Decoding Your Body with Ubiquitous Sensing

Wearable and Contactless Perception for Health and Beyond

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Abstract

As the global population ages, demand for healthcare services is rising. Yet basic services, such as brief check-ups and rehabilitation guidance, remain largely restricted to hospitals and clinics, limiting regular use, especially for patients with chronic conditions. Our research addresses this gap by delivering home-based, affordable care services enabled by ubiquitous, low-cost sensors embedded in everyday devices. Through our designs, patients gain consistent, convenient, and self-service access to essential health services at home. In this paper, we present a case study on the management of chronic respiratory diseases using ubiquitous sensing systems. Specifically, we introduce a "closed-loop" management framework spanning basic vital sign monitoring, disease severity assessment, and rehabilitation training guidance.

CCS Concepts

• **Human-centered computing → Ubiquitous and mobile computing systems and tools**.

Keywords

Ubiquitous sensing, Healthcare, Wearable and contactless sensors

ACM Reference Format:
Wentao Xie. 2025. Decoding Your Body with Ubiquitous Sensing: Wearable and Contactless Perception for Health and Beyond. In *Proceedings of the 2025 ACM CoNEXT Workshop Edge-Cloud Collaboration for AI (ECCAI '25), December 1–4, 2025, Hong Kong, Hong Kong*. ACM, New York, NY, USA, 2 pages. https://doi.org/10.1145/3769696.3771221

1 Introduction

The global population is aging fast, and the healthcare resources for managing chronic diseases, such as chronic obstructive pulmonary disease (COPD), are in critical need. However, current healthcare services (e.g., disease assessment and rehabilitation) for chronic diseases typically require expensive and adhesive medical sensors and rely on the facilitation of healthcare professionals. This limits such services to clinics and hospitals, restricting the frequent adoption of them, which, however, is essential for controlling chronic diseases. Concurrently, consumer devices—earphones, smartwatches, smartphones—are ubiquitous, multimodal, and increasingly compute-capable. This creates a unique opportunity for us to design easily accessible systems to provide health services in the daily living environment, such as at the patient's home, to fulfil their regular need of these health services.

However, achieving such an objective is challenging. First, because no medical-grade sensors are available in these daily devices, the sensing system can only implicitly infer the hidden health conditions by analysing the human signals, such as motions or basic physiological signals. Therefore, bridging the gap between sensory data and health implications is a challenging task. Second, due to the daily living setup, the sensory data acquired by the ubiquitous sensors usually suffer from various human and environmental factors, such as motion artefacts and environmental noise. Together with the limited data quality provided by these cost-efficient sensors, designing a sensing system that is both practical and robust enough for daily usage is another challenge.

In this paper, we present a series of efforts to enable home-based health management with ubiquitous sensors, addressing the aforementioned challenges. Our methodology couples commodity hardware with scalable, efficient data analytics algorithms and robust interference compensation methods to deliver application-tailored solutions. The following part of this paper will use respiratory disease management as a case study, showcasing designs for home-based respiratory **assessment** and **rehabilitation**. Together, these systems demonstrate the feasibility of closed-loop health management delivered entirely via readily available, everyday devices.

2 Respiratory Assessment

Breathing rate (BR) measurement is important for pulmonary disease patients, yet conventional BR measurement methods require adhesive sensors. In our work [5], we develop a contactless BR estimation system that eliminates the need to wear sensors. We innovatively sense BR by playing music near the subject and decode BRs by analysing the reflected music echoes of the subject through advanced audio processing algorithms.

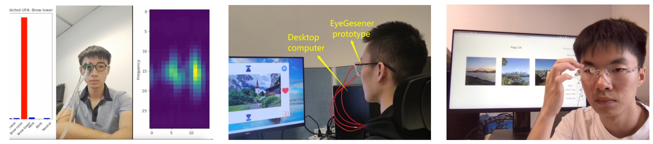
Beyond BR, pulmonary function (PF) screening is vital for the diagnosis of respiratory diseases such as chronic obstructive pulmonary disease (COPD) and asthma. However, traditional PF test methods require an expensive spirometer and the supervision of a well-trained clinician to teach the patient to conduct a complex breathing manoeuvre. To address this issue, we propose a novel earphone-based sensing solution for PF screening, replacing the traditional spirometer, based on the rationale that the breathing sound collected by earphones is a reliable predictor of airflow rate [4]. Furthermore, we extend this idea by designing an effective spectrum reconstruction AI model, allowing PF indicators to be

ECCAI '25, Hong Kong, Hong Kong

ACM ISBN 979-8-4007-2242-4/2025/12
https://doi.org/10.1145/3769696.3771221

Contactless breathing measurement Pulmonary function assessment Breathing exercise guidance

Figure 1: Home-based respiratory management [4–6, 9]



Facial gestures Eye gestures Touch gestures

Figure 2: Interaction gesture sensing on wearables [2, 3, 8]

predicted with only a few casual breaths, thereby eliminating the need for a complex breathing manoeuvre [9]. In this way, the PF test can be conducted at home without the need for clinicians.

3 Respiratory Rehabilitation

In addition to regular disease assessment, respiratory disease patients need to take regular breathing exercises to strengthen their PF, which again need to be supervised by clinicians. In response, we design a non-adhesive and self-service breathing exercise training system equipped with a contactless depth sensor (readily available on commercial mobile devices) to automatically evaluate the quality of breathing exercises in real-time [6]. The system utilises an AI-based depth image processing algorithm to analyse the patient's breathing manoeuvres and automatically provides instructions on how to improve breathing effort using a multitask learning approach, eliminating the need for a therapist, while compensating for artefacts such as body motions and environment changes.

Beyond breathing exercises, effective respiratory rehabilitation also depends on timely airway clearance, i.e., clearing the sputum attaching to the airways. To support this crucial but underserved need in community and home settings, we develop an auscultation-based system that localises accumulated sputum using only a commercially available digital stethoscope [1]. Following standard auscultation protocols, this design aggregates spatially distributed lung sounds and identifies sputum presence across four actionable back regions (upper/lower, left/right) to guide targeted percussion for airway clearance. Technically, it combines a Transformer pretrained with a teacher–student scheme for noise-robust representation learning, with a lightweight classifier that fuses multi-point embeddings to capture inter-region dependencies.

4 Ubiquitous Sensing Beyond Health

In addition to acquiring health implications, the lightweight and cost-efficient nature of ubiquitous sensors makes them suitable for enabling other applications where customised hardware is not available. For example, interacting with digital devices typically relies on large touch panels or external input, but wearables lack the space and resources for such interfaces, making conventional touch panels impractical. To improve usability, we adopt a ubiquitous sensing approach to enable rich, reliable, around-the-device gesture control with minimal or no hardware overhead.

Focusing on smart eyewear and earables, we introduce facial gesture sensing for eyewear [2, 8], which detects facial and eye gestures via miniature ultrasonic sensors that leverage existing audio modules, removing the need for bulky touchpads. We also propose a rim-based touch gesture sensing system for eyewear [3, 7] that aligns input with the forward-facing display: using piezoelectric transducers to inject imperceptible microvibrations and AI to recognise touch-induced vibration patterns, it senses rim gestures "remotely" without adding a physical touchpad to slender frames.

5 Conclusion and Future Work

We present a closed-loop, home-based respiratory management framework using ubiquitous, low-cost sensors, covering vital sign estimation, pulmonary function screening, breathing exercise coaching, and sputum localisation for targeted airway clearance, demonstrating the feasibility of designing health management systems without specialised hardware or constant supervision. Future work will expand ubiquitous sensing to new human activity applications and strengthen practical deployment. On the application side, we will extend home-based healthcare to additional chronic conditions (e.g., asthma, cognitive diseases) and broaden interaction design to other emerging wearables (e.g., smart ring); and build systems that jointly sense signals from different modalities for holistic tasks, such as mental health assessment. On the systems side, our future work will develop efficient, generalizable embedded AI frameworks to handle the resource-constrained nature of ubiquitous devices and improve robustness under user and data heterogeneity.

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