



Wearable multimodal sensing for geriatric healthcare

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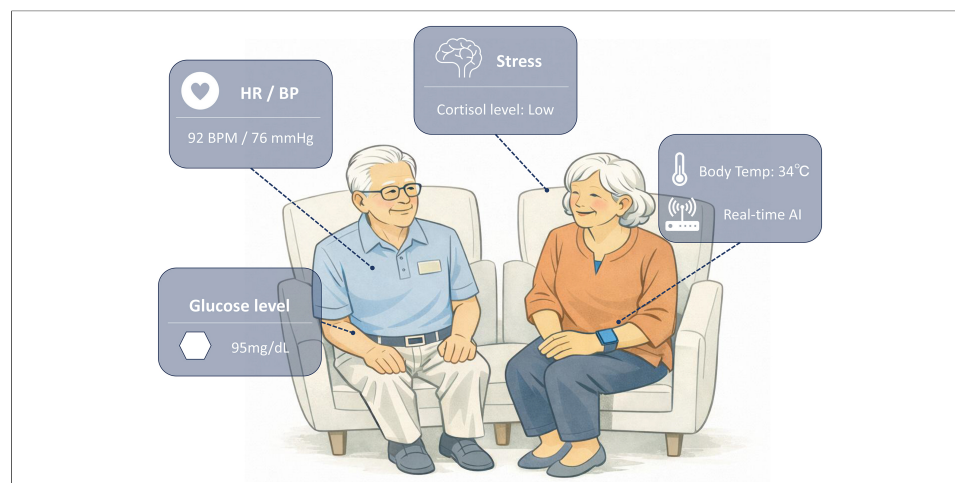
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Abstract

Aging populations face growing multimorbidity, while episodic clinical assessments fail to capture gradual physiological changes unfolding during daily life. Although wearable technologies enable continuous monitoring, single-modality systems provide incomplete and context-limited insight. This Perspective focuses on hybrid wearable sensors that integrate physical and chemical sensing for geriatric healthcare. Hybrid wearable sensing provides a pathway toward continuous, predictive, and personalized geriatric health management. By monitoring continuously multiple health parameters, such multimodal systems have distinct advantages for real-time monitoring, including early risk detection and more personalized health assessment through the integration of complementary physical and biochemical signals. We discuss recent advances in wearable physical sensors, alongside with emerging wearable chemical sensors, then argue that chem-phys hybrid integration enables more interpretable and clinically actionable assessment of aging trajectories than single-modality wearable systems. Finally, we discuss translational requirements and future prospects, including robust real-world operation, AI-driven inference, and integration with telemedicine and home-based care.

INTRODUCTION

As life expectancy rises, multimorbidity increases, including diabetes, cardiovascular,



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renal, and neurodegenerative diseases. However, intermittent clinic-based care provides limited longitudinal insight and often misses early physiological changes, particularly in older adults with mobility constraints and fragmented follow-up. Decisions based on discrete tests, such as blood panels or brief electrocardiogram (ECG) recordings, fail to reflect daily-life physiology, allowing deterioration to go undetected^[1].

These gaps have motivated advanced sensing technologies and biomedical devices that measure health continuously as well as achieve personalized healthcare and treatment interventions. Wearable sensors that interface directly with the body using diverse formfactors, such as epidermal patches, smartwatches and ring-type devices, enabled by advances in skin-compatible and mechanically robust materials, offer continuous, user-friendly physiological monitoring in daily life^[2–11]. Early generations of wearable devices have primarily focused on measurements of physical signals, such as electrocardiography, heart rate, blood pressure, body temperature, or motion, supporting detection of arrhythmias, fall risk, monitoring gait instability, and tracking rehabilitation outcomes in older adults^[12,13]. In parallel, wearable biochemical sensors have emerged to capture molecular level information by continuously monitoring key biomarkers in biofluids, such as sweat or interstitial fluid. However, such single modality wearable sensors fall short of capturing the full spectrum of diverse symptoms experienced by old adults. By integrating well-established physical and chemical sensing modalities into a single unified platform, hybrid wearable systems enable synergistic physiological interpretation that extends beyond isolated signal acquisition and facilitates mechanistic insights into dynamic, system-level health states. Recently developed hybrid wearable devices track multiple biochemical and physiological signals on a single platform, enabling comprehensive monitoring of chronic conditions in older adults [Figure 1]^[14]. These integrated systems provide real-time data streams that support early detection and tailored intervention.

The true clinical value of continuous monitoring depends on translating high-dimensional data streams into interpretable and actionable endpoints. By establishing individualized baselines from longitudinal hybrid wearable data and integrating multi-sensor temporal trends, artificial intelligence (AI)-driven models can identify subtle physiological deviations that precede overt clinical deterioration^[15–17]. By shifting from threshold-based alerts to probabilistic forecasting, AI enables earlier, lower-intensity interventions tailored to individual aging trajectories.

In this Perspective, we map a path towards hybrid wearable sensing for geriatric healthcare, focusing on older adults living with multimorbidity and the need for longitudinal health monitoring. We first summarize recent advances in biophysical wearables that capture cardiorespiratory and mobility-related dynamics, as well as chemical and minimally invasive platforms that access sweat or interstitial fluid for molecular monitoring of metabolic state and therapy response. We then argue that hybrid-based simultaneous tracking of biochemical and biophysical trends, combined with AI-analysis of longitudinal data addresses the elderly multifactorial health trajectories, enhances diagnostic accuracy and enables more clinically actionable assessment. Finally, we discuss key translational requirements, including real-world robustness, interpretable multimodal inference, and integration with telemedicine and home-based care.

THE WAY TO WEARABLE HYBRID SENSORS

Wearable physical and chemical sensors

The widespread adoption of consumer wearables, including smartwatches and rings, enables continuous physiological and behavioral monitoring during daily life^[18]. Beyond these consumer devices, research-grade skin-interfaced systems expand the scope of cardiorespiratory monitoring by integrating soft strain sensors, acoustic sensors, and inertial measurement units (IMUs). By capturing body motion and deformation linked to respiration and cardiac activity, these platforms reveal mechanical–physiological interactions in real-world settings^[19]. Age-adaptive polymeric skin electronics further address geriatric-specific challenges by

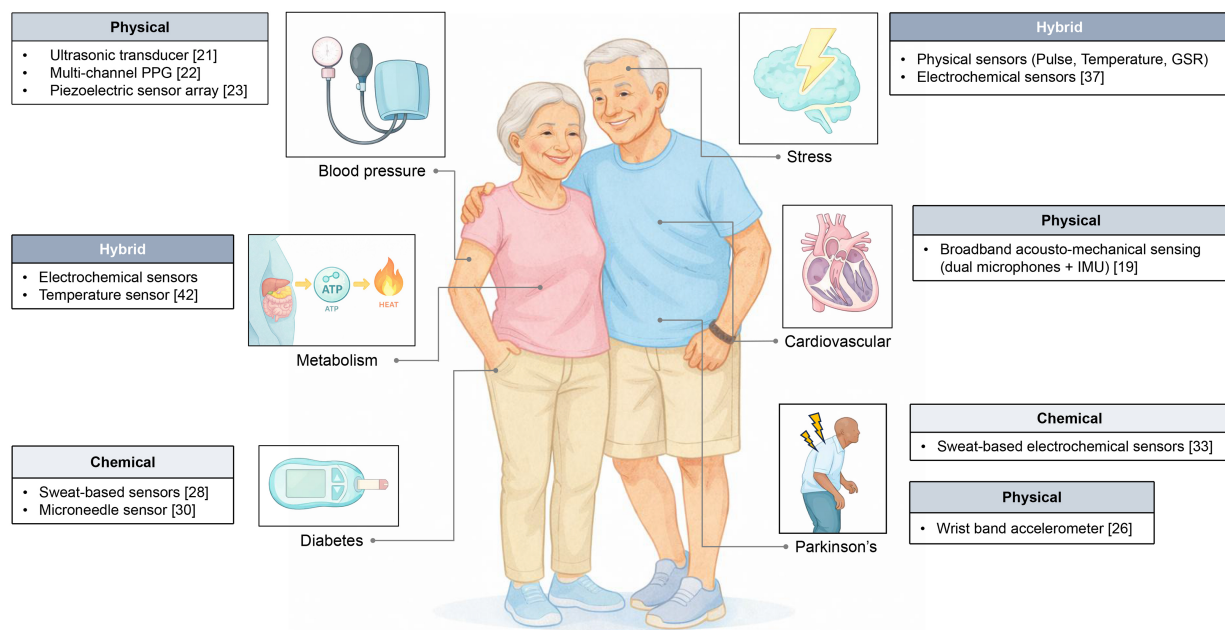


Figure 1. Integration of physical, chemical, and hybrid wearable sensors for holistic monitoring of aging health. PPG: Photoplethysmography; GSR: galvanic skin response; IMU: inertial measurement unit.

accommodating age-related skin changes and preserving signal fidelity across diverse older populations^[20].

In parallel, physical sensing research is increasingly focused on high-impact geriatric risks and chronic conditions. Wearable blood-pressure monitoring now spans ultrasound-based arterial tracking^[21], cuffless optical strategies using multi-channel photoplethysmography (PPG) with finger pressing and learning-based estimation^[22], thin, soft piezoelectric systems designed for continuous wireless monitoring of arterial pulse pressure^[23], and stretchable inductor-capacitor (LC) resonant contact-lens sensors enable intraocular pressure monitoring relevant to glaucoma risk^[24]. Mobility and falls risk are addressed through IMU-based sensing combined with machine learning enables automated fall-risk detection and monitoring from wearable inertial signals^[25]. Physical sensing also contributes to neurodegenerative care, as wrist accelerometry combined with machine learning can detect early motor abnormalities predictive of prodromal Parkinson's disease^[26].

Compared with wearable physical sensing, wearable chemical monitoring faces challenges including biofluid access, biofouling, and signal instability, yet continues to advance rapidly due to the clinical value of continuous molecular monitoring^[27]. Diabetes has driven the rapid progress in wearable chemical sensing, especially through the continuous glucose monitoring (CGM) systems that provide substantial clinical benefits. Additional approaches have demonstrated continuous wearable glucose sensing using passive sweat collection enabled by hydrogel-based interfaces and electrochemical readout strategies^[28]. Beyond glucose, sweat-based platforms broaden the range of clinically relevant metabolites and electrolytes in real time^[29]. Multiplexed electrochemical sensing systems, particularly wearable microneedle platforms have demonstrated continuous simultaneous detection of multiple ISF biomarkers^[30,31]. Sweat has emerged as a noninvasive, information-rich biofluid enabling access to molecular health indicators beyond glucose alone. Early fully integrated sweat sensing systems established the feasibility of simultaneous, real-time analysis of multiple metabolites and electrolytes, during daily activities^[32]. More recently, fingertip bioelectronic systems have shown that passively collected sweat can be used for non-invasive tracking of Parkinson disease levodopa drug following its oral administration, highlighting the potential of sweat analysis for personalized

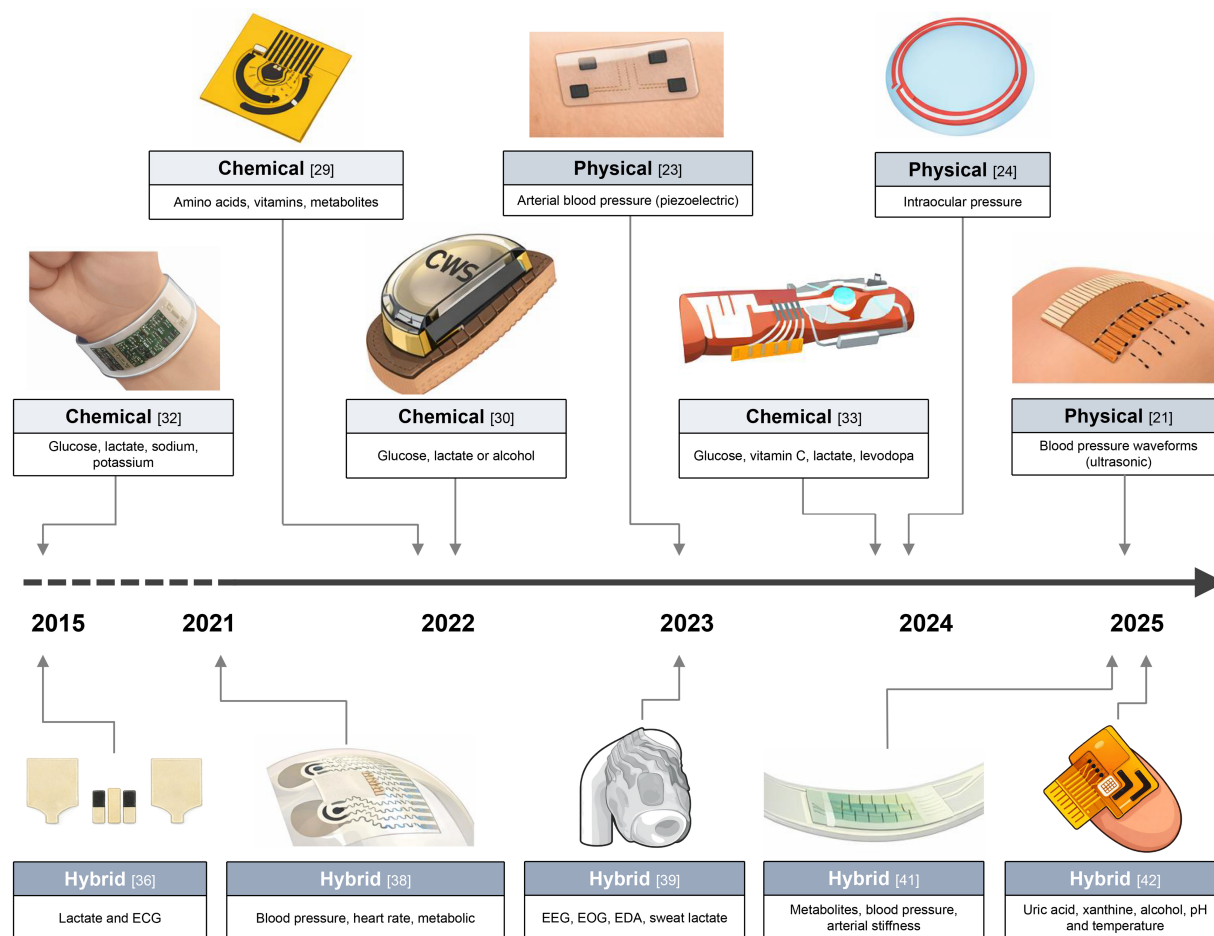


Figure 2. Roadmap of wearable sensing technologies from chem-phys modalities toward integrated hybrid systems. ECG: Electrocardiogram; EEG: electroencephalography; EOG: electrooculography; EDA: electrodermal activity.

drug response assessment in neurological disorders^[33,34]. Building on these developments, autonomous fingertip wearable microgrid platforms have unified sweat-powered energy harvesting, storage, and multi-analyte biochemical sensing within a miniaturized system for continuous, self-sustained monitoring^[28]. Subsequent platforms further integrated wireless transmission and algorithm-assisted analysis for 24-hour biomarker monitoring, including uric acid^[35]. Collectively, these advances demonstrate how sweat-based wearable chemical sensors are evolving toward longitudinal system-level monitoring of metabolism and therapy response in everyday life.

Multi-modal wearable sensor systems

Hybrid wearable systems that simultaneously integrate biochemical sensing with physical vital-sign monitoring have emerged as a practical solution for continuous, home-based health surveillance in aging populations [Figure 2]. Early work demonstrated the feasibility of co-locating chemical and electrophysiological sensors within a single epidermal patch, enabling simultaneous sweat lactate monitoring and ECG recording without signal crosstalk^[36]. This proof-of-concept established that metabolic and cardiac domains can be jointly monitored in a skin-conformal format suitable for prolonged wear. More recently, an AI-assisted physicochemical electronic skin expanded this concept by simultaneously tracking multiple sweat metabolites and electrolytes alongside pulse waveform, skin temperature, and galvanic skin response, enabling robust long-term multimodal monitoring of systemic stress responses^[37].

Subsequent advances extended hybrid sensing platforms toward clinically relevant hemodynamic and metabolic endpoints. An epidermal patch integrating ultrasonic transducers for blood pressure and heart rate with electrochemical sensors for glucose, lactate, caffeine, and alcohol, demonstrated simultaneous monitoring of cardiovascular and biochemical dynamics during daily activities^[38]. Such combined monitoring is particularly relevant for older adults, where dehydration, infection, medication intake, or metabolic imbalance often manifests as coordinated rather than isolated changes in a single parameter.

Hybrid sensing has also diversified into unobtrusive form factors optimized for long-term adherence. Accordingly, different wearable form factors can be employed depending on the anatomical locations best suited for acquiring specific physiological signals. For example, the ear offers a rich source of brain and body biosignals towards continuous cognitive and metabolic health monitoring. An in-ear multimodal sensor, integrating brain electrophysiology with electrochemical lactate sensing, enabled continuous assessment of neurophysiological state alongside metabolic dynamics in real-world settings^[39]. When combined with stimulation mechanisms, such systems open opportunities for personalized neurotherapeutic strategies^[40]. This brain–body integration is particularly compelling in geriatric care, where cognitive decline and metabolic dysregulation frequently co-evolve.

Wrist-worn and minimally invasive hybrid platforms further extend multimodal monitoring for chronic disease management. A flexible wristband integrating microneedle-based interstitial sensing with cardiovascular monitoring enabled simultaneous metabolic and hemodynamic tracking in individuals with diabetes^[41], addressing limitations of single-parameter glucose monitoring in multimorbid older adults.

Finally, advances in sweat interfacing and microfluidics have improved the reliability of biochemical sensing in hybrid systems. A bioinspired microfluidic wearable enabled multiday, multiplexed metabolic monitoring under low-sweat conditions^[42], providing infrastructure for hybrid integration.

Collectively, these studies demonstrate a shift from isolated wearable measurements to integrated chem–phys platforms for longitudinal monitoring. In geriatric populations, hybrid wearables improve interpretability and early detection beyond episodic care.

POTENTIAL OF WEARABLE HYBRID PLATFORMS FOR GERIATRIC CARE

A defining challenge in geriatric medicine is that many age-associated diseases - including neurodegenerative disorders, cardiometabolic dysfunction, and frailty - progress gradually and manifest as coupled changes across physical function, biochemical regulation, and therapeutic response during daily life. Because these transitions unfold continuously outside clinical settings, episodic assessments often fail to capture meaningful dynamics. In the perspective of continuous monitoring, unlike single-modality wearables, hybrid sensors simultaneously measure multiple physiological and biochemical parameters, improving the reliability and predictive accuracy of health assessment.

In conditions, such as Parkinson's disease, the symptom severity fluctuates with medication timing, activity level, stress, and sleep, while disease progression itself is slow and heterogeneous. Wearable hybrid platforms that combine motion sensing, electrophysiology, and biochemical monitoring of therapeutic drugs or stress-related biomarkers can capture these dynamics. By preserving ecological validity and providing high temporal resolution, wearable systems allow clinicians to interpret motor symptoms in the context of concurrent biochemical state rather than relying on sparse clinical snapshots.

The clinical impact of hybrid sensors will depend on their capacity to support personalized and adaptive

care. By linking biochemical indicators with physical signals, hybrid systems can inform closed-loop or semi-closed-loop therapeutic strategies. This is particularly important for older adults, who exhibit altered pharmacokinetics, increased sensitivity to dosing, and multimorbidity that complicates standardized treatment. Hybrid sensing thus offers a pathway toward optimal tailored therapy that balances efficacy and safety.

Translational success depends on long-term wearability, usability, mitigation of biofouling, signal instability^[43], and data security. Modular architectures that allow periodic replacement of chemical components while maintaining long-term physical monitoring address mismatched sensor lifetimes^[44]. To mitigate signal overlap and data confounding in multimodal monitoring, hybrid systems should adopt multi-level data fusion strategies, enabling computational separation of overlapping physiological signatures^[45]. Protecting sensitive biometric information will require secure transmission, edge processing, and privacy-aware frameworks^[46]. Lastly, cost-effectiveness will be a critical determinant for the large-scale adoption of hybrid wearable systems across diverse healthcare settings.

As healthcare shift toward home-centered and preventive models, wearable hybrid sensors are poised to function as a central biological interface between older adults and digital health ecosystems. Integrated with telemedicine platforms and smart home systems, they provide body-level physiological and biochemical ground truth that complements ambient sensing and reduces diagnostic ambiguity. Recent precision health models have illustrated how continuous wearable data, when integrated with telemedicine and smart-home infrastructure, can support individualized risk assessment and proactive care beyond conventional clinic-centered management^[47].

Ultimately, the promise of wearable hybrid sensors in geriatric healthcare lies in seamless integration into daily life. Human-centered design emphasizing unobtrusiveness, intuitive interfaces, minimal maintenance, and energy-efficient operation will be essential for sustained engagement. When coupled with scalable manufacturing and advanced analytics [e.g., AI/machine learning (ML)], hybrid wearable systems offer a foundation for transforming geriatric care from reactive management toward continuous, predictive, and personalized health support. Finally, this work highlights both technological opportunities and the need for large-scale longitudinal validation in multimorbid elderly populations to translate hybrid sensing into clinically meaningful solutions.

DECLARATIONS

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Authors' contributions

Conceptualization: Kim, B.; Ding, S.

Writing - original draft: Kim, B.

Writing - review and editing: Kim, B.; Ding, S.; Wang, J.

Supervision: Ding, S.; Wang, J.

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool ChatGPT (version 5.1, released 2026-11-12) was used for language and graphic editing. The tool did not influence the study design, data collection, analysis,

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Conflicts of interest

Wang, J. is the Advisory Editor Member in the *Soft Science*. Ding, S. is the Guest Editor of the Special Topic “Integrated Wearable Devices for Energy Management and Health Monitoring” in the *Soft Science*. They had no involvement in the review or editorial process of this manuscript, including but not limited to reviewer selection, evaluation, or the final decision, while the other authors have declared that they have no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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