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Wearable Biosensors and Remote Patient Monitoring: Sensing Technologies, Clinical Applications, and Challenges in Digital Health

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ABSTRACT

Health care has long been organized around episodic encounters, a measurement taken in a clinic and then not repeated for weeks or months, yet most of what determines a patient's trajectory happens in the long intervals between visits. Wearable biosensors, worn continuously and non-invasively on the body, promise to close that gap by making physiological and biochemical measurement continuous, and remote patient monitoring (RPM) promises to carry those measurements to clinicians wherever the patient lives. This review surveys the field for an applied-medical-technology audience. We describe the sensing technologies, spanning physical signals such as heart rate, electrocardiography, oxygen saturation, and activity, and the newer biochemical sensing of glucose, lactate, and other markers in sweat and interstitial fluid, and the flexible, stretchable materials that make comfortable skin-worn devices possible. We map the RPM system architecture that connects sensor to clinician through the Internet of Medical Things, cloud computing, and increasingly AI-based analytics, and we review clinical applications across cardiovascular, respiratory, metabolic, renal, gastrointestinal, and wound care. We then take a deliberately balanced view of the evidence, which is genuinely promising in places yet, on the strongest reading, still thin: meta-analyses of randomized trials have often failed to show that monitoring alone changes hard clinical outcomes, and value appears to depend on how monitoring is embedded in care rather than on the device itself. Finally, we examine the barriers that stand between promise and routine practice, sensor accuracy and validation, data quality, privacy and security, interoperability with health records, equity and the digital divide, regulation, and sustained patient adherence, and we argue that these, more than any sensing limitation, now govern the field. The review is narrative and is weighted toward skin-worn devices for chronic-disease monitoring.

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1. Introduction

The dominant model of clinical measurement is episodic. A blood pressure is recorded, a blood sample drawn, a symptom described, and then, typically, nothing further is known until the next appointment. For acute problems this may suffice, but for the chronic diseases that now account for the majority of the world's illness and health spending, cardiovascular disease, diabetes, chronic respiratory and kidney disease, the relevant physiology is continuous and dynamic, and a snapshot taken every few months captures little of it. The consequences are familiar: deterioration that goes undetected until it becomes a crisis, medication effects that are never observed in daily life, and a health system that reacts to events rather than anticipating them.

Wearable biosensors offer a different model. Worn on or near the body and operating non-invasively, they can measure physiological and, increasingly, biochemical parameters continuously and unobtrusively, generating a stream of data about the patient's real life rather than a single reading in an artificial setting. Coupled with remote patient monitoring (RPM), the delivery of those data to clinicians at a distance, they enable a shift from reactive, encounter-based care toward proactive, continuous, and personalized care (Xu, Kim, Walter, Ghaffari, & Rogers, 2022). The enabling technologies have matured rapidly and in parallel: advances in flexible electronics and sensing materials, in low-power connectivity and the Internet of Medical Things, and in the machine-learning methods needed to make sense of continuous signals have together moved wearables from consumer novelties toward instruments of medicine (Tandel, Kumari, Tanwar, Singh, Sharma, & Yamsani, 2024).

The scale of the opportunity is considerable and growing. Populations are ageing, the burden of chronic disease is rising, and health systems in rich and poor countries alike face widening gaps between the demand for care and the workforce available to provide it. A technology that can monitor patients continuously and at a distance speaks directly to each of these pressures, promising earlier detection, fewer avoidable admissions, and care that reaches beyond the walls of the clinic to the home and the community. The market for wearable health devices has expanded accordingly, and the devices themselves have crossed an important threshold, from step-counting consumer gadgets toward instruments capable of clinically meaningful measurement. Whether that capability translates into better health, however, is a separate question, and one this review takes seriously rather than assuming.

This review provides an integrated account of wearable biosensors and remote monitoring for readers concerned with applied technology in the medical sciences. We pursue four questions. What can wearable biosensors measure, and how? How are those measurements delivered and used in clinical care? What does the evidence say about whether they improve outcomes? And what obstacles keep their impact uneven and their promise partly unrealized? In answering, we draw deliberately on the field's multidisciplinary character, which spans biomedical engineering and materials science, information technology and data science, clinical medicine, public health, and the social and environmental sciences that shape how such technologies are actually used, and we note the growing engagement of clinical communities worldwide, including in the Gulf, with AI-supported diagnosis and monitoring (Sulthan et al., 2025).

2. Scope and Method

This is a narrative review supported by a structured search of the biomedical, engineering, and digital-health literature. We drew on recent systematic reviews, meta-analyses, scoping reviews, and primary studies, prioritizing high-quality syntheses of clinical outcomes alongside landmark and current work on sensing technology, and we supplemented database searching with citation tracing. The review is organized from the device outward: from what wearables sense and how they are built, through the system that connects them to care and the clinical domains they serve, to the evidence on outcomes and the barriers to adoption. We concentrate on skin-worn and body-worn devices used for the monitoring of chronic disease, where the literature is deepest, while noting adjacent developments. The account is interpretive rather than exhaustive, and it is intended to convey the balance of the field's promise and its problems.

3. Sensing Technologies and System Architecture

At the heart of a wearable is a sensor, and the range of what sensors can now measure has broadened markedly. The most mature devices track physical and physiological signals, heart rate and electrocardiography, blood oxygen saturation, respiration, temperature, blood pressure, and movement, from which activity, gait, and sleep can be derived. A newer and rapidly advancing class measures biochemical and molecular markers, detecting analytes such as glucose, lactate, electrolytes, and hormones in accessible biofluids like sweat and interstitial fluid, bringing laboratory measurement to the skin surface (Vo

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& Trinh, 2025). Figure 2 organizes these two families of sensing.

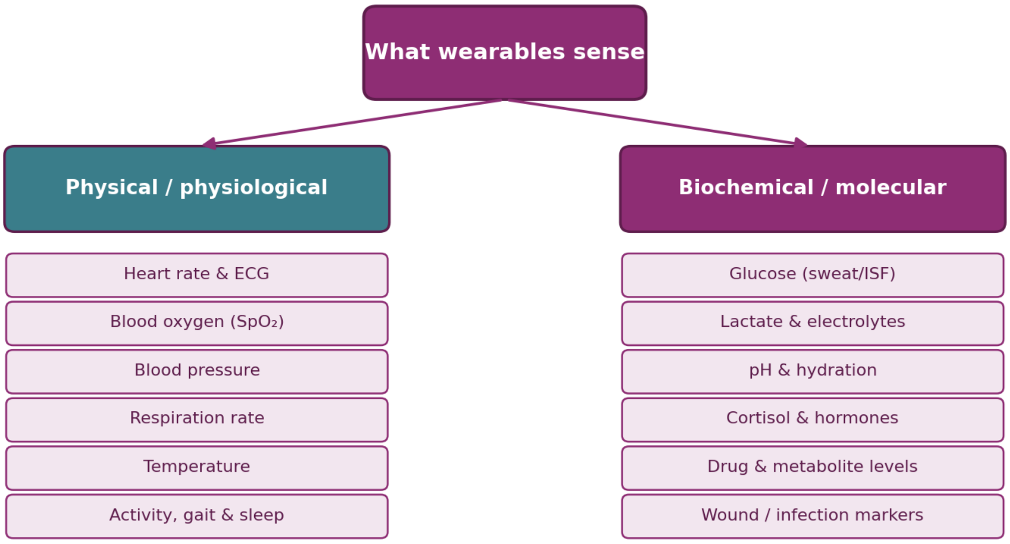

Figure 2. The two principal families of wearable sensing: physical/physiological signals and biochemical/molecular markers.

What has made continuous, comfortable measurement possible is progress in materials. Flexible and stretchable electronics conform to the skin and move with the body, and advances in nanomaterials and electrochemistry have produced sensors that are sensitive, selective, and robust to the mechanical deformation of daily wear. Non-enzymatic electrochemical glucose sensors built on engineered nanomaterials, for example, can track sweat glucose continuously and follow the trends seen in blood, pointing toward non-invasive alternatives to fingerstick testing (Li et al., 2023; Shu et al., 2021). Self-powered and energy-harvesting designs further reduce the reliance on batteries that limits real-world use (Vo & Trinh, 2025). Table 1 summarizes the principal sensing modalities.

Form factor and power are quiet but decisive determinants of whether a device is actually used. The field has moved from rigid wrist-worn units toward skin-conformal epidermal patches, microfluidic devices that sample and route sweat, e-textiles woven into clothing, and, at the frontier, minimally invasive microneedle and ingestible sensors that reach analytes the skin cannot. Each form factor trades comfort, signal quality, and invasiveness differently, and the right choice depends on the clinical question rather than on novelty. Power is the constraint that shadows all of them: continuous sensing and transmission are energy-hungry, and the batteries that supply them add bulk and demand recharging that erodes adherence, which is why energy-harvesting and self-powered designs that draw on body heat, motion, or biofluids are more than an engineering curiosity, they are part of what will make continuous monitoring sustainable in real life (Vo & Trinh, 2025).

A sensor, however, is only the first element of a system. Remote monitoring depends on an architecture that carries data from the body to the clinician and back, shown in Figure 1: body-worn sensors transmit to a gateway, typically a smartphone, over the Internet of Medical Things; data flow to cloud infrastructure where they are stored and analysed, increasingly by AI models that filter noise and flag clinically meaningful events; and the resulting insight reaches clinicians and electronic health records, closing the loop with feedback and intervention to the patient (Huang, Chen, & Liao, 2025). The value of the whole depends on every link of this chain, a theme we return to when we consider the barriers to adoption.

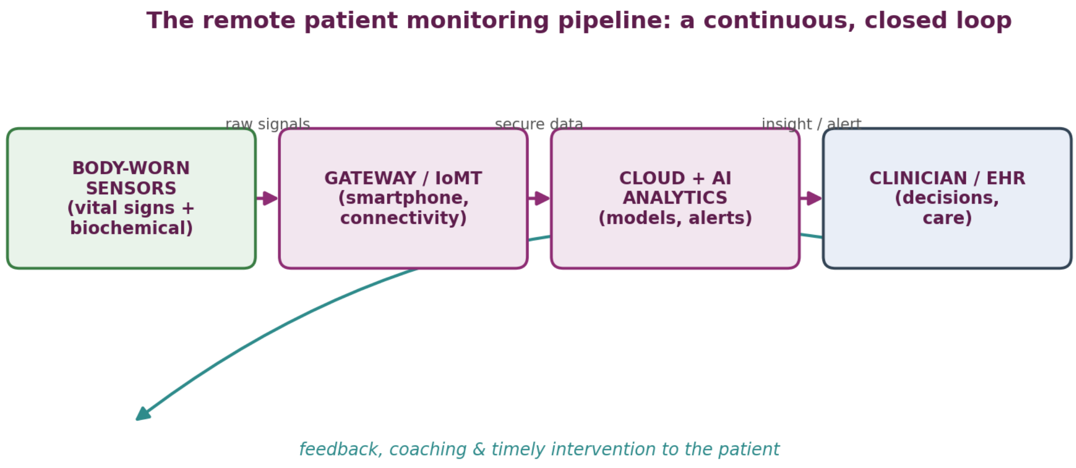

Figure 1. The remote patient monitoring pipeline as a continuous closed loop, from body-worn sensors through connectivity and analytics to the clinician and back to the patient.

Table 1. Principal wearable sensing modalities and their targets.

Modality	Example parameters	Typical method
Cardiac / vascular	Heart rate, ECG, blood pressure.	PPG, electrodes, oscillometry.
Respiratory / oxygenation	SpO_2, respiration rate.	Pulse oximetry, impedance.
Metabolic / biochemical	Glucose, lactate, electrolytes.	Electrochemical sweat/ISF sensing.
Thermal	Skin/body temperature.	Thermistors, infrared.
Motion / functional	Activity, gait, sleep, falls.	Inertial measurement units.
Wound / tissue	pH, moisture, infection markers.	Colorimetric / electrochemical patches.

4. Clinical Applications

Wearable monitoring has been applied across most of medicine, and its natural home is the management of chronic disease, where continuous data most clearly improve on episodic assessment. In cardiovascular care, wearables support arrhythmia detection, blood-pressure tracking, and the remote delivery of cardiac rehabilitation, which studies suggest can match centre-based programmes while reaching patients who would otherwise be excluded (Bola et al., 2025). In respiratory disease, continuous monitoring of activity and physiological signals can detect exacerbations early and support remote pulmonary rehabilitation across conditions from chronic obstructive pulmonary disease to cystic fibrosis (Armstrong, 2026). In metabolic disease, continuous glucose monitoring has already changed the management of diabetes, and sweat-based sensing points toward fully non-invasive successors (Li et al., 2023).

The reach extends further. In nephrology, digital platforms integrating wearable data support the early detection and remote management of chronic kidney disease (Deng, Xue, & Methakanjanasak, 2025). In gastroenterology, wearables and companion applications are being used to monitor symptoms and reduce hospitalizations in inflammatory and motility disorders (Reddy & Chawla, 2025). And in wound care, biosensor patches that track pH, temperature, and infection markers enable the real-time surveillance of healing and, in closed-loop designs, can even trigger therapy (Vo & Trinh, 2025). Table 2 maps the principal application domains and the evidence supporting them.

A further and rapidly growing domain is neurological disease and rehabilitation, where the continuous, objective measurement of movement that wearables provide is particularly valuable. Inertial sensors and smartwatches can quantify gait, tremor, and mobility in conditions such as Parkinson's disease, stroke, and

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multiple sclerosis, and machine-learning models applied to these signals have reported high accuracy for tasks such as fall-risk and mobility-decline prediction, supporting both rehabilitation and the early detection of deterioration (Gu, Kim, Kim, & Yoo, 2026). Because so much of neurological status is expressed through movement that a clinic visit captures only briefly and artificially, continuous monitoring in the patient's own environment offers a genuinely richer picture, and this domain is among those where the case for wearables is strongest.

Table 2. Clinical application domains of wearable monitoring and supporting evidence.

Domain	Representative use	Evidence
Cardiovascular	Arrhythmia detection; remote cardiac rehabilitation.	Bola et al. (2025)
Respiratory	Exacerbation prediction; remote rehabilitation.	Armstrong (2026)
Metabolic / diabetes	Continuous & non-invasive glucose monitoring.	Li et al. (2023); Shu et al. (2021)
Renal	Early detection and remote CKD management.	Deng et al. (2025)
Gastrointestinal	Symptom monitoring; reduced hospitalization.	Reddy & Chawla (2025)
Wound / infection	Real-time healing and infection surveillance.	Vo & Trinh (2025)

5. The Evidence on Clinical Outcomes

Enthusiasm for wearables should be measured against the evidence that they improve outcomes, and here honesty requires nuance. The technology's potential is not in doubt, but demonstrating that continuous monitoring changes hard clinical endpoints has proved surprisingly difficult. An influential meta-analysis of randomized trials of remote monitoring with wearable biosensors found no statistically significant effect on any of six clinical outcomes, from blood pressure to body mass index, and noted that studies were highly heterogeneous and that the interventions that did work were those built on behaviour-change models and personalized coaching rather than on the device alone (Noah et al., 2018). More recent scoping and systematic reviews reach a similar verdict: the field is expanding rapidly, but rigorous evidence of clinical effectiveness remains scant, randomized trials are few, and heterogeneity across devices, diseases, and protocols makes synthesis difficult (Lodewyk et al., 2025; Gu, Kim, Kim, & Yoo, 2026).

This does not mean wearables do not work; it means that the device is necessary but not sufficient. Earlier systematic reviews of non-invasive remote monitoring found predominantly positive results across chronic conditions, but with small samples and short follow-up that limit confidence (Vegesna, Tran, Angelaccio, & Arcona, 2017). The emerging lesson is that value is created not by measurement in itself but by the system around it, the analytics that turn raw signals into meaningful alerts, the clinical pathways that act on those alerts, and the behavioural support that keeps patients engaged. A useful way to frame the analytics is through diagnostic performance: a monitoring algorithm that flags a deterioration is judged, like any test, by its sensitivity and specificity and summarized by the area under the receiver operating characteristic curve,

$$\text{AUROC} = P(\text{ score(case)} > \text{score(control)}),$$

the probability that the algorithm ranks a true event above a non-event, with values approaching one indicating strong discrimination; wearable-plus-machine-learning systems have reported high AUROCs for tasks such as fall and mobility-decline prediction (Gu et al., 2026). Yet a discriminating alert is clinically useful only if it is acted upon and only if patients wear the device consistently, which introduces a second, humbler metric, data yield or adherence, the fraction of expected readings actually captured,

$$\text{Yield} = \text{(observed readings)} / \text{(expected readings)},$$

a quantity that real-world studies too often leave unreported and that frequently falls well below what efficacy would require. The honest summary is that wearables have demonstrated remarkable technical capability and real promise, but that translating that promise into reliable improvements in outcomes depends

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on integration, engagement, and evidence that the field is still assembling.

6. Enabling Analytics: AI and the Internet of Medical Things

If sensing generates the data, it is analytics that create the value, and artificial intelligence has become central to the field. Continuous multimodal streams from wearables are too voluminous and too noisy for manual interpretation, and machine-learning models are increasingly used to denoise signals, extract features, detect anomalies, classify activity and physiological states, and predict clinical events before they occur (Huang et al., 2025). Integrated with the Internet of Medical Things, these methods underpin what has been called a digital healthcare Industry 5.0, in which connected wearables and AI analytics deliver continuous, personalized, and proactive care (Tandel et al., 2024). This analytical layer is also where wearables connect to the broader movement toward AI-supported medicine, from precision diagnosis to the mining of multi-omic and physiological data for individualized management (Sulthan et al., 2025; Alshamsi & Alhammadi, 2025). The dependence on AI, however, imports AI's own challenges, of data quality, bias, interpretability, and validation, which we consider next.

Two architectural choices increasingly shape how well this analytical layer performs in practice. The first is where computation happens. Running models at the edge, on the device or the nearby gateway rather than only in the cloud, reduces latency for time-critical alerts, lessens dependence on continuous connectivity that cannot be assumed everywhere, and keeps sensitive data closer to the patient, though it constrains the size of model that can be deployed. The second is how models are trained without pooling raw data: privacy-preserving approaches such as federated learning let models learn across many patients and sites while the underlying records stay local, which is attractive both for privacy and for building models that generalize across diverse populations rather than reflecting a single hospital's case mix (Huang et al., 2025). These are not merely technical refinements; they bear directly on the trust, equity, and real-world reliability on which adoption ultimately depends.

It is also worth being clear that analytics can introduce harm as well as value. A model that alarms too readily produces alert fatigue and erodes clinicians' trust, while one tuned too conservatively misses the events it was meant to catch; the balance between sensitivity and specificity is therefore a clinical decision, not a purely technical one, and it should be set with the consequences of each kind of error in view. Bias is a related danger: a model trained mostly on one population may perform worse on others, quietly widening disparities under the appearance of objectivity. These considerations return the argument to a theme that runs through this review, that the intelligence in a monitoring system is only as trustworthy as the data, validation, and human judgement surrounding it.

7. Challenges to Adoption

The barriers that keep wearable monitoring from routine clinical use are now largely not sensing problems but system, evidence, and governance problems. The first is accuracy and validation: consumer-grade convenience is not the same as clinical-grade reliability, and many devices have not been validated against clinical standards across the diverse populations and conditions in which they are used (Xu et al., 2022). The second is data quality and interpretation: continuous streams are noisy and artefact-prone, and distinguishing signal from noise, and meaningful change from normal variation, is non-trivial. The third is privacy and security: continuous, intimate health data create serious risks if intercepted or misused, and trust depends on protecting them (Huang et al., 2025).

Further barriers are organizational and social. Interoperability with electronic health records and clinical workflows is frequently poor, so that data collected are not easily acted upon (Deng et al., 2025). Equity is a growing concern: without deliberate attention, wearables may widen rather than narrow health disparities, benefiting the connected and affluent while bypassing the older, poorer, and less digitally literate populations who often have the greatest need, a concern that is especially acute in low-resource settings (Armstrong, 2026). Regulation is still maturing, and the pathway by which a monitoring device or algorithm earns clinical trust is not fully settled. And underlying all of these is adherence: the most sophisticated device is worthless if it is left in a drawer, and sustaining engagement over months and years remains one of the field's hardest problems. Table 3 summarizes these challenges and the field's responses.

Table 3. Barriers to wearable and RPM adoption and emerging responses.

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Barrier	Why it matters	Emerging response
Accuracy & validation	Consumer grade ≠ clinical grade.	Clinical validation studies; medical-grade devices.
Data quality & interpretation	Noisy streams obscure meaningful change.	AI denoising; robust signal processing.
Privacy & security	Intimate continuous data at risk.	Encryption; security-by-design; governance.
Interoperability	Data not integrated into care.	Standards; EHR integration.
Equity & digital divide	May widen disparities.	Inclusive design; access programs.
Regulation & adherence	Trust pathways unsettled; engagement fades.	Regulatory frameworks; behavioural support.

8. Discussion

Read as a whole, the field presents a characteristic pattern of an emerging medical technology: extraordinary and genuine technical progress running ahead of the evidence and the systems needed to convert it into better health. The sensing capabilities are real and advancing quickly, from clinical-grade vital-sign measurement to the once-improbable prospect of non-invasive biochemical monitoring, and the analytical tools to interpret continuous data have matured in step. What has not kept pace is the demonstration, in rigorous trials, that continuous monitoring reliably improves the outcomes that matter, and the building of the clinical, regulatory, and social infrastructure through which it could. The honest reading of the evidence is therefore neither the uncritical enthusiasm of the technology's promoters nor dismissal, but recognition that the decisive work now lies less in the sensor than in the system.

Three implications follow. First, because value depends on integration rather than measurement alone, the highest-leverage investments are in clinical pathways, analytics, and behavioural support that turn data into action, and in the rigorous trials that will show which configurations work. Second, the field's multidisciplinary character is not incidental but essential: realizing the promise of wearables requires engineers and materials scientists, data and information-technology specialists, clinicians and public-health researchers, and the social and environmental scientists who understand how technologies are adopted and how they interact with the conditions of people's lives. Third, equity must be designed in rather than hoped for, so that a technology capable of extending care to the remote and underserved does not instead deepen the divide; the growing engagement of research and clinical communities across regions, including the Gulf and the wider Global South, with digital and AI-supported monitoring is an encouraging sign that the conversation is broadening (Sulthan et al., 2025; Alshamsi & Alhammadi, 2025).

Looking ahead, several developments are likely to define the field's next phase. The integration of multiple sensing modalities, physical and biochemical, into a single coherent picture of the patient promises richer and more specific inference than any one signal allows, and the notion of the digital biomarker, a validated, sensor-derived measure that stands in a defined relationship to a clinical state, offers a path to the kind of rigorously characterized endpoints that regulators and clinicians can trust. Combining continuous physiological data with genomic, clinical, and environmental information points toward a genuinely personalized and predictive medicine, in which a deterioration is anticipated from the convergence of many weak signals rather than detected from one strong one. None of this is guaranteed, and each step raises the same questions of validation, privacy, and equity that the present raises; but the direction of travel is toward monitoring that is more continuous, more integrated, and more deeply woven into care.

A realistic timeline matters here. The history of digital health is littered with technologies that were declared transformative before the evidence and the systems were ready, and wearables risk the same fate if promise is mistaken for proof. The more durable path is incremental: to establish, condition by condition and pathway by pathway, where continuous monitoring genuinely changes outcomes, to build the analytics and clinical workflows that act on the data, and to accumulate the trial evidence that justifies scale. Progress of this kind is less dramatic than the rhetoric of revolution, but it is what turns a promising technology into standard care, and it is the work to which the field should now principally address itself.

It is worth adding a word on an often-neglected dimension that this review's authorship is well placed to

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raise: the environmental and social footprint of continuous monitoring at scale. Billions of connected sensors imply energy consumption, electronic waste, and the manufacture of devices from materials whose supply and disposal carry environmental costs, and a technology promoted partly on grounds of sustainability in health-system terms should be honest about its own. Equally, the meaning that patients attach to being continuously monitored, the sense of reassurance for some and of surveillance or burden for others, shapes whether devices are worn and trusted, and it varies across cultures and communities in ways that engineering alone cannot anticipate. Attending to these environmental and human dimensions is not peripheral to the technology's success but part of designing it responsibly, and it is one reason the field benefits from the breadth of disciplines, from environmental science to the humanities, that now engage with it.

Table 4. Priority actions for realising the value of wearable monitoring, by stakeholder.

Stakeholder	Near-term action	Longer-term action
Device developers	Validate against clinical standards; design for comfort and adherence.	Build energy-efficient, sustainable, medical-grade devices.
Health systems	Integrate wearable data into EHRs and clinical pathways.	Embed monitoring in care models with acting-on-alert protocols.
Researchers	Run rigorous RCTs reporting adherence and real-world yield.	Standardise outcomes and analytics for comparability.
Regulators	Clarify validation and approval pathways for devices and algorithms.	Set data-privacy, security, and interoperability standards.
Policymakers	Fund access programs to prevent a digital divide.	Ensure equitable deployment, including in low-resource settings.

9. Limitations

This review has limitations. As a narrative synthesis it represents the principal themes and influential works rather than an exhaustive census, and its selection reflects judgement. It is weighted toward skin-worn devices for chronic-disease monitoring, so its conclusions transfer less securely to implantable, ingestible, or ambient sensing and to acute and inpatient settings. The evidence base is heterogeneous and fast-moving, with relatively few large randomized trials and inconsistent reporting of adherence and real-world performance, which limits the strength of any synthesis. Much of the outcome evidence also comes from high-income settings, so its generalizability to the low-resource environments where remote monitoring might matter most is uncertain. These constraints temper the confidence of specific claims without unsettling the review's central conclusions.

10. Conclusion

Wearable biosensors and remote patient monitoring embody a compelling vision: to replace the episodic snapshot with a continuous picture of health, and to carry care from the clinic into the patient's daily life. The sensing technologies that make this possible have advanced remarkably, spanning physical and, increasingly, biochemical measurement built on flexible materials and connected through the Internet of Medical Things and AI analytics, and their clinical applications now reach across most of chronic-disease medicine. Yet the field's central lesson is one of proportion: the device is necessary but not sufficient, and the evidence that continuous monitoring improves hard outcomes remains, on the strongest reading, still to be firmly established. The barriers that matter now, accuracy and validation, data quality, privacy, interoperability, equity, regulation, and adherence, are barriers of system and evidence rather than of sensing. The task ahead is to build the clinical pathways, the rigorous trials, and the inclusive design through which the genuine promise of wearable monitoring can be turned into reliable, equitable improvements in health.

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