaining search conditions described in the previous paragraph were applied to ensure consistency in study selection.

The publication selection process is outlined in Fig. 2, which illustrates how the PRISMA methodology is applied to refine the search results. The first screening phase excluded studies without a DOI or those lacking full-text access. The second phase involved a deeper review of the remaining results, filtering out publications that did not meet the research requirements regarding species, measurements, and study conditions. The selected publications were managed using Mendeley Reference Manager, and the information and data were collected and analysed in Excel Spreadsheets (Version 16.83).

To complement the theoretical research, the authors' participation in real-world projects over the years provided practical insights and validation for the proposed framework. These projects focused on developing and deploying animal wearables for location tracking, virtual fencing, heart rate monitoring, respiratory rate monitoring, and lameness detection. Through these experiences, it was possible to observe the challenges and solutions in wearable design for animal monitoring within diverse contexts.

This methodological structure has facilitated a comprehensive approach to designing and applying wearable biosensing systems in animals, identifying both key elements and areas requiring further innovation. Building on this foundation, specific categories were established to guide the proposed methodology and structure the discussion of results in the following sections.

3. Critical design factors

The analysis of critical design factors in biosensing wearables for the physiological monitoring of dogs and cats is essential to understanding the variables that affect device performance, adaptability, and usability. This section presents the factors identified through the systematic review of 115 scientific publications categorised according to the 5Ws+1H Method (Fig. 3), as well as insights gained from work on practical projects. The objective is to provide a detailed description of the key elements influencing the development and use of these devices, along with questions that encourage reflection on each factor and its associated design principles.

From this point forward, the terms "devices" and "wearables" in this document refer specifically to biosensing wearable devices for the physiological monitoring of dogs and cats.

3.1. Why

Defining the research objective is a fundamental step in designing and applying biosensing wearable devices for monitoring physiological parameters in dogs and cats. This process enables the evaluation of the utility and applicability of these devices from an ethical and functional perspective and consequently aligns with the 3Rs Principle in experimentation [65,66]:

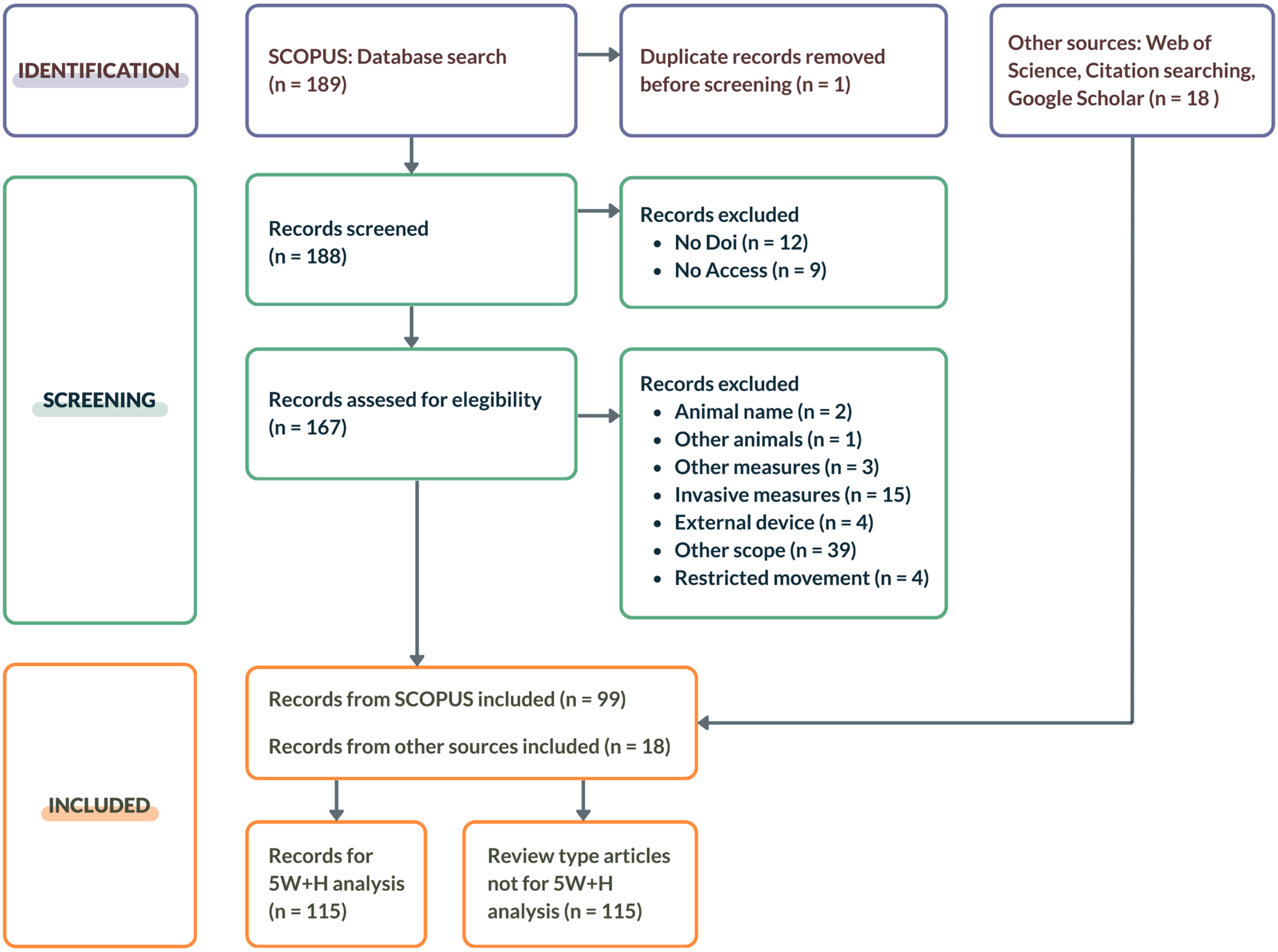

Fig. 2. Publication selection process.

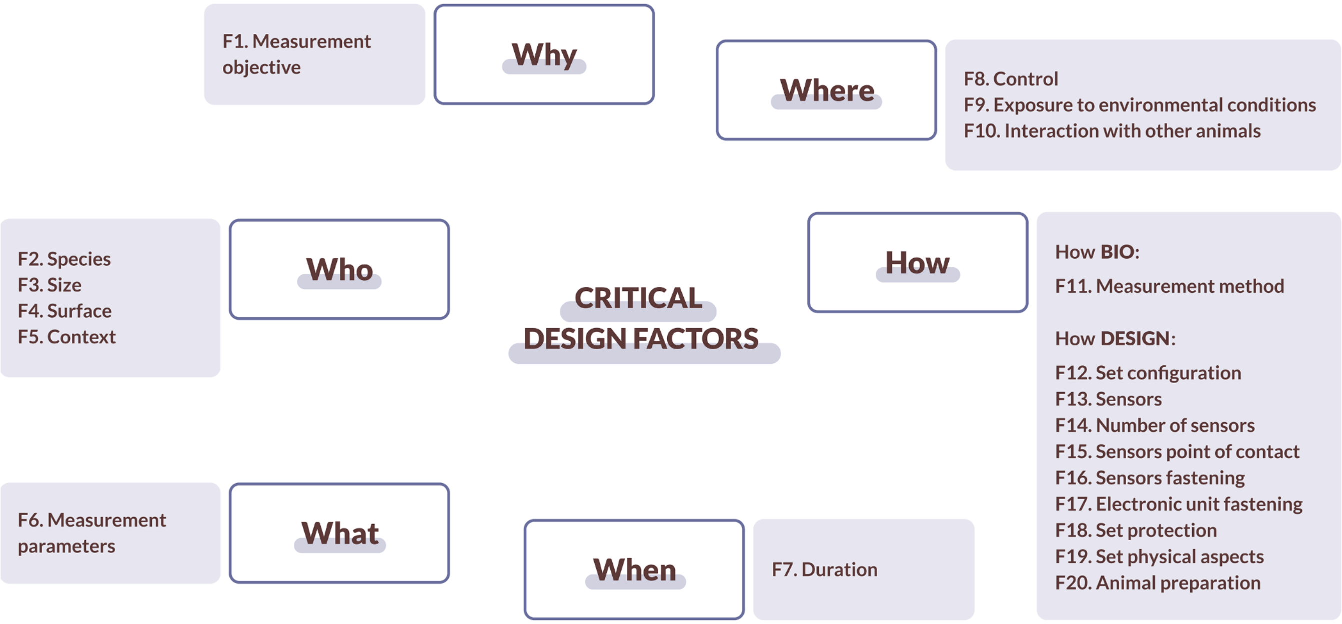

Fig. 3. Critical Design Factors Mind map.

- **Replacement**: Biosensing wearables should only be used if the same information cannot be obtained with equally effective yet less invasive systems.
- **Reduction**: The number of animals monitored should be minimised whenever possible.
- **Refinement**: Monitoring conditions should be optimised to reduce discomfort and enhance well-being.

Clearly defining the purpose of the measurement not only improves the quality and relevance of the data obtained but also serves as the foundation for the other design categories: the animal user to be monitored (Who), the parameters to be measured (What), the duration of the measurement (When), the environment in which the device will be used (Where), and the necessary methods (How).

3.1.1. Factor 1: Measurement objective

Wearables are primarily designed for three main purposes: monitoring physical health, monitoring mental, emotional, and social health (mental health), and assessing or improving performance. Specific applications can be identified within these objectives, many of which are interrelated, demonstrating the multifunctionality of biosensing systems in animal monitoring.

3.1.1.1. Physical health. In the field of physical health, wearables are used to detect, prevent, or manage diseases, as well as to study pathologies in clinical and laboratory settings. Some devices are used for medical applications, where the primary focus is on individual animal monitoring to diagnose specific conditions or track treatment progression. For instance, a biosensing device might be used for electrocardiographic monitoring in a cat with a history of syncope [67]; in veterinary research to study common diseases and explore new treatment strategies [68]; or to provide precise data on the effects of new drugs and therapies, especially in laboratory animals [69]. These applications require a high level of precision and reliability to ensure diagnostic validity and clinical relevance.

3.1.1.2. Mental, emotional and social health. Wearables are also valuable tools for studying mental health, encompassing animal well-being and communication between humans and animals. In this context, biosensing systems can detect emotional changes in animals, allowing caregivers to take proactive measures to improve their quality of life. For instance, a wearable might be used to identify signs of heat stress in dogs during walks in high-temperature environments, helping to minimise the risk of heatstroke [49]; in working animals, such as guide or rescue dogs, to monitor emotional states and prevent stress or exhaustion-related issues, thereby optimizing their performance [70]. Research in this area also explores how specific stimuli affect animal well-being, whether to enhance individual care or optimise working conditions. For example, a wearable may be used to evaluate interventions to reduce stress in shelter cats [48], or to investigate the onset of stress in laboratory dogs caused by thunderstorms [71]. These applications involve interpreting data within context and identifying subtle physiological changes.

3.1.1.3. Performance. Finally, to assess or improve performance, biosensing wearables aim to measure and optimise the physiological output of animals performing specific tasks. This applies to herding, guide, assistance, and rescue dogs, whose activities require precise monitoring to maximize their well-being and effectiveness. Some devices focus on the early detection of stress, fatigue or physical strain, while others are used to improve communication between the animal and its handler, refining human-animal interaction in working environments. For instance, devices might be used to detect early signs of stress or exhaustion in a herding dog engaged in intense activities, enabling adjustments to working conditions [40], or in police dogs, to track changes in heart rate and respiration associated with the detection of explosives, weapons, drugs, or bodies, improving operational efficiency and human-animal interaction [72]. These applications demand lightweight, stable, and resilient designs suitable for challenging contexts.

These general objectives and their specific requirements introduce considerations that directly impact design decisions (Table 1). This initial process not only enables the designer to prioritize which functionalities to develop and anticipate the challenges associated with each objective. Early identification of these specific requirements facilitates the integration of technical, ethical, and functional solutions, ensuring that the device fulfils its purpose and remains adaptable to the needs of the end user.

Table 1
Key Questions and design principles by factor: F1. Measurement objective.

Factor	Key design questions	Proposed classification	Design principles
F1. Measurement objective	- What is the need driving the study? Use the Five Whys technique to clearly define the measurement objective. Repeatedly asking “why?” helps identify the root cause of the need and ensures that wearable use aligns with the principles of Replacement, Reduction, and Refinement (3Rs).	Physical health	Prioritise validated methods and adjust the recording duration to achieve the required diagnostic resolution.
		Mental, emotional and social health	Use comparative parameters across states and minimise intrusiveness, as it may alter behaviour.
		Performance	Avoid interference with the animal’s mobility or function, and synchronise physiological data with recorded activity.

3.2. *Who*

In the context of biosensing system design, the end user plays a pivotal role. In this case, the end users of devices are animals, which introduces unique challenges that require a specialised approach. User-Centred Design (UCD), widely applied in developing technologies for humans [73,74], provides a valuable framework by prioritizing the user’s needs, characteristics, and contexts. However, when the end user is an animal, these methodologies must be adapted to account for specific aspects of animal welfare and human-animal interaction. The fields of Animal-Computer Interaction (ACI) and Animal-Centred Design (ACD), an extension of UCD, advocate for the development of technological solutions that respect both the capabilities and limitations of the animal user, minimizing interference and promoting acceptance [57, 59].

This analysis focuses on four key factors that directly influence the design of wearables: species, size, body surface, and context. Identifying and addressing these characteristics from the early stages of design ensures that the devices are effective, ethical, and tailored to the user’s real needs.

3.2.1. *Factor 2: Species*

The species of the animal user is the first defining element in the design of biosensing wearables (Table 2). Each species, and even subspecies or breeds, has specific physiological, anatomical, and behavioural characteristics that influence how they interact with devices and must be considered. Dogs are generally more tolerant and accustomed to wearing accessories, facilitating wearable acceptance. In contrast, cats tend to be more reserved and sensitive to changes in their immediate environment, making adaptability and minimal intrusiveness essential design considerations.

3.2.2. *Factor 3: Size*

The animal’s size is a fundamental factor that directly impacts key parameters such as fit, weight distribution, volume, comfort, and device ergonomics, all of which influence the feasibility of wearables across different species and breeds. Ensuring an appropriate size and fit is essential for maintaining functionality and user acceptance.

The wide range of sizes in dogs, from small to giant breeds, presents unique design challenges (Table 3). A device that functions well for a small dog may not be suitable for a larger one [75,76], due to differences in body proportions, strength, and tolerance to wearable weight. In contrast, although the size range is more uniform for cats, the design must account for their relatively low weight and agility [55], which can affect wearable stability and comfort.

Table 3
Key questions and design principles by factor: F3. Size.

Factor	Key design questions	Classification	Design principles
F3. Size	- What is the animal’s weight?	Large dog: dogs > 25 kg	Consider the use of heavier, distributed systems where appropriate.
	- Does the animal’s size limit the number, type, or placement of components?	Medium dog: dogs 10–25 kg	Pay attention to weight distribution. Larger animals may support certain systems, but there is a risk of overloading them.
	- Is it necessary to design different size variants, or would an adjustable or modular solution be sufficient?	Small dog (dogs < 10 kg or puppies) and cats < 10 kg	Use compact, lightweight, and discreet configurations positioned in protected areas.
		Dogs of different sizes	Opt for modular or adjustable solutions.

Size also influences how the wearable interacts with the animal’s anatomy. A large dog may have a broader chest, allowing for the placement of larger or multiple sensors, whereas a smaller animal may require compact elements to avoid restricting mobility. The device’s stability on the animal’s body is directly linked to how well it fits the specific proportions of the wearer.

Additionally, the weight distribution of the device relative to the wearer’s size is critical to prevent discomfort and interference with posture or mobility. A commonly used guideline in wearable design for animals is that the weight of the wearable should not exceed 5 % (or 3 %) of the animal’s body weight [77].

3.2.3. *Factor 4: Body surface*

The animal’s body surface influences the design of measurement sensors -biosensing components that register physical and chemical magnitudes and convert them into signals- as well as the methods required to ensure adequate sensor contact with the animal’s skin. Factors such as fur length and texture directly affect wearable devices’ accuracy, stability, and practicality (Table 4).

Animals with long fur pose a significant challenge for wearables, as the fur can act as a barrier, hindering direct contact with the skin. This can compromise measurement accuracy, particularly for physiological parameters that require continuous and stable contact, such as electrical

Table 2
Key questions and design principles by factor: F2. Species.

Factor	Key design questions	Classification	Design principles
F2. Species	- Which species / subspecies / breeds is the wearable intended for?	Dog	Consider using more visible sensors or multiple contact points, and explore systems with broader coverage.
	- Are there specific sensory, social, or behavioural needs that must be respected?	Cat	Favour solutions that require minimal handling and respect the animal’s need for control and familiarity.

Table 4
Key questions and design principles by factor: F4. Body surface.

Factor	Key design questions	Classification	Design principles
F4. Body surface	- What type of coat does the animal have?	Long fur	Avoid sensors sensitive to insulation or consider prior preparation; adjust fastening to compensate for coat volume without compromising stability.
	- How does it affect measurement accessibility, system stability, and visual acceptability?	Short fur	Consider using direct-contact sensors. Take advantage of areas with exposed skin.
		Fur of different lengths	Design for tolerance to variability. Select areas with similar coat interference, use adaptive fastenings to ensure contact.

heart activity (ECG) or surface temperature. In these cases, preparatory steps such as shaving, applying gels, or using conductive solutions are often necessary [56,75]. Conversely, measurement sensors can establish more direct and consistent contact in animals with short fur, improving data reliability.

Body surface characteristics also influence the attachment between the device and the body. Long fur may act as an additional layer between the device and the body, increasing the risk of displacement during high-mobility activities or interactions with other animals. Ensuring a secure and stable fit is essential to maintaining measurement consistency in dynamic environments.

Moreover, the body surface also impacts the aesthetic and functional aspects of the design. Devices should be discreet and respect the animal's natural appearance, particularly in private ownership contexts, where owners are often reluctant to accept visible or invasive changes to their pets [56,75].

3.2.4. Factor 5: Context (social)

Building on the previous observation about the body surface, the animal's context plays a crucial role in defining the social, ethical, and operational conditions associated with its use of wearables. This context also extends to factors such as the measurement environment and duration, which will be explored in later sections. Context shapes human expectations, usage conditions, and the practical limitations of the device (Table 5).

For laboratory animals, usage conditions can be adjusted as needed. In this setting, the primary focus is on technical reliability and measurement accuracy, as studies often prioritize data quality over other considerations. For instance, temporary modifications, such as shaving or applying conductive gels, are commonly used to optimize device performance. In contrast, the usage context is fundamentally different for privately owned animals, such as pets or assistance animals. Here, aesthetic and welfare concerns require design solutions that balance functionality, comfort, and social acceptance. The device must not only meet technical requirements but also respect both the needs of the animal and the expectations of caregivers.

3.3. What

Precisely defining the physiological and behavioural parameters to be monitored is crucial in the development of biosensing wearable systems, as these factors determine not only the device's design but also its applicability and effectiveness in achieving the objectives outlined in the "Why" category (Table 6).

Table 5
Key questions and design principles by factor: F5. Context (social).

Factor	Key design questions	Classification	Design principles
F5. Context (social)	- Who determines acceptance of the device—the caregiver or technical staff?	Private owner	Design systems that respect the animal's appearance, even if this involves partially compromising technical resolution.
	- What social, aesthetic, or ethical constraints apply?	Laboratory	Prioritise technical accuracy over aesthetics, and consider interventions if they improve measurement reliability.

The selection of parameters directly influences the choice of measurement methods, the physical design of the wearable, and the necessary sensors to ensure accurate and non-invasive measurements. These parameters must align with the purpose of the measurement (physical health, mental health, or performance) while also addressing the specific needs of the animal wearer and its context.

3.3.1. Factor 6: Measurement parameters

This analysis has grouped measurement parameters into four main categories: cardiac, respiratory, temperature, and behaviour. These categories represent the most monitored areas in animal health and performance tracking, providing essential data for assessing physiological and behavioural states.

3.3.1.1. Cardiac parameters. Cardiac parameters are one of the most common focuses in physiological monitoring due to their relevance in assessing physical health and stress responses. This category includes:

- **ECG (electrocardiogram):** It provides a graphical representation of the heart's electrical activity, enabling the identification of abnormalities such as arrhythmias or a detailed evaluation of cardiac function. It is suitable when detailed analysis of cardiac function is required.
  Example: Testing the hypothesis that a certain medication affects the heart rate of healthy cats [78].
- **HR (heart rate):** It measures the number of beats per minute and is one of the most widely used parameters. It can be used for general monitoring in dynamic contexts, where continuity of recording is more important than exhaustive diagnostic accuracy.
  Example: Identifying physiological and behavioural responses to a standardized physical examination in a simulated veterinary environment [79].
- **HRV (heart rate variability):** It analyses variations in the time between consecutive heartbeats. It is useful as an indicator of autonomic balance and emotional or stress state. It requires uninterrupted recordings with high signal quality.
  Example: Investigating the effect of the time a dog is left alone on its behaviour and cardiac activity [80].

Although HR and HRV are commonly obtained from electrocardiographic signals, in many cases—depending on the measurement technique (Table 11)—these parameters are derived from pulse signals instead, yielding pulse rate (PR) and pulse rate variability (PRV), respectively [81]. These metrics are extracted by detecting the arrival of the blood pulse at a specific measurement site rather than from the heart's electrical activity.

3.3.1.2. Respiratory. Respiratory parameters are essential for identifying pulmonary, metabolic, or stress-related issues. These include:

- **RR (respiratory rate):** It measures the number of breaths per minute. It is a versatile parameter that can be used in studies on physical health, stress, or performance.

Table 6
Key questions and design principles by factor: F6. Measurement parameters.

Factor	Key design questions	Classification		Design principles
F6. Measurement parameters	- Which parameters are most appropriate given the system's goal and the animal's characteristics? - What combination offers the most meaningful insight? - How do factors such as duration, environment, methods, or available devices constrain—or become constrained by—this choice?	Cardiac	ECG	The same parameter can be extracted through different methods, each with its own requirements (see Table 11, Table 12). As such, the design principles depend on the specific measurement method used (see Table 13, Table 16).
			HR	
			HRV	
		Respiratory	RR	
			Respiratory wave	
			SpO2	
		Temperature	External	
		Behaviour	Activity level	
			Recognition of activities	
			Posture	
			Vocalisation	

Example: Monitoring RR in military working dogs to detect heat stress during activity [82].

- **Respiratory wave:** It provides a detailed analysis of respiratory patterns. It is recommended for studies requiring detailed analysis of respiratory patterns, making it particularly useful in advanced studies or for specific diagnoses. It demands prolonged recordings under stable, controlled conditions.

  Example: Conducting preclinical evaluations to assess the safety of medications [83].
- **SpO2 (oxygen saturation):** It measures the amount of oxygen transported in the blood. It is suitable as an indicator of oxygenation in contexts involving respiratory or metabolic risk. Its use is justified when homeostasis is expected to be compromised.

  Example: Evaluating SpO2 in dogs during transport flights to monitor their response to the pressurized environment.

3.3.1.3. *Temperature.*

Body temperature is a fundamental indicator in health assessment, allowing for the detection of fever, heat stress, or hypothermia. This study focuses on surface temperature measurement, as it is the least invasive method for monitoring thermoregulation:

- **Surface temperature**: It enables monitoring the animal's thermoregulation and response to different environmental conditions. It can be used to detect thermal changes associated with fever, stress, or environmental exposure. Ensuring a sufficient sampling rate is essential to capture relevant variations.

  Example: Exploring domestic and neighbourhood-level risk factors associated with increased heat exposure in dogs [49].

3.3.1.4. *Behaviour.*

Although behavioural parameters are not the primary focus of this research, they complement physiological biosensing by providing a more comprehensive picture of animal well-being:

- **Activity level:** It measures the degree of movement or energy expenditure over a given period. It can be inferred from data such as speed, distance travelled, or movement intensity. It is useful for assessing energy levels, rest, or exertion, providing a general context on the animal's physical state.

  Example: Recording a military working dog's activity level to correlate with respiratory rate patterns, assessing its physiological response and identifying early signs of thermal strain [82].
- **Activity recognition:** It classifies specific types of movement (such as walking, running, or resting) based on kinematic patterns. It provides an integrated view of the animal's state and improves accuracy by aligning analysis with specific tasks or routines.

  Example: Differentiating between rest periods and physical activities (e.g., running or walking) in a dog to identify optimal moments for measuring heart rate under baseline conditions or during exercise, thereby improving the accuracy of physiological data [81].
- **Posture:** It evaluates sustained body position (standing, lying, sitting). It is particularly useful in clinical and well-being applications, as it provides additional context to other physiological data. It is relevant when assessing rest, discomfort, or pain.

  Example: Assessing posture changes in shelter dogs to evaluate the effects of environmental enrichment on stress levels and well-being [29].
- **Vocalisations:** It examines vocal patterns emitted by the animal in terms of frequency, duration or intensity, to assess its emotional and physical state. Sounds like barking, whining, or growling can be differentiated. It is relevant when seeking acoustic cues related to social interaction, stress, or attention-seeking behaviour. Its usefulness increases in sound-sensitive environments.

  Example: Correlating vocalisation patterns with HRV to assess stress levels in dogs with noise sensitivity when exposed to fireworks [84].

3.4. *When*

The duration of measurements is a decisive factor in the design and applicability of wearables, as it directly impacts the technical requirements of the device, including energy autonomy, storage capacity, and connectivity. These factors, in turn, define or limit other functional and formal aspects, such as the number and variety of parameters that can be measured, as well as the device's size and weight (Table 7).

While continuous physiological monitoring is the focus of this study—and the direction of biosensor innovation—discrete measurements are also considered to provide context-comparative insights and to support the design of systems that may evolve toward continuous use.

To ensure that measurements are representative or focus on specific moments of temporal interest, two key aspects must be considered:

- **Sampling phase**: Selecting relevant periods that reflect the animal's natural physiological cycles is essential to maximise the functionality of devices. For instance, in diurnal animals, measuring during sleep provides insights into resting states, while measuring during activity periods captures physical and behavioural responses related to movement and interaction.
- **Key events**: Defining critical moments in time, such as seasonal changes, periods of stress, reproductive stages, or work activities, ensures that measurements address relevant conditions and allow analysis of their impact on the animal's physiological and behavioural parameters.

3.4.1. *Factor 7: Duration*

Depending on the purpose of the monitoring and the usage context, measurements can be classified primarily into Discrete and Continuous measurements, with the latter varying in continuity levels, ranging from hours to days, weeks, months, or even years (Table 7).

Table 7
Key questions and design principles by factor: F7. Duration.

Factor	Key design questions	Classification		Design principles
F7. Duration		Discrete	Seconds or Minutes	Consider using more compact devices with lower energy demands. Use fast-activating sensors and prioritise ease of placement, immediate usability, and reliability within short time windows.
	- What level of continuity is needed to meet the study goals?	Continuous	Short (<24 hour or circadian)	Pay attention to avoiding oversizing. Prioritise lightweight, compact devices that require no maintenance.
	- When do the most relevant physiological changes occur?		Medium (1 - 7 days)	Balance robustness and flexibility.
	- What constraints affect duration, and how does duration affect other design decisions?		Long (> 1 week)	Apply low-power strategies and efficient data storage. Ensure fixings can be checked or readjusted easily, where possible, without interfering with data collection.
			Prolonged (> 6 months)	Prioritise long-term comfort and minimise the need for intervention. Use replaceable modules and self-diagnostic sensors to maintain study continuity. Consider recharging strategies, such as solar or inductive power.

3.4.1.1. Discrete measurements. Although not the central focus of this study, discrete measurements are also considered due to their relevance in clinical evaluations, experimental validations, or controlled studies. These measurements focus on capturing data over a limited period, offering a precise snapshot of a particular moment or condition, which can be valuable for diagnostics or the analysis of specific events. However, their dependence on a specific moment may reduce their effectiveness when physiological or behavioural states change rapidly. Nonetheless, discrete data can support the design and calibration of continuous systems, especially in early-stage testing or when contextualising long-term observations.

3.4.1.2. Continuous measurements. Continuous measurements enable prolonged monitoring, ranging from hours to weeks or months, providing rich and detailed data that capture temporal variations and complex patterns. These measurements are essential for longitudinal studies, treatment follow-ups, and animal welfare investigations under real-world conditions. Unlike discrete measurements, continuous measurements offer a comprehensive view of the animal's state, allowing for the analysis of both immediate responses and progressive changes. However, continuous measurements pose greater challenges in device design. The longer the monitoring period, the more advanced energy autonomy, storage, and data transmission systems are required to manage the large volumes of data generated [84].

3.5. *Where*

Understanding the physical and environmental context in which the wearable will be used is essential for adapting its design to ensure functionality, durability, and compatibility with the animal. Environments can vary significantly in terms of control, exposure to environmental conditions, and interaction with other animals, each introducing distinct challenges and technical requirements.

3.5.1. *Factor 8: Control*

The degree of human control over the environment directly influences both the supervision of the device and its reliability (Table 8). In controlled environments, such as laboratories or veterinary clinics, devices are constantly monitored, allowing for quick correction in cases of improper fit or external interference. In contrast, human supervision is limited in uncontrolled environments, such as open spaces.

3.5.2. *Factor 9: Exposure to environmental conditions*

The environmental conditions in which a wearable is used not only impact its durability and functionality but also influence the safety of the animal. Biosensing devices must be designed to withstand external factors while ensuring they do not pose a risk of injury or discomfort to the wearer (Table 9).

In outdoor environments, animals may be exposed to extreme temperatures, humidity, rain, dirt, or rough terrain, requiring devices with greater physical resilience. In contrast, indoor environments, such as hospitals, laboratories, or homes, pose fewer challenges in terms of environmental resistance, but safety remains a concern.

3.5.3. *Factor 10: Interaction with other animals*

The wearable faces additional risks in environments where animals interact with others of the same or different species. Other animals may bite, scratch, or manipulate the device out of curiosity, especially if they perceive it as a foreign object. These interactions can lead to device displacement, structural damage, or even injuries to the wearer. If such interactions occur, it is crucial to consider the species and behaviour of the interacting animals. Each species exhibits different interaction patterns, which can affect how the wearable is handled, perceived, and potentially damaged. Additionally, the wearable must not pose a risk to the interacting animals. For example, if a dog accidentally bites another

Table 8
Key questions and design principles by factor: F8. Control.

Factor	Key design questions	Classification	Design principles
F8. Control	- Will the device be used in a supervised setting or with full animal autonomy? - What scope is there for adjusting or addressing issues during measurement?	Yes	Value favours precision over robustness.
		No	Prioritise autonomous solutions that resist to movement and environmental variability. Ensure continuous sensor contact and data integrity without human intervention.

Table 9
Key questions and design principles by factor: F9. Exposure to environmental conditions.

Factor	Key design questions	Classification	Design principles
F9. Exposure to environmental conditions	- Will the device be used outdoors? - What extreme environmental conditions could compromise its performance or safety?	Yes	Ensure structural strength and use durable materials. Include thermal insulation, waterproofing, and shapes that prevent snagging or detachment.
		No	Allow for lighter solutions, but avoid sharp edges, loose parts, or materials prone to wear from friction or ambient moisture.

animal’s wearable, the materials should be non-toxic and free of sharp edges that could cause injuries (Table 10).

In isolated environments, these risks are lower but do not entirely disappear. For anxious or curious animals, a poorly adapted design may trigger repetitive or aggressive behaviours toward the wearable, leading to premature failure or inaccurate readings—especially critical in continuous monitoring scenarios.

3.6. How

The "How" category refers to wearables’ methods and mechanisms to collect and process physiological data. This category is divided into two main dimensions: How-Bio, which focuses on the biometric methods used for measurements, and How-Design, which examines sensors, fastening systems, and device configurations. Both aspects are closely interrelated and play a critical role in determining the precision of biosignals, the device’s ergonomics, and its acceptability to the animal wearer.

3.6.1. How-Bio

How-Bio defines the non-invasive biometric methods used in wearable devices for physiological monitoring of dogs and cats, as covered in this study. These methods rely on a variety of physical and biological techniques to enable the accurate and continuous capture of physiological and behavioural parameters, forming the basis for biosensor integration in wearable systems.

Table 10
Key Questions and Design Principles by factor: F10. Interaction with other animals.

Factor	Key design questions	Classification	Design principles
F10. Interaction with other animals	- Will the animal share space with others while wearing the device? - Can the wearer or other animals manipulate, damage, or remove the wearable? - Can the device’s visual salience be minimised?"	Yes	Use materials resistant to biting, scratching, and pulling, and ensure designs are safe for animals interacting with the device. Integrate discreet colours and shapes, along with secure and reliable attachment systems.
		No	Prioritise comfort and lightness, but ensure the design withstands the animal’s attempts to remove the device.

3.6.1.1. Factor 11: Measurement method. The measurement method used in a wearable is directly related to the physiological or behavioural parameter being monitored (Table 11). Below is a description of these main measurement methods:

- **Biopotential** [85]: It detects electrical signals generated by the bioelectric activity of body tissues, such as the heart.
- **Bioimpedance** [76]: It measures the electrical resistance of an animal's body to the passage of a low-intensity alternating current.
- **Force** [83]: It detects mechanical changes in the animal's body. Primarily used to measure the expansion and contraction of the thorax during inspiration and expiration cycles. It provides information on respiratory rate and patterns.
- **Magnetic Impedance** [76]: It uses alternating magnetic fields to detect changes in the electromagnetic properties of the body associated with respiratory movement. Variations in the thoracic volume and position alter magnetic impedance, enabling the recording of respiratory rate.
- **Inertial Measurement** [86]: Also referred to as seismocardiography (SCG). It records body movements and vibrations associated with physiological processes such as heart and respiratory rates. Although it indirectly measures these parameters, it provides valuable insights into variations by analysing signals from thoracic movements or body pulsations. It is highly effective for assessing physical activity but has limited precision for physiological parameters.
- **PPG (Photoplethysmography)** [83]: It emits light onto the skin and measures the amount of reflected or transmitted light to detect changes in blood volume caused by heartbeats. It is suitable for monitoring pulse rate and oxygen saturation (SpO2). SpO2 is specifically measured using two specific wavelengths—red and infrared—while other wavelengths, such as green, are often used to obtain pulse rate or pulse rate variability.
- **Infrared**: It captures the thermal radiation emitted from the animal's body surface, converting it into a temperature reading using specific algorithms.
- **Thermal Balance** [49]: It stabilizes a thermal sensor in direct contact with the animal's skin, allowing it to reach the same temperature as the skin.
- **Sound recording** [41]: It captures and analyses acoustic waves generated during breathing, such as sounds produced during inhalation and exhalation.

While Table 11 highlights the applications of each measurement method, Table 12 provides a comparative evaluation of their technical and operational characteristics, allowing for a better understanding of their advantages and limitations.

The presented characteristics must be considered in the device's design to ensure accuracy, usability, and reliability under real-world conditions (Table 13).

3.6.2. How-Design

The physical design of a wearable for animals encompasses a set of critical factors, ranging from sensors to mechanical aspects required to ensure reliable operation in real-world conditions. This section considers the requirements derived from the other categories (Why, Who, What, When, Where, and How-Bio), which define the animal's characteristics, the parameters to be monitored, the intended duration of data acquisition, the usage environment, and the selected biosensing method. These considerations ensure that the device is not only functional for the human user but also ergonomic, safe, and acceptable for the animal wearer.

Blanco et al. (2017) propose a structured framework for smart device design, which defines the essential elements required to ensure functionality, adaptability, and usability in wearable technology. This framework outlines key hardware and software components, including sensors for data collection, actuators, user interfaces, communication modules, energy management systems, and processing units. By integrating these components effectively, smart systems can support continuous biosensing through accurate signal acquisition, seamless interaction, and optimised performance across various applications.

Based on this framework, this work considers two primary components as critical to the design of wearables biosensing systems for animals: (i) the sensors, which establish direct contact with the animal to capture physiological signals while ensuring minimal interference to natural behaviour, and (ii) the electronic unit, which houses the power source, communication subsystems, and a processing or intelligence unit that coordinates all components. In some cases, electronic units may also incorporate user interfaces for device control and feedback to the human user.

Table 11
Correspondence between measurement methods (How-Bio) and the parameters that can be derived (What).

Method - How-Bio	Parameter - What
Biopotential	ECG, HR, HRV, RR
Bioimpedance	PR, PRV, RR, Respiratory wave
Force	RR, Respiratory wave
Magnetic impedance	RR
Inertial measurement	PR, PRV, RR
PPG (Photoplestimography)	PR, PRV, RR, SpO2
Infrared	External temperature
Thermal balance	External temperature
Sound recording	RR

3.6.2.1. Factor 12: Set configuration. The integration of sensors and the electronic unit -referred to as the set- is a key factor in determining the functionality and adaptability of a wearable device (Table 14). The device configurations can be classified into three major categories based on the relationship between these elements:

- **Sensors separated from the electronic unit** [88]**:** Sensors are physically detached from the electronic unit, which is located elsewhere in the wearable system or even in a remote module. This approach is particularly beneficial when the measurement point requires mobility or independent access, such as respiratory bands connected to a back-mounted module.
- **Sensors integrated into the electronic unit** [89]**:** Sensors are embedded directly within the electronic, forming a single compact structure. This design is common in small devices, such as patches or pulse oximeters, and facilitates placement and handling. However, it may limit flexibility regarding positioning and adaptability.
- **Electronic unit managing multiple separated sensors** [46]**:** A single electronic unit controls multiple sensors distributed across different contact points on the animal. This design enables simultaneous and holistic monitoring of multiple physiological parameters but may increase system complexity due to higher energy consumption and connectivity demands.

3.6.2.2. Factor 13: Sensors. Sensors are the primary physical connection between the biosensing wearable and the animal's body, and their characteristics vary significantly depending on the measurement method employed (Table 15, see Section 3.6.1.1 – Factor 11: Measurement method).

The following section describes the various types of sensors used in wearable biosensing systems, outlining their applications, advantages, and limitations. Their design and placement must consider key factors such as the type of contact, adaptability to the animal's body, and potential environmental constrains that may impact functionality and accuracy (Table 16):

Table 12
Comparative characteristics of different measurement methods.

Method	Precision	Contact Required	Variety of Positions	Temporal Resolution	Energy Demand	Sensitivity to	Sensitivity Level	Motion Artifacts
Biopotential	Very High	Very High	Low	Very High	Low	Electrical noise, electrode impedance value	Very High	Very High
Bioimpedance	High	High	Medium	High	Medium	Tissue density, extreme movements	High	High
Force	Medium	Low	Low	Medium	Low	Anatomical variations	Medium	High
Magnetic Impedance	High	Medium	Medium	High	Medium	Electromagnetic interference	High	Medium
Inertial Measurement	Medium	Very Low	Very High	High	Medium	Rapid movements	Very High	Very High
PPG	High	Medium	Very High	High	Medium	Blood perfusion variability, hair density	High	Medium
Infrared	Medium	Low	Very High	Very High	Low	Environmental exposure, hair density	High	Low
Thermal Equilibrium	High	High	Medium	Medium	Medium	Constant contact, stabilization time	Medium	Medium
Audio Recording	High	Medium	Very High	High	Medium	Environmental noise, anatomical interference	Very High	Very High

Scale: 5 points (Very High, High, Medium, Low, Very Low).

Table 13
Key questions and design principles by factor: F11. Measurement method.

Factor	Key design questions	Classification	Design principles
F11. Measurement method	- Which method is most suitable for obtaining the desired parameter (see Table 11) under real-world conditions, considering its specific requirements (see Table 12)? - Alternatively, if a device is already available, which parameters can be reliably extracted using its embedded method?	Biopotential Bioimpedance Force Magnetic impedance Inertial measurement PPG (Photoplestimography) Infrared Thermal balance Sound recording	Assess the characteristics of each method (Table 12) and consider the design principles relevant to the corresponding sensor (Table 15, 16).

Table 14
Key questions and design principles by factor: F12. Set configuration.

Factor	Key design questions	Classification	Design principles
F12. Set configuration	- How much mobility or independence do the sensors need from the main module to adapt to the animal, the context, and the measurement method? - Can one sensor be used to collect multiple types of data?	Sensors integrated into the electronic unit Sensors separated from the electronic unit Electronic unit managing multiple separated sensors	Minimise device size and optimise its attachment to a single stable area. Distribute sensors across optimal anatomical locations and ensure stable connection with the central module. Implement modular fixings or partial anchor points that allow sensor placement to be adjusted without disrupting the overall system. Synchronise sensors and ensure a robust architecture to prevent data loss.

Table 15
Measurement sensors in relation to the methods they are used for and their need for direct contact.

Methods (How-Bio)	Sensors (How-Design)		Direct contact
Biopotential Bioimpedance	Electric	Electrode (Wet; Dry)	Yes
Force	Deformation	Deformable substrate (Strain gauge; Force sensitive resistor; Piezoelectric sensor; Strain coil)	No
Magnetic impedance	Magnetic	Front plane coil	No
Inertial measurement	Motion	Accelerometer and/or gyroscope	No
PPG (Photoplestimography)	Optics	Transmitter LED/receiver LED	Yes
Infrared		Infrared temperature sensor	Yes
Thermal balance	Thermal contact	Contact probe	Yes
Sound recording	Audio	Audio element (Microphone)	Yes
		Audio element (Stethoscope)	Yes

- **Wet electrodes** [90]**:** They provide high signal quality but require direct skin contact and prior preparation (e.g. shaving, cleaning). Their performance declines over time as the conductive gel dries, limiting their use in long-term monitoring.
- **Dry electrodes** [84]**:** They eliminate the need for conductive gel and are better suited for extended use. However, their accuracy can be affected by fur, skin irregularities, or movement artefacts.

Table 16
Key questions and design principles by factor: F13. Sensors.

Factor	Key design questions	Classification	Design principles
F13. Sensors	- Which sensor can measure the desired parameter with enough accuracy for this species and context? See Table 15	Wet electrode	Apply to clean, shaved skin, and replace if the conductive gel dries out or loses adhesion during prolonged recordings.
		Dry electrode	Place on flat, low-mobility skin. Apply uniform pressure using flexible surfaces to compensate for the absence of gel.
		Deformable substrates	Integrate into supports that conform to the body without restricting expansion.
		Front-plane coil	Align with the thorax and insulate using non-conductive materials to prevent external magnetic interference.
		Accelerometer / gyroscope	Use mechanical filtering elements between the body and the sensor to reduce oscillations that could distort the signal.
		LED emitter/ receivers	Block ambient light using opaque enclosures to maintain a stable photoplethysmography signal.
		Infrared sensors	Orient towards areas sheltered from wind and sunlight, or place in shaded cavities to reduce environmental variability.
		Contact probes	Ensure constant skin contact using thermally conductive padding that maintains stability without applying pressure.
		Microphones	Protect using acoustic foam or domes that filter environmental noise without distorting the signal.
		Electronic stethoscopes	Integrate into semi-rigid mounts that maintain continuous pressure on the skin and dampen external vibrations.

- **Deformable substrates** [45]**:** They include sensors like strain gauges or piezoelectrics. They must closely follow thoracic movements, requiring good mechanical coupling and stable positioning.
- **Front-plane coils** [76]**:** They are sensitive to external magnetic interference and demand consistent placement to ensure reliable respiratory signal acquisition.
- **Accelerometers and/or gyroscopes** [91]**:** They do not require direct skin contact but depend on firm coupling to the body to accurately capture micro-movements.
- **LED emitter/receivers** [83]: They require precise alignment and shielding from ambient light. Their performance depends on anatomical features such as fur density and skin pigmentation.
- **Infrared sensors:** They offer fast, non-contact temperature readings but are highly sensitive to environmental variability (e.g. wind, sunlight). Although they do not require direct contact, in wearable applications they are often placed in contact with the skin to facilitate secure attachment, as seen in some devices developed for livestock [92].
- **Contact probes** [49]**:** They require prolonged, stable skin contact to match the skin's temperature.
- **Microphones** [82]**:** They capture respiratory sounds or vocalizations and must be strategically placed near respiratory pathways to ensure optimal recording quality.
- **Electronic stethoscopes** [93]**:** They highly precisely record internal sounds, such as heartbeats or respiratory sounds but require strong and consistent body contact.

Table 17
Key Questions and Design Principles by factor: F14. Number of sensors.

Factor	Key design questions	Classification	Design principles
F14. Number of sensors	- How many sensors are needed for a reliable signal? - What factors limit the number of sensors that can be used?	1	Prefer multifunction sensors to maximise the information gathered.
		2	If both sensors measure the same parameter, place them symmetrically and synchronise them; if they measure different parameters, choose anatomically suitable locations for each one.
		>2	Organise the system into functional modules (if using more than one type of sensor or method) to facilitate assembly and maintenance. Ensure there is no interference between sensors, and design clear, orderly connections to prevent tangling or failure.
		Continuous	Use elastic materials to support morphological adaptation and ensure uniform contact.

3.6.2.3. Factor 14: Number of sensors. The number of sensors required in a biosensing wearable depends directly on the measurement method and the level of precision needed. Some applications can function with a single sensor, while others require multiple contact points to ensure measurement accuracy or capture signals from different body areas (Table 17).

Using multiple sensors, such as in cardiac monitoring via biopotentials (ECG) [94,95], improves data quality by enabling signal triangulation. However, each additional sensor increases design complexity, weight, and attachment requirements, which may affect the animal's comfort and mobility. Conversely, systems with a single sensor, such as PPG or temperature-based devices [49], simplify the design, reduce the impact on the wearer, and enhance usability. However, they may limit the number of parameters that can be measured simultaneously. Some configurations employ continuous sensors, such as respiratory bands with integrated copper wire [45], which allow data collection over a broader body area, ensuring greater consistency in signal acquisition.

3.6.2.4. Factor 15: Sensors point of contact. The placement of sensors on the animal's body is critical for the functionality and precision of biosensing wearables, as each contact point has distinct characteristics that can influence signal quality, animal comfort, and design adaptability (Table 18). The most representative contact points for sensors include the thorax, extremities, neck, tail, ear, and snout (Fig. 4), each offering unique advantages and challenges in terms of sensor stability, accessibility, and data reliability:

- **Thorax** [96]: It provides proximity to the heart and lungs, making it ideal for measuring cardiac and respiratory parameters.
- **Limbs** [97]: They offer access to measure activity, force, balance, or temperature. This category includes legs, shoulders, armpits, and groin, each presenting different challenges. While extremities are constantly interacting with the environment, increasing wear and

Table 18
Key questions and design principles by factor: F15. Sensors point of contact.

Factor	Key design questions	Classification	Design principles
F15. Sensors point of contact	- Which anatomical site offers the most reliable signal with minimal interference? - How might the animal's features or context affect contact quality or signal reliability? - Which areas are easiest to access for placing, adjusting, or removing the sensor?	Thorax	Choose flexible or small-area sensors that follow heart, respiratory and physical movements without losing contact.
		Limbs	Avoid areas exposed to direct impact or friction with the ground.
		Neck	Avoid constant or uneven pressure.
		Tail	Use lightweight, flexible sensors that do not alter natural movement or create a dragging sensation.
		Ear	Minimise sensor volume and secure it with soft fixings that prevent jolting or discomfort.
		Snout	Account for the area's high sensitivity and avoid interference with feeding or social interaction.

motion artefacts; armpits and groin, provide greater sensor stability but may accumulate moisture.

- **Neck** [86]: It allows easy placement of collar-based devices, facilitating heart rate measurements via PPG or general activity levels.
- **Tail**: It offers temperature and behavioural tracking, particularly for activity and posture analysis.
- **Ear**: It enables non-invasive measurements of surface temperature and cardiac parameters via PPG, benefiting from thin skin and superficial blood flow.
- **Snout** [41]: It provides direct access to the airways, facilitating respiratory rate measurements and vocalization analysing.

3.6.2.5. Factor 16. Sensors fastening. The fastening method used for sensors directly influences the stability of the signal and the device's acceptance by the animal wearer. Inadequate attachment can lead to motion artefacts, signal loss, or animal discomfort, compromising the overall reliability of biosensing systems (Table 19). Below are the main fastening methods identified:

- **Adhesive** [98]: It uses glue or adhesive materials to attach the sensor directly to the animal's skin. This method is ideal for small sensors requiring precise contact. However, it may cause skin irritation, particularly in sensitive animals or those with dense or oily fur, which can complicate adhesion.
- **Band** [99]: It consists of an adjustable strap made of fabric or plastic, positioned around the perimeter of the measurement site, such as the thorax or limbs. Provides stable and reusable fastening.
- **Halter** [41]: It offers firm and specific fastening but may be less tolerated by some animals due to its placement in a highly sensitive area. It is primarily used for devices placed around the animal's head, such as for measurements at the snout or ears.
- **Collar** [91]: It functions similarly to a band but is adapted for the animal's neck. Commonly used in devices monitoring activity or heart rate.
- **Garment** [76]: It integrates sensors into textile elements, such as shirts or advanced textile constructions, distributing sensors over broader body areas, providing stability and minimizing discomfort, making it ideal for applications requiring multiple measurement points or bulkier devices. However, it can be more complex to implement and less tolerated by animals unaccustomed to wearing garments.
- **Bandage** [100]: It uses fabric bandages to secure sensors at specific points, offering a versatile and adaptable fastening method. Nonetheless, it may be labour-intensive and require periodic re-application to ensure consistent sensor positioning, particularly during extended monitoring sessions.

3.6.2.6. Factor 17: Electronic unit fastening. The fastening of the electronic unit follows similar principles to those used for sensors in Factor 16, employing adhesives, bands, collars, garments, bandages, and halters. However, its design must account for additional requirements related to its larger size, increased weight, and potential sensitivity to movement (Table 20). The fastening method must ensure sufficient mechanical stability to prevent displacement that may compromise signal acquisition or disrupt connectivity, while remaining comfortable

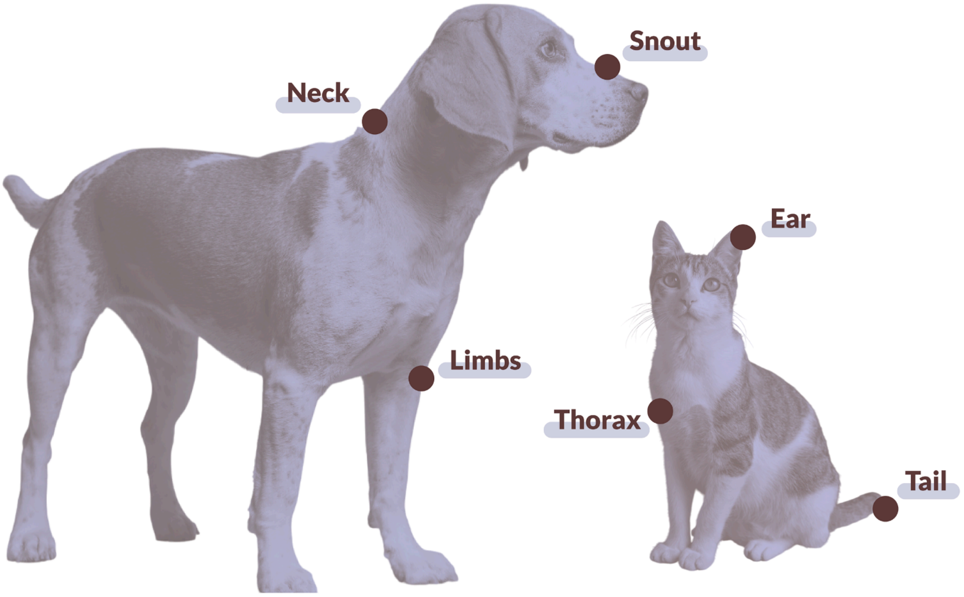

Fig. 4. Interface-to-animal contact points.
Figures adapted from images by *Freepik* (dog) and *Tom Johnny Fotografias* on Pexels (cat).

Table 19
Key questions and design principles by factor: F16. Sensors fastening.

Factor	Key design questions	Classification	Design principles
F16. Sensors fastening	- Which attachment methods best suit the sensor and chosen body area? - How might the expected duration of use or the animal's environment affect this choice? - What materials or structures could help keep the sensor stable without causing discomfort?	Adhesive	Use it only for small sensors and short durations. Avoid areas with dense fur, fat, or moisture.
		Band	Choose elastic, breathable materials. Adjust to prevent shifting without restricting mobility.
		Collar	Ensure a firm yet comfortable fit. Consider double anchoring if heavy sensors are included.
		Halter	Use only with habituated animals. Distribute pressure.
		Garment	Select anatomically designed garments with dedicated sensor pockets. Ensure secure fixation without excessive compression.
		Bandage	Mark alignment guides or sensor anchor points, enabling consistent repositioning during reapplication.

Table 20
Key questions and design principles by factor: F17. Electronic unit fastening.

Factor	Key design questions	Classification	Design principles
F17. Electronic unit fastening	- What attachment options can support the weight and size of the electronic unit without limiting the animal's mobility? - Which body areas offer the best balance of comfort, stability, and access to connections or sensors?	Adhesive	Use only for very lightweight modules. Avoid if there is a risk of heating or if fur prevents proper adhesion.
		Band	Use wide straps with good contact surface. Distribute weight and provide lateral stability to prevent swinging.
		Collar	Ensure the collar supports the weight without rotating. Consider adding double anchoring) if connectors or sensors are attached.
		Halter	Use the halter structure to distribute weight between the muzzle and neck without stressing sensitive areas. Include double anchoring if cables or sensors are attached.
		Garment	Choose garments with structural support or built-in reinforcements to house electronics without allowing the module to hang or shift. Use fabrics with padded areas to accommodate the unit
		Bandage	Use wraparound bandages to stabilise the module over areas such as the back or hip. Adjust without compressing muscle structures or altering posture.

to minimize its impact on the animal's natural behaviour.

Device configurations described in Factor 12 are directly related to the fastening strategy. In some cases, the electronic unit and sensors share a common attachment system—such as an integrated collar or band—optimising ergonomics and reducing the number of contact points [101]. These components must be fastened separately in other scenarios, as in certain ECG measurements [95]. Electrodes may be placed on the animal's thorax, while the electronic unit is attached to the neck or back, connected via discreet cables or wireless technologies. This separation allows for greater flexibility, ensuring the electrodes and the electronic unit function optimally without compromising signal quality or animal comfort.

3.6.2.7. Factor 18: Set protection. The protection of the wearable set plays a crucial role in ensuring device durability and measurement accuracy. Depending on the monitoring characteristics and the animal's environment, additional measures may be necessary to shield the wearable from external factors such as humidity, dirt, extreme temperatures, or interactions with other animals. The main protection options include bandages, garments, bands, and additional adhesives [48, 89,102], which enhance the stability and security of the device. In more specific cases, protective elements such as Elizabethan collars can be employed [103].

Implementing adequate protective measures ensures the device's longevity and improves data quality [104], particularly in dynamic or challenging environments. However, protection systems must be discreet to prevent altering the natural usage conditions of the device. Overly robust or poorly designed protections can lead to restrictions in mobility, increased discomfort, and reduced device acceptance. Unnecessary protective measures may also add unwarranted complexity to the design, diminishing overall effectiveness. Therefore, selecting protective measures should balance functionality, wearer comfort, and measurement reliability (Table 21):

3.6.2.8. Factor 19: Set physical attributes. The physical design of the sensors and electronic unit is fundamental to ensuring technical performance and acceptance by animal and human users (Table 22). This factor encompasses characteristics such as size, weight, shape, material, robustness and visibility:

- **Size and Weight:** The device must be proportional to the animal's body to avoid interfering with mobility or daily activities. If the system is too large or heavy, it may cause discomfort, hinder movement, or be rejected by the wearer. However, focusing solely on this factor may be overly simplistic, as other design elements also contribute to usability.
- **Shape:** The external geometry influences how well it conforms to the animal's anatomy and movement. Poorly adapted geometries can compromise comfort, stability, and usability. Over time, inadequate shape integration may lead to pressure accumulation, poor fit, or friction, all of which can reduce data reliability or lead to early device rejection—especially in continuous monitoring scenarios.
- **Material:** The choice of materials directly affects comfort, durability, and hygiene. Inadequate materials may cause irritation, retain moisture or dirt, degrade with exposure to saliva or environmental conditions, and reduce the device's lifespan or signal stability.
- **Robustness:** The mechanical resistance of the device determines its ability to withstand typical animal activities such as scratching, jumping, or interacting with other animals. If robustness is insufficient, the device may deform, shift, or break, compromising signal quality, animal safety, or the lifespan of the system.
- **Visibility and Colour:** The visual appearance of the device may influence its acceptance and suitability depending on the intended context. In some situations, the device should remain discreet to

Table 21

Key questions and design principles by factor: F18. Set protection.

Factor	Key design questions	Classification	Design principles
F18. Set protection	- What environmental could affect the device's integrity or performance? - Which body areas or system components may need extra protection? - What materials or solutions could provide protection without limiting mobility or ventilation?	Extra-Adhesive	Use as additional reinforcement in demanding conditions (rain, friction).
		Band	Use as an outer protective layer against dirt or snagging. Ensure it does not block sensors or ventilation points.
		Garment	Use as a comprehensive solution for long-term studies.
		Bandage	Use in clinical or short-term applications.
		Others: Elizabethan collar	Use only in cases where the animal exhibits compulsive manipulation.

Table 22

Key questions and design principles by factor: F19. Set physical attributes.

Factor	Key design questions	Classification	Design principles
F19. Set physical attributes	- What size and weight proportions best suit the animal's species, body size, and activity level? - What shapes or volumes allow the device to integrate with the body without causing pressure points or irritation? - Which materials offer suitable biocompatibility, durability, and ease of maintenance? - How robust must the device be based on physical activity or interaction with the environment or other animals? - How visible should the device be, depending on its context of use?	Size and weight	Ensure the complete system does not exceed 3–5 % of the animal's body weight. Adjust volume and distribution to avoid compromising balance or mobility.
		Shape	Adapt the geometry to the contact area, avoiding sharp edges and rigid volumes. Use ergonomic designs that conform to the anatomy.
		Material	Select biocompatible, breathable, and easy-to-clean materials. Prioritise those resistant to sweat, saliva, or moisture, and able to retain their shape with prolonged use.
		Robustness	Reinforce areas most exposed to impact or animal interference. Use sealed or structured housings to protect electronics without adding unnecessary bulk.
		Visibility and colour	Choose colours and finishes suited to the context: for example, use neutral tones that blend with the animal's fur when discretion is needed, or bright colours and LEDs when frequent visual monitoring is required.

avoid drawing attention from other animals or humans, especially in multi-animal environments or public settings. In others, visibility becomes an asset—for instance, when caregivers need to identify the device quickly or monitor its status during daily routines.

3.6.2.9. Factor 20: Animal preparation. In some cases, animal preparation may be required to ensure optimal sensor performance, particularly biosensing wearables that depend on direct and stable contact with the body surface. Preparatory actions can vary depending on the measurement method, the sensor used, and specific characteristics of the animal, such as coat type or skin sensitivity. Among the main preparations required are the following:

- **Cleaning with water, alcohol, or soap** [54]: It removes grease, dirt, or moisture that could interfere with sensor adhesion or signal quality. For example, biopotential sensors require a clean surface to minimize noise and ensure effective electrical contact.
- **Shaving** [105]**:** It exposes the skin in long-haired animals, improving direct contact with sensors. However, shaving can be invasive, affecting device acceptance.
- **Gel application** [46]**:** It enhances measurement quality for biopotential or bioimpedance sensors by reducing electrical resistance between the skin and the sensor.
- **Moistening** [85]**:** It improves conductivity of additional gels. Water or saline solution can be a less invasive alternative to enhance signal quality.

While these preparations are essential for ensuring signal quality, they also present challenges. Some animals may resist these interventions, increasing stress and altering behaviour. Additionally, shaving or chemical applications can cause discomfort or skin irritation [89], potentially affecting the device's acceptance. Therefore, priority should be given to designing devices that function effectively without significant modifications to the animal to minimize required preparations (Table 23).

Beyond physical preparations, implementing an adaptation period is crucial to ensure device acceptance and minimise rejection or discomfort caused by new wearables. This process should be managed gradually depending on species, individual temperament, and device characteristics:

- **Preliminary exploration:** Allow the animal to examine the wearable before placement, helping reduce initial stress. A prototype of the wearable without electronic components but weighted to match the final device can be used.
- **Gradual placement:** Introduce the device progressively, starting with short usage periods and gradually increasing over time.
- **Behavioural monitoring:** Observe the animal for signs of stress, discomfort, or rejection, adjusting device design or placement if necessary.

Ergonomic, and discreet designs can shorten this adaptation period, ensuring measurements are more representative of the animal's natural state and avoiding artifacts related to stress.

3.7. Relational process of categories

After detailing each of the 20 critical factors involved in the design of physiological monitoring wearables for dogs and cats, it becomes essential to understand how these elements interact within a cohesive system. The design and development of such devices is not a linear process but rather an interconnected system, where decisions made in one category directly influence others. This integrated and systemic approach facilitates a more efficient and context-aware design, ensuring that both the technical and welfare needs of animal and human users are addressed holistically. Within this process, the Why (objective) and Who (user) categories serve as fundamental starting points. Defining the purpose of the measurement and the characteristics of the user determines both the parameters to be measured (What) and the most appropriate biometric method to obtain them (How-Bio). However, in

Table 23
Key questions and design principles by factor: F20. Animal preparation.

Factor	Key design questions	Classification	Design principles
F20. Animal preparation	- What physical or behavioural traits (e.g. fur type, skin sensitivity, contact tolerance) affect the use of direct-contact sensors? - How can the measurement method, sensor type, and attachment system be adapted to avoid animal preparation? - If some preparation is needed, which interventions are least invasive and most compatible with study timing or the animal's routine? - How should the adaptation protocol be structured to support device acceptance without causing stress or altering behaviour?	Cleaning with water, alcohol or soap Shave Apply gel Moisten	Allow a gradual adaptation period before data collection and avoid preparation steps to minimise stress: use sensors tolerant to fur, moisture, and dirt; favour wraps, bands, or textile structures over adhesive-based solutions; and position sensors in naturally accessible areas—such as the ear pinna, armpits, or groin—to ensure signal quality without extensive handling.

some cases, the limitations of the available measurement methods restrict the parameters that can be monitored. The Where (environment) and When (duration) categories not only influence the selection of parameters and methods but can also be defined by them. The process culminates in the physical design of the device (How-Design). Factors related to sensors, contact points, fastening, and device protection are directly shaped by the decisions made in the preceding categories. Fig. 5 illustrates this relational structure, highlighting how design decisions in each category propagate and interact, reinforcing the importance of a systems-level perspective in the development of wearable physiological biosensing technologies.

To further support this systemic model, Table 24 presents a matrix that maps the interrelationships between the 20 critical factors. Each cell in the matrix represents the nature and intensity of the influence between two factors, reading the relationship from the factor in the row to the factor in the column using the following coding:

- **'0′ (identity):** Used along the diagonal to indicate self-comparison.
- **'–' (no influence):** The factor is considered independent in that direction. For example, animal size (F3) and body surface characteristics (F4) are unrelated, since large dogs may have either short or long fur.
- **'+' (direct influence):** A decision in one factor has a direct and consistent effect on the other. For instance, exposure to environmental conditions (F9) clearly affects sensor protection strategies (F18).
- **'±' (contextual influence):** The influence is conditional and only becomes relevant under specific circumstances, typically mediated by a third factor. For example, the connection between the measurement objective (F1) and the sensor contact point (F15) depends on the selected parameter (F6) and the biometric method used (F11).

This matrix provides a strategic overview that supports coherent and anticipatory decision-making, enabling designers to trace the downstream effects of each choice across the entire design space. It also serves as a validation tool, helping to detect inconsistencies or constraints that may have been overlooked. Moreover, when a device is already available, the matrix can assist in evaluating its suitability and refining those factors that still open to contextual definition or adaptation within a specific design.

A particularly relevant insight from the matrix is the centrality of Factor 1 (Objective). This factor exhibits either direct or contextual relationships with all other factors, yet it is not directly influenced by any of them—unless if a device is being evaluated, in which case the available measurement method (F11) may retroactively constrain what can be achieved. This asymmetry confirms its foundational role: the objective defines the purpose of the system and guides every downstream decision. While it may be gradually refined during development, it must be clearly defined from the outset, as it serves as the conceptual and functional anchor of the entire design.

In this framework, Factor 11 (Measurement method) acts as a bridge. It directly affects all aspects of How-Design (F12–F18) and is, in turn,

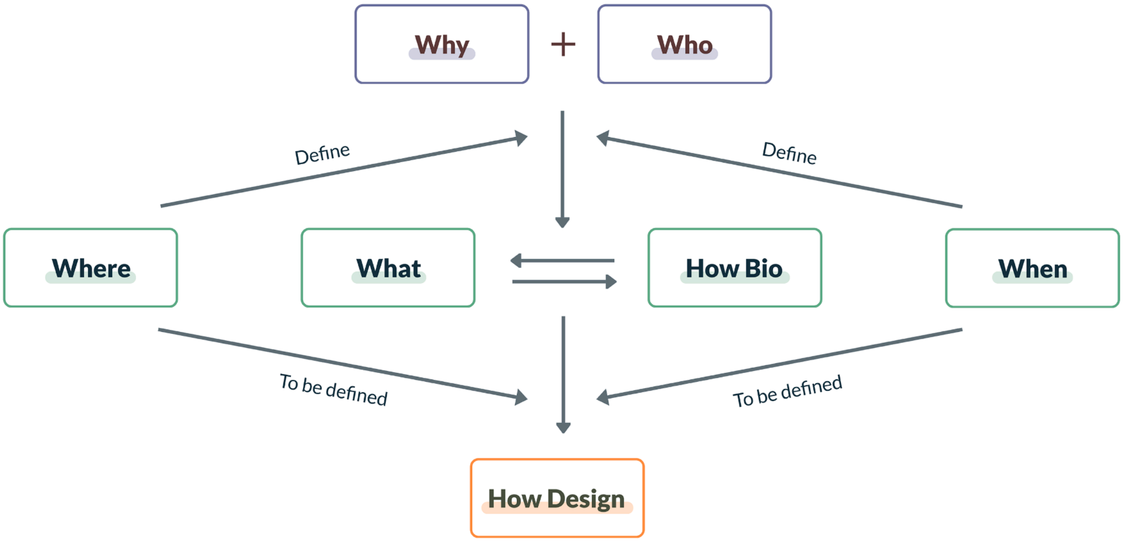

Fig. 5. Relational process among categories.

Table 24

Relational factor matrix. (1: Measurement objective; 2: Species, 3: Size; 4: Body surface; 5: Context; 6: Measurement parameters; 7: Duration; 8: Control; 9: Exposed to environmental conditions; 10: Interaction with other animals; 11: Measurement method; 12: Set configuration; 13: Sensors; 14: Number of sensors; 15: Sensors point of contact; 16: Sensors fastening; 17: Electronic unit fastening; 18. Set protection; 19: Set physical attributes; 20: Animal preparation).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	+	±	±	±	+	+	+	+	+	+	±	±	±	±	±	±	±	+	±
2	±	0	+	+	-	±	±	±	±	+	±	±	±	±	±	±	±	+	+	±
3	±	±	0	±	-	±	+	-	-	-	±	+	+	+	+	+	+	+	+	-
4	±	±	-	0	-	+	±	±	±	±	+	±	+	+	+	+	+	+	+	+
5	±	-	-	-	0	±	+	+	±	+	±	±	±	±	±	±	±	±	+	+
6	±	-	±	±	±	0	±	±	±	±	+	±	±	±	±	±	±	±	+	±
7	±	-	+	+	±	+	0	+	±	±	+	+	+	±	+	+	+	+	+	±
8	±	-	±	±	+	+	+	0	±	±	+	+	±	±	+	+	+	+	+	±
9	±	-	±	-	-	+	+	+	0	-	+	±	+	±	±	+	+	+	+	-
10	±	±	±	±	+	±	±	±	-	0	+	±	±	±	+	+	+	+	+	-
11	+	±	±	+	±	+	+	+	+	±	0	+	+	+	+	+	+	+	+	+
12	±	±	+	±	±	±	+	+	±	±	±	0	±	+	+	+	+	±	+	-
13	±	±	+	+	±	±	+	±	+	±	±	+	0	±	±	+	+	±	+	+
14	±	±	+	+	±	±	±	±	±	±	±	+	±	0	+	+	+	±	+	-
15	±	±	+	+	±	±	+	+	±	+	±	+	±	+	0	+	+	±	+	+
16	±	±	+	+	±	±	+	+	+	+	±	-	-	-	-	0	+	+	+	-
17	±	±	+	+	±	±	+	+	+	+	±	-	-	-	-	+	0	+	+	-
18	±	+	+	+	±	±	+	+	+	+	±	-	-	-	-	+	+	0	+	-
19	±	±	±	±	±	±	±	±	±	±	±	±	±	±	±	±	±	±	0	±
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0

contextually affected by them. This bidirectional relationship highlights the dual role of the measurement method: it limits and is shaped by design decisions.

Another important observation concerns Factor 6 (Parameter), which directly influences only F11 (Measurement method) and F19 (Physical attributes), and exerts a broader contextual influence on the rest of the system through them.

Interestingly, Factor 19 is impacted by all technical decisions, yet it does not influence any of them directly. This reflects the foundational design principle *form follows function*, whereby physical attributes are shaped by functional requirements, not the reverse. Nevertheless, these attributes exert contextual influence across the system, as design choices in one component may constrain or enable others.

The matrix also reveals how certain relationships shift depending on the phase of the design process. The directional influences from columns F2-F12 and F2-F18 down to row F10—illustrate how contextual factors define the technical requirements when designing a new device. Conversely, the inverse relationships—from columns F12-F2 and F12-F10 down to row F18 reflect how the characteristics of an existing device constrain the selection of study conditions during device evaluation.

Factors 16, 17, and 18 (related to fastening and protection) are defined by prior components in the design process (F12–F15) but do not influence them in return. This directionality reflects their operational dependence: fastening and protection strategies emerge from previous choices—such as sensor configuration, number, and placement—rather than determining them.

Lastly, Factor 20 is defined by the others, but it does not influence any factor in return. The tendency in wearable design is to work towards devices that require minimal animal preparation, making Factor 20 a consequence rather than a cause.

Together, these patterns of influence reveal the internal logic and hierarchy that underpin the framework. The matrix not only makes these relationships explicit but also supports a more structured, transparent, and informed process in the design and evaluation of animal wearables.

4. Discussion

This study has identified 20 key factors in the design of wearables for physiological monitoring in dogs and cats, based on a comprehensive review of scientific literature and participation in real-world projects. The findings highlight the importance of a holistic approach that integrates the characteristics of the animal user with technical, temporal, and environmental requirements of biosensing systems. Furthermore, they underscore how the interactions between factors can significantly influence the functionality and acceptance of the device.

The discussion section has been structured in two parts: the first addresses current trends in the design of animal health wearables, while the second explores the applicability and distinct contributions of the proposed framework.

4.1. Trends in animal health wearables

This section discusses the trends observed across the analysed categories, identifying key areas of interest and major emerging challenges. A set of reference tables is included to facilitate access to relevant literature, each corresponding to a category, compiling design factors along with their associated references. These tables serve as a quick-access guide for researchers and developers, enabling them to locate studies aligned with their specific requirements.

By examining current designs, this section aims to provide a deeper understanding of the evolving landscape in wearable biosensing for animals. It also underscores areas where further exploration and innovation are needed to improve the functionality, applicability, and welfare implications of these devices.

4.1.1. Current “Why”

The most common purpose identified in the reviewed literature is monitoring physical health (Table 25), representing over 70 % of the analysed studies. In contrast, research focusing on emotional and social health, and performance, represents a minority despite their growing relevance to animal welfare. This imbalance reflects a strong tendency toward clinical and veterinary applications, leaving considerable potential for expanding the scope of physiological biosensing to address the effects of environment and human-animal relationships on animal health.

Beyond their intended applications, many studies simultaneously assess device reliability, whether in proprietary or commercial designs, covering aspects such as technical performance, software integration, physical form factor, and functionality [39–41,45–49,52–56,72,76,81–83,85–88,91–93,95,102,105–117]. This dual-purpose approach highlights the increasing emphasis on measurement accuracy, reinforcing the need to ensure high-quality data collection, a critical factor in promoting the effective adoption of wearable biosensing technologies in animal health.

4.1.2. Current “Who”

Dogs dominate the landscape of wearable applications (Table 26), accounting for 90 % of the reviewed studies, while cats are less represented. This discrepancy is likely due to behavioural challenges and lower tolerance for devices, which make wearable adoption more complex in felines. These differences highlight the need for more species-specific adaptations to ensure ergonomic, functional, and well-accepted designs for underrepresented animals.

Some studies address how factors such as body surfaces characteristics or animal size influence their device selection or design [39,83,86,88,103,107,109,111], while others conclude that these variables contribute to observed failures [56,75,108,114] or modify results [76].

Table 25
“Why” references correspondence.

Category		Proposed classification	References
Why	1. Measurement objective	Physical health	[45,49–55,67–69,76,78,82,85–89,91,93,94,96,97,99–106,108–112,114–116,118–161]
		Mental, emotional and social health	[28,29,46–49,56,70,71,75,76,79–81,83,86,90,91,95,98,107,112,113,117,162–168]
		Performance	[39–41,46,72,76,83,86,91,92,112,166,167]

Table 26
“Who” references correspondence.

Category		Proposed classification	References
Who	2. Species	Dogs	[28,29,39–41,45–47,49–52,56,68–72,75,76,79–83,85–92,94–120,122–126,128,130–138,140–158,160–168]
		Cats	[48,53–55,67,78,94,110,122,128,140,160]
	3. Size	Large dog: dogs > 25 kg	[41,47,50,52,70,72,81,85,86,88,91,94,95,104,107,110,120,123,124,132,135,140,147,150,153,155,166]
		Medium dog: dogs 10–25 kg	[45,69,83,97,101,103,114,119,120,126,127,129,142,145–147,149,150,159,161,162,166]
		Small dog: dogs < 10 kg or puppies	[39,90,123,137,143,152]
		Dogs of different sizes	[51,56,68,71,75,76,79,80,83,87,90,92,98,101,105,106,108,109,114,116,117,129,130,133,134,137,143,154,163,167]
		Cats < 10 kg	[48,53–55,67,78,94,110,122,128,140,160]
	4. Body surface	Long fur	[39,41,46,47,70,76,85,86,91,94,104,109,110,140,142,155,166]
		Short fur	[45,50,67,69,83,89,96,97,101,103,107,114,119–121,124,127,128,133,142,146,149–152,154,159,162,166]
		Fur of different lengths	[51,52,68,72,75,79,80,83,87,89,92,93,98,99,101,105,107–109,114,122,124,129,130,133,134,136,137,139,147,154,159,167]
	5. Context (social)	Private owner	[28,29,39–41,46,47,49–56,67,68,70–72,75,76,79–81,83,85–95,97–99,101–112,114,116,117,120–125,127–140,142,147,149–151,154,159,162–168]
		Laboratory	[45,48,69,71,78,83,97,101,114,119,120,127,142,144–147,149,153,156–159,162,164]

Additionally, many studies mention the need to shave the animal or apply conductive gel to improve sensor contact (Table 26 – Animal preparation). However, in most of the reviewed studies, species and breed are documented as study variables, allowing for inferences about size or coat type, yet rarely translating into explicit design considerations. This oversight reveals a significant gap, as the specific characteristics of the animal user are seldom integrated into the design process in a conscious and structured manner.

Despite the importance of Animal-Centred Design and Animal-Computer—discussed in the introduction as essential approaches for aligning technology with animal welfare—none of the reviewed publications on physiological monitoring in dogs and cats reference these concepts. This may be due to research in this field primarily focusing on wearables’ technical and biomedical aspects, prioritising them over user experience considerations from the animal’s perspective. This gap underscores the need to adopt design approaches that prioritise the needs and limitations of the animal user from the earliest stages of design, considering not just anatomy, but also behaviour, social interactions, and environmental conditions.

4.1.3. Current “What”

The "What" category highlights a strong predominance of cardiac parameter monitoring, accounting for 85 % of the measured parameters, followed by respiratory parameters and temperature (Table 27). Among cardiac parameters, HR (47 %) is the most frequently monitored, while ECG (32 %) and HRV (21 %) are also notably represented. Although respiratory parameters are secondary, RR appears in 13 out of 115 publications, whereas the respiratory wave is highly underrepresented,

Table 27
“What” references correspondence.

Category	Proposed classification			References
What	6. Measurement parameters	Cardiac	ECG	[50,51,54,55,67–70,78,88,89,91,94,97,98,102,103,105–107,110–112,115–117,119,123,124,126,128,129,132–135,137–143,148,150–152,154–161]
			HR	[28,29,39,40,46–48,51–56,67,68,70,75,78–80,83,85,86,89,91–102,104,105,107–111,113–119,121,122,124,126,127,129,130,133,135–140,143,144,146,148,149,151–153,156,158,159,162,165–168]
			HRV	[28,29,39,46,48,51,53,56,71,75,80,83,86,89,90,92,95,98,103,112,113,117,119,120,122,126,129,137,145,146,148,158,163–165]
		Respiratory	RR	[41,45,46,72,76,81–83,86,91,92,99,137]
			Respiratory wave	[83]
			SpO2	–
		Temperature	External	[49,127]
		Behaviour	Activity level	[39,81,82,104]
			Recognition of activities	[28,29,39,51,56,71,72,75,76,80,84,89,95,99,100,108–111,117,123–125,165,167–169]
			Posture	[28,29,56,71,79,80,83,90,108,168]
			Vocalization	[28,29,56,71,80,90,168,169]

with only one publication. Body temperature is addressed to a limited extent despite its relevance to health. Additionally, one-third of the studies combine physiological and behavioural data, primarily physical activity, indicating a growing interest in holistic approaches that offer a more comprehensive assessment of the animal’s physiological and behavioural state or establish meaningful correlations between them.

When analysing the purposes of measurement (Why) in relation to the selected parameters (Fig. 6), notable differences emerge. ECG is primarily used for physical health purposes, likely due to its ability to provide detailed and diagnostic information on cardiac electrical activity, which is essential for clinical applications. In contrast, heart rate (HR) demonstrates greater versatility owing to its simplicity and applicability across various contexts, making it relevant for studies on physical health, behaviour, and performance. HRV, on the other hand, is more prevalent in non-clinical studies, as it is linked to stress and autonomic nervous system balance, making it ideal for research on well-being and emotional states. Respiratory rate (RR) stands out in performance-related articles, likely because it enables the evaluation of real-time physiological responses during intense activities.

These trends accentuate the importance of selecting parameters aligning with the study’s objectives while also reveal underexplored areas, such as the respiratory wave analysis. This process underscores the need to diversify approaches in future studies, expanding the range of monitored parameters and their contexts of use to improve the comprehensiveness and impact of biosensing applications in animal health.

4.1.4. *Current “When”*

The "When" category reveals a clear predominance of short-duration continuous measurements (Table 28), accounting for nearly 80 % of the reviewed studies. Among these, 62 % correspond to circadian cycles of 8 to 24 h, 30 % are limited to periods of up to 2 h, and 8 % span between 2 and 8 h. This emphasis on shorter durations aligns with the technical feasibility of current wearable devices, which are constrained by energy autonomy and stability over extended use. In contrast, discrete measurements and long-duration continuous monitoring appear far less frequently in the literature.

Measurement duration is a commonly reported parameter, with only

Table 28
“When” references correspondence.

Category	Proposed classification			References
When	7. Duration	Discrete	Seconds or Minutes	[39,52,79,81,87,96,99,106,108,113,114,163]
		Continuous	Short (<24 hour or circadian)	[28,29,39–41,45,47,48,50,51,53–56,68–71,75,76,78,80,82–84,86,88–91,93–95,97,98,100,101,103,104,109,110,112,115–128,130–140,142–147,149,151–154,156–162,164,165,167–169]
			Medium (1 - 7 days)	[49,102,105,129,141,166]
			Long (> 1 week)	[89,107,111]
			Prolonged (> 6 months)	–

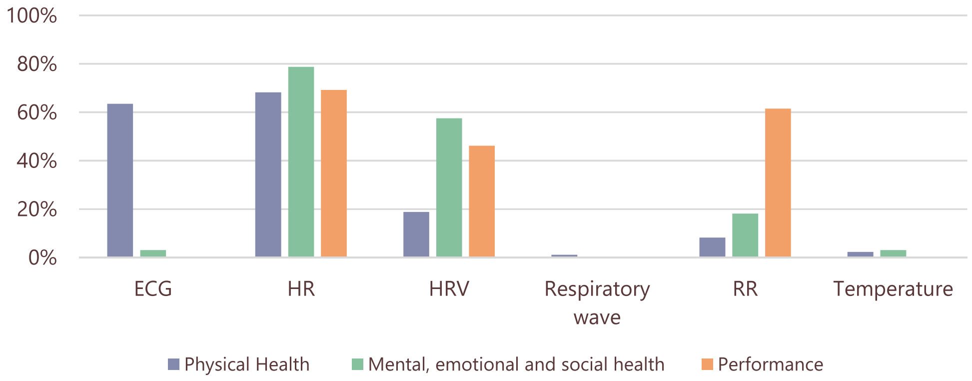

Fig. 6. Parameters (What) based on the purpose of the publication (Why).

5 % of studies omitting this information. However, few publications reflect critically on how the chosen monitoring timeframe influences the device's technical design, usability, or the ecological validity of the collected data.

The prevalence of circadian measurements highlights the importance of capturing daily physiological variability, but it also represents an opportunity to expand the use of longitudinal monitoring. These extended recordings could facilitate the analysis of more complex physiological patterns or cumulative effects, such as those linked to chronic stress. Optimizing wearables for prolonged monitoring requires overcoming key technical challenges, including enhancing energy autonomy, minimizing intrusiveness, and ensuring device stability for the animal wearer.

4.1.5. *Current "Where"*

The "Where" category shows the significant influence of the environment on measurement conditions and device design (Table 29). However, 30 % of the reviewed studies do not specify the usage environment, and in many cases where it is mentioned, generic terms such as "Home" or "Hospital" are used without detailing specific conditions. These environments are often assumed to be controlled, with no environmental exposure or animal interactions. Still, the lack of detailed reporting limits the replicability and hinders the extrapolation of results to more diverse scenarios.

Only over half studies that specify the environment are conducted in real-world implementation settings. Within these real-world studies, nearly all occur in controlled environments, with 75 % lacking exposure to external environmental conditions, and half reporting no interaction with other animals. However, in 14 % and 45 % of cases, respectively, these conditions are not reported (Fig. 7).

This predominance of controlled environments reflects the need to minimize external variables that could compromise measurement quality. Factors such as humidity, dirt, and temperature fluctuations can introduce noise into the data or damage devices, explaining why most wearables have not yet been tested in challenging field conditions. Additionally, limiting interaction with other animals helps reduce the risk of device displacement, signal artifacts, or damage caused by unexpected behaviours.

Table 29
"Where" references correspondence.

Category		Proposed classification	References
Where	8. Control	Yes	[28,29,39,41,45,47–49,51–56,68,70–72,75,76,78–80,82–84,86,88–90,93–104,106,109,110,112–115,117,119–125,127,128,130–132,135–137,140–142,146,153,159,162–169]
		No	[40]
	9. Exposure to environmental conditions	Yes, which ones?	[40,41,47,49,70,82,163,165]
		No	[28,29,39,45,48,51–56,68,71,72,75,76,78–80,83,84,86,88,90,93,94,96–103,106,110,112–115,117,119–122,127,128,131,135,140–142,146,153,159,162,164,166–169]
	10. Interaction with other animals	Yes, With which ones? How is it?	[40,165]
		No	[28,29,39,45,47,48,52,54,56,70–72,75,76,78–80,82–84,86,90,93,96,97,99–101,103,113,114,119–121,127,142,153,159,162,164,166–169]

While controlled environments are essential for early-stage validation and technical reliability, expanding into more realistic and variable contexts is necessary to advance biosensing technologies toward broader and more continuous deployment.

4.1.6. *Current "How-Bio"*

The "How-Bio" category highlights the strong link between the biometric methods used in wearables and the physiological parameters they measure. The reviewed data (Table 30) show that biopotential is the predominant method in 86 % of cases. This predominance reflects its high precision and suitability for monitoring cardiac parameters such as ECG, HR, and HRV. As such, biopotential remains the reference standard in current research, underscoring the central role of cardiac biosensing in physiological monitoring. In contrast, alternative methods, including bioimpedance, force measurement, PPG, and thermal balance, are much less frequently used, with similar occurrence rates. This reflects the limited diversification of measurement techniques, despite their potential advantages for parameters such as respiratory rate and surface temperature.

The underrepresentation of alternative methods may stem from the limited availability of devices designed for these techniques or the perception that they require greater animal preparation or technical adjustments. However, incorporating less conventional methods could expand the precision and scope of physiological data, particularly in studies integrating physiological and behavioural measurements. Moreover, additional techniques currently used in human biosensing—such as ballistocardiography [170] or pulse rate estimation through thermal measurement of arteries [171]—may evolve and eventually be adapted for animal use, offering new opportunities for non-invasive monitoring. This emphasizes the need to explore and validate alternative approaches for the future development of wearables.

4.1.7. *Current "How-Design"*

The "How-Design" category examines the physical attributes of wearable systems, including sensors, fastening methods, protection, and set configuration, all of which directly influence device functionality and user acceptance (Table 31). The predominant measurement methods and the specific requirements of each study strongly influenced design decisions.

The analysis reveals that 59 % of the sensors are wet electrodes, followed by dry electrodes (27 %), while other sensors have minimal and relatively equal representation. This prevalence is largely due to their compatibility with biopotential measurement, the most widely used method for cardiac monitoring. However, electrodes pose challenges for prolonged or continuous monitoring, including the need for animal preparation and high sensitivity to movement, which can lead to artifacts.

Although half of the studies do not detail the animal preparation procedures, when reported, most require modifications, with shaving being the most common (76 %), followed by alcohol cleaning (40 %) to remove skin grease and gel application (45 %) to improve electrode contact.

Regarding sensor fastening methods, adhesives are predominant for wet electrodes, commonly used in Holter devices, while bands with embedded electrodes are more frequent in dry electrode devices, such as Polar units.

In terms of set design, 20 % of studies use custom-built devices, showing a trend toward integrated units. However, 40 % of publications do not specify how the electronic unit is carried, which is a critical consideration, as is typically the heaviest component. When detailed, bands (25 %) and garments (20 %) are the most commonly used methods, emphasising the need for stability and comfort (Fig. 8).

These results highlight the need for more consistent documentation of animal preparation and device protection procedures, which are essential for reproducibility and welfare assessment. Additionally, they

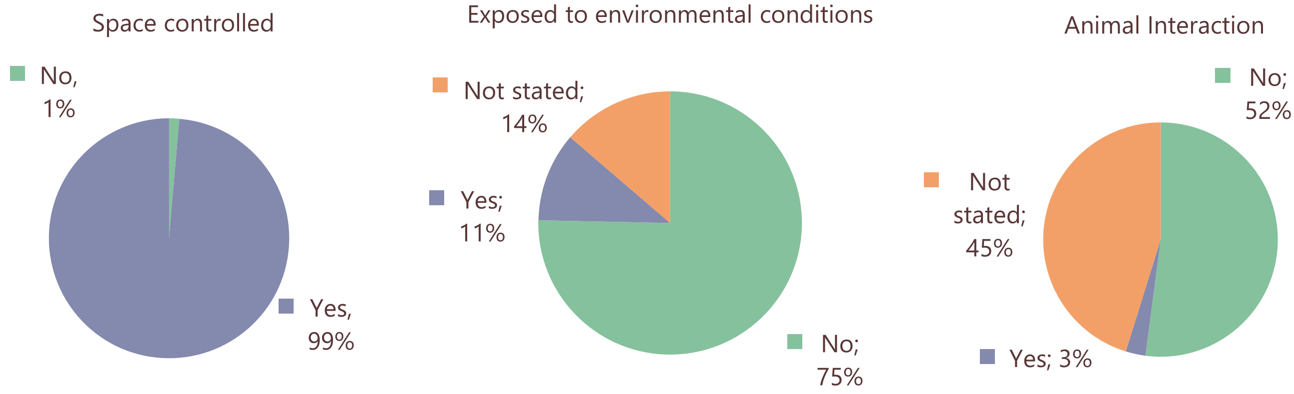

Fig. 7. Current overview of use environments.

Table 30
"How-Bio" references correspondence.

Category		Proposed classification	References
How-Bio	11. Methods	Biopotential	[28,29,39,40,46–48,50–56,67–71,75,78–81,84,86–91,93–169]
		Bioimpedance	[76]
		Force	[45,83,87,91]
		Magnetic impedance	[76]
		Inertial measurement	[76,87,91,106]
		PPG (Photoplestimography)	[76,81]
		Infrared	–
		Thermal balance	[49]
		Sound recording	[41,72,82,93]

underscore the importance of designing wearable biosensing systems that minimize invasiveness and disruption, enhance animal acceptance, reduce stress responses, and improve data reliability in continuous monitoring applications.

4.2. *Framework applicability and future work*

This section examines the practical relevance and broader implications of the proposed 20-Factors Framework. Building on the trends and design gaps identified in the previous section, it explores how the framework can be operationalised in concrete design scenarios, compared against existing models, and projected toward future developments.

The analysis highlights its potential as both a diagnostic and design-enabling tool, capable of guiding interdisciplinary collaboration between researchers, developers, and animal care professionals. In addition, this section considers how the framework can contribute to future innovation by addressing ethical, regulatory, and species-related challenges, ultimately supporting the development of more responsible, effective, and welfare-oriented wearable technologies.

4.2.1. *Practical integration: case study on thermal stress in cats*

To illustrate how the critical factors identified in this study can be applied in a practical context, a case study is presented, focusing on the continuous monitoring of thermal stress in cats with chronic renal disease (Table 32). This example demonstrates how each of the 20 interrelated factors influences the design and configuration of a wearable system, highlighting the key decisions made based on the animal user's needs, environmental conditions, and research objectives. The implementation of this case underscores the importance of a holistic approach in the development and selection of devices, ensuring both the quality of measurements and the well-being of the animal:

The case was developed as a realistic simulation of design decision-making under demanding physiological and behavioural conditions. Rather than presenting measured outcomes, it serves to illustrate how the proposed framework can guide structured reasoning and help anticipate critical constraints in the design of wearables for animal health monitoring.

4.2.2. *Comparative analysis of design frameworks*

To position the 20-Factors Framework within the emerging landscape of Animal-Centred Design methodologies, a comparative analysis was conducted with two recognised approaches: the Wearer-Centered Framework (WCF) [59] and the Welfare through Competence (WtC) model [60]. While all three are grounded in the shift from User-Centred Design to Animal-Centred Design, they differ significantly in scope, level of technical detail, and application focus (Table 33).

The comparative analysis highlights the distinct contribution of the 20-Factors Framework in bridging conceptual approaches and technical practice. Models such as WCF and WtC provide robust foundations for guiding design through ethical, behavioural, and ecological dimensions, incorporating standardized species knowledge and contextual factors. However, their methodological and strategic focus makes them less suited to inform detailed technical decisions in the early stages of the design process—particularly in interdisciplinary contexts where engineers, designers, and clinicians must align around shared specifications. The 20-Factors Framework addresses this gap by introducing structured criteria and design-oriented variables that enable the translation of welfare principles into concrete design parameters. Its strength lies not only in its specificity, but also in its capacity to render ethical and contextual considerations actionable at the level of system configuration. Rather than replacing existing models, it complements them by adding a practical layer to the decision-making process.

4.2.3. *Outlook and future directions*

The 20-Factors Framework also opens a range of forward-looking opportunities for research, design, and policy innovation. Its structured composition and modular architecture make it well suited not only for guiding current development practices, but also for scaling across emerging domains of application, species diversity, ethical scrutiny, and regulatory formalisation.

Wearable biosensing technologies hold untapped potential in areas such as emotional well-being, human-animal interaction, and performance monitoring beyond clinical contexts. These domains, increasingly central to fields like ethology and animal-assisted interventions, demand more integrative design approaches that combine physiological, behavioural, and contextual data, as illustrated in *Section 4.1 Trends in Animal Wearables*. The framework can support this shift by helping identify meaningful parameter combinations (e.g., HRV with posture or vocalisation) that reflect affective or social states. It also guides the development of devices for long-term use in naturalistic environments, where comfort, resilience, and ethical acceptability are essential. In

Table 31
“How-Design” references correspondence.

Category		Proposed classification	References
How-Design	12. Type of set	Sensors separated from the electronic unit	[28,29,39–41,45,47,48,50–56,67–72,75,76,78–84,86,87,89–91,94–105,108,109, 113–169]
		Sensors integrated into the electronic unit	[49,89,100,107,110–112]
		Electronic unit managing multiple separated sensors	[46,76,81,87,91,93,106]
	13. Sensors	Electrode	[28,29,39,40,46–48,50–56,67–71,75,76,78–81,84,86–91,93–105,107–169]
		Deformable substrate	[45,83,87,91]
		Front plane coil	[76]
		Accelerometer and/or gyroscope	[76,87,91,106]
		Transmitter LED/receiver LED	[46,76,81]
		Infrared temperature sensor	–
		Contact probe	[49]
		Audio element (Microphone)	[41,82]
		Audio element (Stethoscope)	[72,93]
	14. Number of sensors	1	[41,46,49,76,81,82,87,91,106]
		2	[28,29,40,47,48,52,56,71,72,75,76,79,80,84,86,89,93,99–101,107,110–114,118, 162–164,167–169]
		≤5	[39,46,48,54,55,70,78,81,86–88,90,91,93,95,96,98,100,102–106,108,114,115,119–122, 131,135,138,140,144,159,165,166]
		>5	[94,115,117,125]
		Continuous	[45,83]
	15. Sensors point of contact	Thorax	[28,29,39,40,45–48,50–56,70–72,75,76,78–81,83,84,86–91,93–96,98–107,110–116, 118–125,127,131,138,140,144,147,153,159,161–169]
		Limbs	[97,114]
		Neck	[49,72,78,82,87,91,93]
		Tail	–
		Ear	–
		Snout	[41]
	16. Sensors fastening	Adhesive	[39,48,50,51,53–55,67–70,76,78,81,86,88–91,94,95,97,98,100,102–105,107,109–112, 114–117,119–161,165,166]
		Band	[28,29,39,40,45–48,52,56,71,72,75,79–81,83,84,86,87,91,93,96,99,101,113,114,118, 162–164,167–169]
		Collar	[49,82,87,91]
		Halter	[41]
		Garment	[39,76,108]
		Bandage	[100]
	17. Electronic unit fastening	Adhesive	[89,110–112]
		Band	[28,29,40,46–48,52,56,71,80,81,84,86,87,91,93,99,101,113,114,118,124,162–164, 167–169]
		Collar	[41,49,82,87,91,96]
		Halter	–
		Garment	[39,45,72,76,78,83,88,94,95,102–105,108,116,119,120,125,159,161,166]
		Bandage	[53,70,86,100,107,117,121,122,165]
		Extra-Adhesive	[89]
	18. Set protection	Band	–
		Garment	[39,40,45,72,76,78,83,86,88,89,94,95,100,102–105,107,108,116,118–121,124,125,159, 161,166]
		Bandage	[29,39,47,48,54,56,70,81,86,100,103,105,107,110–112,114,117,119–122,124,140,165]
		Others: Elizabethan collar	[103,119]
	19. Set physical attributes	Size and weight, Shape, Material, Robustness, Visibility and colour	–
	20. Animal preparation	Cleaning with water, alcohol or soap	[29,47,52,54,86,89,100,102,103,105,107,110,112,113,117,119–121,123,124]
		Shave	[29,39,40,47,48,51,52,54,55,71,76,81,86,88,89,94,95,100,102–105,107,110–114,117, 119–125,165,166]
		Apply gel	[28,39,40,46–48,52,56,71,75,79,81,113,114,118,163,164]
		Moisten	[86,89,165]

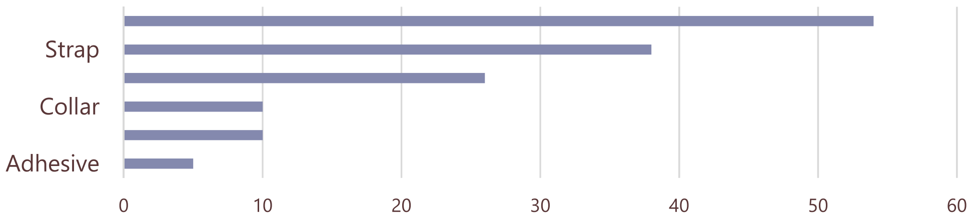

Fig. 8. Fastening of the electronic unit.

doing so, it contributes to a broader, more holistic understanding of animal health that integrates both medical and emotional dimensions.

Although this study centres on dogs and cats, the 20-Factors Framework is designed to be adaptable to a wide range of species, including livestock, wildlife, and exotics. Core categories such as Why (measurement objective), When (duration), and How-Bio (method) are

Table 32
Case Study.

Category	Implications
Why: Purpose of the measurement	
F1.Objective: Evaluate the effects of heat stress in cats with chronic renal disease.	Aims to identify heat-related patterns influencing disease progression and guide management strategies. Cameras will monitor the cat's activity to correlate with physiological data.
Who: Animal user characteristics	
F2.Species: Domestic cats (Felis catus).	Chronic renal disease makes cats more reserved, stress-sensitive, and less tolerant of external devices. Their flexibility increases the likelihood of attempting to remove the device.
F3.Size: <10 kg.	The small size and weight of these animals limit space for placing sensors and the electronic unit. The set necessitates an extremely lightweight design.
F4.Body surface: Varied hair lengths.	Design must accommodate both short- and long-haired cats, minimising reliance on direct skin contact while ensuring stable and comfortable attachments.
F5.Context: Privately owned cats with known chronic renal disease.	Devices should be minimally visible and non-invasive to ensure caregiver acceptance. An easy-to-use design will improve adherence to the study protocol and measurement consistency.
What: Measurement parameters	
F6.Parameters: Respiratory Rate (RR) and surface temperature.	Respiratory rate is a direct indicator of the response to heat stress. Temperature reflects thermoregulation under varying conditions.
When: Duration of measurement	
F7.Duration: Continuous 12-hour diurnal measurement for 5 consecutive days per season for a year. The device will be removed at the end of each daily period.	Daily removability reduces battery demands and enables a compact design but requires easy handling and durability to maintain consistency.
Where: Environment of use	
F8.Control: Fully controlled home environment by caregivers.	Caregivers monitor conditions, allowing device adjustments in extreme cases. Cats can move freely within the area; therefore, the device must be resistant to natural movements such as walking, jumping or turning.
F9.Exposure to environmental conditions: Indoor study with household temperature variations.	No extreme environmental restrictions, but materials must prevent heat buildup that could interfere with temperature readings.
F10.Interaction with other animals: No direct contact with other animals.	No need for additional protective measures against bites or scratches or other physical damage caused by curiosity or aggression.
How-Bio: Measurement method	
F11.Method: Force for inhalation and exhalation. Thermal equilibrium for temperature.	Accurately captures respiratory movements without requiring direct skin contact. Thermal equilibrium probes stabilise with the skin for precise temperature readings.
How-Design: Physical design	
F12.Set configuration: Electronic unit separate from sensors.	In cases of small animals, the spacing allows the sensors to be positioned at the most suitable points for measurements without restrictions imposed by the location of the electronic module.
F13.Sensors: Deformable substrate (strain gauge wire) for RR. Metal probe for temperature.	The gauge accurately captures thoracic expansion. The temperature probe has to be designed to penetrate the fur in long-haired cats and incorporates redundancy for measurement continuity.
F14.N° of sensors: 2	Each measurement needs its own interface. It is essential that the gauge does not cause interferences in the area where the probe is located, maintaining the stability of both measurements. Minimising the number of sensors reduces stress and increases acceptance.
F15.Sensors contact points: Thorax for RR. Tail base for temperature.	The thorax provides optimal respiratory motion detection, acquiring accurate and consistent data. The base of the tail provides a stable, protected surface that facilitates accurate measurement of surface temperature. The probe in the tail is less visible and may be more acceptable to the cat and its handler, even allowing for minimal localised shaving.
F16.Sensors fastening: Elastic band around the thorax embedded in a textile harness for RR. Small adjustable band for base tail temperature.	The strain gauge band must be light and adjustable, with calibrated elasticity to accommodate chest movement without affecting measurements. It is integrated into an adjustable textile harness, specifically designed for cats, ensuring even pressure distribution for a secure yet comfortable fit. The temperature probe is secured with a soft textile band at the base of the tail, protected by a harness extension to maintain stability and comfort. The harness design allows for easy removal and attachment, ensuring daily usability while maintaining measurement consistency throughout the study.
F17.Electronic unit fastening: Textile harness.	The electronic unit shall be integrated into a secure pocket of the textile harness. Positioned over the shoulder blades for stability and weight distribution, with easy removal for charging and adjustments.
F18. Set protection: No additional protection.	The harness design inherently protects the strain gauge, eliminating the need for extra shielding. The harness extension provides an additional layer of protection against displacement or external interference of the contact probe.
F19.Set physical attributes: Size and weight of the set proportional to the size of the animal, ergonomic shapes, biocompatible, resistant and easy-to-clean materials, colours that match the cat's coat.	The design must be compact and lightweight, using advanced materials that ensure strength without adding unnecessary weight. It should be ergonomic, avoiding hard edges or pressure points, and conforming to the cat's anatomy for maximum comfort. The harness and bands should be made of flexible, breathable polymers to enhance wearability. A discreet design will prevent the device from drawing the cat's attention, improving acceptance and usability.
F20.Animal preparation: Minimal shaving at the base of the tail in long-haired cats and gradual adaptation period.	Shaving is localised and minimally visible. As the measurement period is relatively short, only one shave per season will be necessary. Cats, due to their sensitive nature, need a phased introduction of the harness to ensure acceptance, starting with short wear periods and gradually increasing duration.

readily transferable across species, as they depend primarily on physiological and research-driven variables. In contrast, categories like Who (species-specific traits, size, social context) and How-Design (sensor placement and physical configuration) demand species-specific adaptations(sensor placement and physical configuration) demand species-specific adaptations [172]. For example, in livestock such as cattle, weight tolerance and attachment strategies often require integration into halters or ear tags [173]. In wildlife and zoo animals, challenges related to limited handling, behavioural unpredictability, and

Table 33
Comparative overview of the 20-Factors Framework, WCF, and WtC.

Category	20-Factors Framework	WCF (Wearer-Centered Framework)	WtC (Welfare through Competence)
Principle	User-Centered Design → Animal-Centered Design	User-Centered Design → Animal-Centered Design	User-Centered Design → Animal-Centered Design
Scope and application	Research and Requirements Definition for animal wearable design	Research and Requirements Definition for animal wearable design	Research, Requirements Definition, Ideation, Prototyping, and Evaluation for designing technological interventions to improve animal welfare
Technical Specificity	Defines components, configurations, and very detailed technical criteria.	Heuristic tool for wearability requirements; no detailed technical specification.	Focused on methodological and strategic aspects; does not include technical specifications.
Features	- Focuses on minimal animal interference. - Focuses on scientific reliability. - Explicit and open technology implication starting from a justified and contextualized measurement need. - Detailed animal variables: species behaviour, size, fur. Includes relations with other animals. - Explicit temporal factors (duration, scheduling, seasons). - Detailed consideration of indoor/outdoor conditions and human supervision. Includes relations with other animals. - Informs concrete design decisions: components, location, fixation, interface interaction. - Maps design interdependencies through a factor interaction matrix.	- Focuses on comfort and behavioural acceptance. - Deep standardized species knowledge and general animal variables. - Attention to environmental fit. Considers interactor ecology. - Highlights conflicts and trade-offs between wearer needs, human users, and system constraints.	- Focuses on animal agency, autonomy, and competence. - Specific and closed technology implication focusing on a clearly defined welfare objective. - Integrates species and individual-level welfare needs. - High context relevance: environmental enrichment and variation are central. Considers population dynamics.

robustness necessitate autonomous and non-invasive designs. By preserving modularity while adjusting for morphological and ecological variability, the framework supports cross-species applicability, with potential utility in precision livestock farming, ecological fieldwork, and zoological research.

As biosensing and animal data tracking technologies advance, they bring critical ethical and regulatory challenges. While the framework promotes minimal intrusiveness and Animal-Centred Design, it also highlights the need for human accountability in areas such as informed consent, data management, and device validation. In the case of companion animals, human guardians act as consent proxies [174], underscoring the importance of transparent communication about monitoring goals, risks, and data use. The handling of sensitive physiological data (e.g., ECG, HRV, activity) further raises concerns regarding privacy and security. Adopting principles aligned with the General Data Protection Regulation (GDPR) [175]—such as data minimisation, on-device processing, and user control—can improve compliance and public trust.

The 20-Factors Framework offers a structured basis for advancing regulatory practices in the still-fragmented field of animal wearables. Several of its categories—such as environmental exposure, animal preparation, sensor contact, and fastening methods—align with principles outlined in international standards like ISO 10993 (biocompatibility) [176], ISO/IEC 60601 (electrical safety) [177], and OIE welfare guidelines [178]. These overlaps suggest its potential as a bridge between design and regulation, helping harmonise safety, usability, and welfare criteria. Future work could explore formalising the framework into a design audit tool or pre-certification checklist compatible with ISO-based systems, supporting unified standards and facilitating smoother transitions from research to clinical or commercial use.

To further strengthen its applicability, the framework should be validated across a wider range of use cases through case-based testing, participatory design workshops, and iterative co-design with researchers, developers, and caregivers. Its dual capacity to function as both a formative and summative evaluation tool—supporting the entire development cycle from initial requirements to post-deployment analysis—offers a robust foundation for future refinement. Ultimately, its continued evolution will depend on interdisciplinary engagement and empirical validation within academic and applied contexts.

5. Conclusions

This study presents a comprehensive framework for the design of wearables for monitoring physiological parameters in dogs and cats, identifying 20 critical factors structured according to the 5Ws+1H Method. This relational approach systematically integrates the specific characteristics of the animal user with technical, temporal, and environmental requirements, facilitating informed and holistic design decisions.

Despite these advancements, the limited application of Animal-Centred Design (ACD) in current research reveals a gap in consciously incorporating the animal user's needs into wearable system design. Integrating these considerations from the early stages of development would enhance the functionality and precision of biosensing wearables and their acceptance, ensuring they meet the behavioural and physiological needs of the animal, while also addressing the monitoring requirements of the human user.

This framework is not restricted to the design of new devices but can also be applied to evaluating and selecting existing wearables. By applying the identified categories and factors, commercial devices can be systematically analysed to determine whether they meet the necessary characteristics for a specific application. This approach enables more informed decision-making, ensuring the selected device is functional, acceptable for human and animal users, and suitable for its intended context.

Declaration of generative AI and AI-assisted technologies in the writing process

While preparing this work, the authors used ChatGPT to check and improve orthography and grammar. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Marta Siguín: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Roberto Casas:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Oscar Casas:** Writing – review & editing, Validation, Supervision, Resources, Conceptualization. **Teresa Blanco:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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