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Dolna 17, Warsaw,
Poland 00-773
+48 226 0 227 03
editorial_office@rsglobal.pl

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WEARABLE HEALTH TECHNOLOGIES IN CHRONIC DISEASE MANAGEMENT: CURRENT APPLICATIONS, BARRIERS, AND FUTURE PERSPECTIVES

Mateusz Mierniczek *(Corresponding Author, Email: mateusz.mierniczek19@gmail.com)*
St. Raphael's Voivodeship Specialist Hospital in Czerwona Góra, Chęciny, Poland
ORCID ID: 0009-0009-9571-7859

Maria Mierniczek
St. Raphael's Voivodeship Specialist Hospital in Czerwona Góra, Chęciny, Poland
ORCID ID: 0009-0000-9108-1552

Aleksandra Mierniczek
MSWiA Hospital in Gdańsk, Gdańsk, Poland
ORCID ID: 0009-0003-5596-2135

Kinga Kaczmarska
Provincial Integrated Hospital, Kielce, Poland
ORCID ID: 0009-0001-2468-430X

Kinga Rosołowska
St. Raphael's Voivodeship Specialist Hospital in Czerwona Góra, Chęciny, Poland
ORCID ID: 0009-0003-7992-060X

Jarosław Dudek
St. Raphael's Voivodeship Specialist Hospital in Czerwona Góra, Chęciny, Poland
ORCID ID: 0009-0005-1273-5682

ABSTRACT

Wearable technologies are driving a paradigm shift in chronic disease management from clinics to patients 'everyday environments. Their applications are diverse: early arrhythmia detection in cardiology, optimal glycemic control in diabetology, remote monitoring in pulmonology, and opening new paradigms for objective assessment in neurology and medication adherence. This constant stream of data drives proactive, personalized & data-driven healthcare.
Many of those advances are still limiting widespread clinical integration. Technical challenges regarding data validation and algorithmic transparency remain, alongside complex ethical questions about data privacy and the risk of algorithmic bias. Also, unresolved economic issues like reimbursement models threaten to increase health inequalities The future of digital health will depend on integrating wearable data with artificial intelligence. It will unlock predictive analytics to forecast disease exacerbations and enable the development of reliable digital biomarkers within the vision of P4 medicine - predictive, preventive, personalized, and participatory.
This narrative review critically summarizes the available data, identifies these ethical and practical obstacles, and suggests ways to safely, successfully, and fairly incorporate wearable technology into standard medical procedures.

KEYWORDS

Wearable Devices, Chronic Disease Management, Digital Health, Artificial Intelligence, Digital Biomarkers, Remote Patient Monitoring

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Introduction

Wearable devices have quickly changed how doctors manage long-term illnesses. Patients no longer need to visit clinics for checks; instead, small devices worn on the body track signs day and night, putting the patient at the center of care [1-6]. Biosensors and other health monitors not only warn of problems early, allowing doctors to tailor treatment, but also monitor diseases for years. In cardiology, patients use these tools to detect atrial fibrillation and record their heart rhythm [7-12]. People with diabetes wear continuous glucose monitors that continuously display glucose levels, helping them adjust their diet or insulin intake independently [13-15]. Pulmonology and rehabilitation programs similarly benefit from remote monitoring of respiratory function and physical activity [16-19]. Devices also help track Parkinson's tremors and remind people to take drugs on time [20-24].

Despite these advances, widespread clinical integration is impeded by significant barriers, ranging from technical challenges like data accuracy and validation to complex ethical, privacy, regulatory, and economic concerns [25-30]. To address these challenges and unlock future potential, advances in biosensor design [31] are providing the high-quality data needed to fuel sophisticated AI-driven predictive models [32] that are upending traditional approaches to technology adoption [33]. They include advanced models such as the "Digital Twin" and require seamless integration of health data to develop the next generation of reliable digital biomarkers [34-36]. The entire technological trajectory corresponds to the overall predictive, preventive, personalized, and participatory vision of P4 medicine [37]. Nevertheless, this promise is tempered by the substantial evidence-to-practice gap, and its ultimate success is dependent on building trustworthy and ethical AI, an issue highlighted by issues like algorithmic bias [38-40]. And this vision is contextualized within global strategies for digital health and the need for global health equity [41-42]. This narrative review synthesizes current evidence, assesses practical and ethical barriers, and projects future directions for safe, effective, and equitable adoption of wearable technologies in chronic disease management.

Methodology

This paper is based on a narrative review of the scientific literature examining the role of wearable technologies in chronic disease management. A comprehensive search was conducted in the PubMed, Scopus, and IEEE Xplore databases to identify relevant publications from January 2010 to October 2025. This timeframe was selected to capture the evolution of modern wearable devices - from their early development to their current clinical and analytical applications.

The search strategy employed combinations of the following keywords: *"wearable devices," "chronic disease management," "digital health," "artificial intelligence," "digital biomarkers,"* and *"remote patient monitoring."*

This review synthesizes findings from peer-reviewed literature, emphasizing conceptual frameworks, large-scale clinical investigations, and systematic reviews published in high-impact journals. The analysis is organized to provide a comprehensive overview of clinical applications, a critical appraisal of technical, ethical, and regulatory barriers, and an exploration of future directions for the integration of wearable technologies into evidence-based healthcare practice.

Results and Discussion

The Theoretical Foundations of Wearable Health Technologies

Wearable technologies are rewriting the rules of healthcare. This represents a paradigm shift in global health systems, with accompanying market growth from early predictions of USD 30 billion to over USD 61 billion by 2022 [1,2]. With this financial explosion comes an explosion of personal health data, ending the reactive, clinic-bound model of care. It is now a continuous shift that aims at integrating health monitoring into everyday routines, an important transition given that chronic diseases account for more than 70% of all

deaths worldwide [2]. This evolution reflects a broader redefinition of care delivery models to meet evolving global chronic disease burdens.

At the core of this transformation is the power of continuous monitoring. Instead of relying on isolated snapshots of health taken during infrequent clinical visits, these technologies offer a continuous film, capturing the subtle fluctuations of chronic conditions as they happen [4]. The academic interest in this area has been explosive, with recent scoping reviews routinely analyzing dozens, and in some cases over a hundred, individual studies to map the evidence [3, 4, 5]. This rich, longitudinal data provides a context that is impossible to replicate in a sterile clinical environment. In effect, the center of healthcare is relocated from the hospital to the home, arming clinicians with a far deeper and more nuanced understanding of an individual's health trajectory.

Continuous data collection directly supports patient self-management and empowerment [2, 3]. Wearable devices function as biofeedback loops, making invisible physiological processes visible and actionable. For someone living with a chronic illness, this leads to heightened feelings of awareness and control. Seeing how their diet, activity, or stress affects health metrics makes people active co-pilots in their own health journey and empowers to make informed daily choices.

But a central paradox defines the current landscape. Their tremendous promise - flagging a dangerous health event hours before it becomes critical - or fine-tuning a treatment plan in real time - is constrained by equally large barriers. [1]. Such hurdles include: how to distinguish meaningful signals from noise in raw data; creating a digital health divide; handling data privacy; and the psychological burden of constant self-monitoring.

These trends suggest a future in which digital tools become standard medical practice [6]. The technology should become a functionally invisible standard part of a healthcare system built on prediction and prevention. This fundamental transition from addressing illness in clinics to managing health in life demands appreciation of the clinical applications, technical challenges and ethical questions raised in this review.

Applications of Wearable Technologies in Cardiology

In cardiology, wearable technology has already demonstrated profound and immediate clinical impact. With consumer-grade smartwatches and heart monitors equipped mainly with photoplethysmography (PPG) sensors, arrhythmia screening has been transformed from a specialized clinical tool to a mass-market phenomenon. This is a critical development because it addresses a fundamental limitation of traditional diagnostics: the challenge of capturing paroxysmal and often asymptomatic atrial fibrillation (AF). Unlike a 24- or 48-hour Holter monitor, which provides only a brief observational window, continuous wrist-based monitoring can identify sporadic events over weeks or months. Algorithms behind these devices have been validated: one large study reported 93.7% sensitivity and 99.6% specificity when compared with simultaneous ECG patch recordings [7]. Its accuracy was demonstrated in this study and was the turning point towards a reliable, large-scale screening device..

Its real-world utility was demonstrated at the population scale in the Apple Heart Study involving over 400,000 participants in a completely remote trial. Here we describe an example of modern digital research: enrollment via a smartphone app and a novel workflow in which participants with irregular pulse notifications are asked to undergo a telemedicine consultation and mail an ECG patch for confirmation. The results were compelling: The positive predictive value for detecting AF was 84% for all participants who received notification and wore the patch. Hence, such large-scale screening demonstrated the feasibility and showed that AF could be identified early in the course of stroke risk reduction.

But this torrent of data is also a sword that requires a critical interpretation of its clinical utility. These landmark studies have a major limitation in generalizability because they recruited younger, healthier, and more technologically literate participants than the typical cardiology patient, who is often older and has multiple comorbidities [8]. Their performance has not been rigorously validated in these more complex "noisier" patient populations. False positives also strain healthcare systems. A very specific algorithm will produce many false alerts in a low-prevalence population, resulting in unnecessary patient anxiety, avoidable primary care visits, and expensive specialist consultations - this is sometimes called the "worried well" trumping the truly sick. That demonstrates a crucial difference: such devices can be useful screening tools, not diagnostic instruments. Because of those results, major clinical bodies like the European Society of Cardiology have issued specific guidance. It is written that a notification from a wearable device is only a starting point, meaning that a formal diagnosis of AF requires confirmation with a standard 12-lead ECG before making any therapeutic decisions [9].

Beyond atrial fibrillation, the rich data stream from wearables paints a picture of cardiovascular health. Key to this is continuous monitoring of heart rate variability (HRV) which is now considered a fundamental biomarker of autonomic nervous system function in many medical specialties [10]. HRV quantifies variation in time between consecutive heartbeats and is thus an excellent, non-invasive proxy for sympathetic versus parasympathetic activity. Chronically low HRV is an established marker of poor prognosis in cardiology and represents autonomic dysfunction typical of heart failure. Longitudinal HRV tracking gives clinicians a sensitive tool to monitor disease progression and therapy response [10].

In addition, wearable cardiology is rapidly moving towards what many would term its "holy grail": blood pressure monitoring - accurate, continuous, and cuffless. The most common cardiovascular disease is hypertension, which is asymptomatic and controlled only with frequent measurements. A major step forward here is the development of novel algorithms that use the PPG signal together with its second derivative, analyzed using advanced semiclassical signal analysis techniques. That approach has produced excellent precision, with mean absolute errors of 5.37 mmHg for systolic and 2.96 mmHg for diastolic pressure. With this level of accuracy, we meet or exceed the requirements of the AAMI and have received a grade A from the British Hypertension Society [11].

In cardiology, wearables are ultimately moving beyond event detection towards prediction and prevention. With many continuous data streams such as HRV, activity patterns, sleep quality, and blood pressure trends, you can build your own "digital phenotype." Using this rich multimodal dataset and applying artificial intelligence and machine learning models can yield personalized algorithms that predict adverse cardiovascular events, such as heart failure decompensation, days before they occur [12]. This is their ultimate promise: All to change the whole model of cardiovascular medicine from a reactive "find and fix" model to a predictive "predict and prevent" era of personalized care. Future research on wearable cardiology must be validated in older, multi-morbid populations, and continuous data streams must be incorporated into electronic health records and clinical workflows to enable timely medical decisions and not just as an observational tool. In summary, wearable technologies allow continuous rhythm monitoring at large scales and earlier detection of atrial fibrillation. Validation studies show good diagnostic sensitivity, but few clinical benefits in older or multimorbid populations. Efforts to integrate wearable data into clinical systems and develop transparent AI models for adverse cardiac events will determine future progress.

The Shift to Dynamic Monitoring in Diabetology

And behind all of this is diabetology - not cardiology - which has been profoundly changed by wearable technology. Diabetes management has traditionally relied on two main data points: capillary finger-prick testing and glycated hemoglobin (HbA1c), along with intermittent self-monitoring of blood glucose. HbA1c provides a three-month average of glycemic control but is fundamentally unsuited to capturing glycemic variability - the dangerous daily fluctuations between hyperglycemia and hypoglycemia that cause acute and chronic complications. Two identical "good" HbA1c values may have very different glycemic profiles: One has stable control, and the other has dangerous highs and lows.

Fortunately, continuous glucose monitoring (CGM) systems have replaced static snapshots with a continuous, high-resolution data stream. But for many years, this information was not standardized in its interpretive framework. True clinical utility of CGM came when internationally accepted actionable metrics were established. A key 2019 international consensus report established TIR as the central parameter for glycemic control [13].

This consensus set the optimal glucose range for most patients at 70 to 180 mg / dL (3.9 to 10.0 mmol / L) and defined therapeutic targets:

Time in Range (TIR): More than 70% of readings are within target range.

Time below range (TBR 70 mg/dL): <4% of readings.

Time above range (TAR > 180 mg/dL): <25% of readings.

Clinical impact of this standardization is immense. They stopped using a single retrospective average and instead used a dynamic and actionable percentage to enable clinicians and patients to make timely data-driven treatment decisions. Meta-analysis supports this change. HbA1c and quality of life were also significantly improved with the use of continuous glucose monitoring (CGM) in Type 1 diabetes, with reduced fear of hypoglycemia [14]. But this lower anxiety has more than a psychological benefit - it also leads to better adherence, fewer severe hypoglycemic events, and better long-term outcomes. For Type 2 diabetes patients, real-time CGM feedback is a motivator - data becomes action. Systematic reviews confirm that this feedback increases patient self-efficacy and engagement by illustrating the immediate physiological consequences of

diet, exercise and medication adherence. That, in turn, promotes long-term lifestyle changes and lowers daily psychological distress associated with diabetes self-management [15].

However, despite these well-documented clinical and psychosocial benefits, the real-world impact of CGM remains constrained by persistent structural and sociotechnical barriers. Chief among them are the high out-of-pocket costs of sensors and transmitters, inconsistent reimbursement policies, and limited insurance coverage, all of which perpetuate a two-tiered healthcare landscape in which access to transformative technologies remains largely restricted to affluent or privately insured populations. And this financial inequity risks widening existing health gaps rather than reducing them. Also important are usability and accessibility issues. Many patients - older adults or those with low digital literacy - find the operation requirements of CGM systems daunting. Tasks like pairing sensors with smartphones, devices, calibrating, navigating through applications / reading data-rich graphical outputs lead to frustration and disengagement. These usability barriers often lead to technology abandonment, and patients fail to take full advantage of CGM's clinical benefits [22,27].

Emerging initiatives to simplify device interfaces, feed CGM data directly into electronic health records, and expand public insurance reimbursement promise to democratize access. But they remain unevenly applied and fragmented within health systems. To address these inequities, CGM and the broader revolution in wearable diabetology must succeed: providing personalized, proactive, and psychologically supportive diabetes care to all patients—regardless of socioeconomic status or digital fluency. Continuous glucose monitoring has changed diabetes management from static retrospective control to real-time data-driven care. CGM improves glycemic control, patient confidence, and treatment adherence, but access is limited by high costs, low reimbursement, and usability issues for many patients. Fair coverage, simplified device interfaces, and full glucose data integration into clinical workflows should be future goals.

Emerging Applications in Pulmonology and Rehabilitation

Given the prevalence of chronic respiratory diseases worldwide, wearable technology for pulmonology is one of the most exciting and rapidly expanding areas of digital medicine. Chronic Obstructive Pulmonary Disease is the third most common cause of death globally in terms of morbidity, mortality, and healthcare costs. The Global Initiative for Chronic Obstructive Lung Disease (GOLD) bases its strategy on acute exacerbations [16]. Unlike cardiology, where arrhythmia detection can be performed with simple electrical measurements, the "gold standard" of lung function - spirometry - can not be easily or passively measured. Thus far in this domain, wearable research has split along two major directions: Physical activity as a long-term health proxy, and advanced, sensor-based systems for early detection and prediction of exacerbations.

The first strategy capitalizes on consumer-grade wearables, such as smartwatches and accelerometer-equipped fitness trackers, as practical tools within pulmonary rehabilitation. Physical activity levels are among the strongest independent predictors of exacerbation frequency, hospital readmission, and mortality in patients with COPD. And now these high-quality systematic reviews and meta-analyses support that notion. A study, which was published in the National Journal of Digital Medicine found that interventions with wearable devices were associated with statistically significant increases in daily physical activity (SMD = 0.44) and health-related quality of life (SMD = 0.42) across 17 randomized controlled trials [17]. Its significance has led to a series of new systematic reviews quantifying long-term effects of wearable-assisted rehabilitation on clinical outcomes [18]. Continuous activity tracking affords a subtle but powerful clinical insight: A sudden unexplained decline in daily activity several days before exacerbations is an objective, earlier warning sign than self-reported symptoms. This underscores the ability of passive, continuous monitoring to convert subjective experiences into quantifiable and actionable clinical data.

The second and technologically more advanced route of innovation includes accelerometers, strain sensors, plethysmography-based systems, and even acoustic sensors used for cough frequency analysis. The COVID-19 pandemic was a major driver of the development of devices that could track respiratory metrics, such as coughing, breathing, and airflow variations, more closely [19]. The ultimate goal is to create robust, predictive algorithms capable of detecting impending exacerbations before symptom onset, moving beyond reactive oxygen saturation monitoring toward a predictive, continuous model of respiratory care.

Nevertheless, the implementation of wearables in pulmonology remains uniquely vulnerable to the “signal versus noise” dilemma. Metrics such as physical activity, respiratory rate, or cough frequency are powerful but imperfect surrogates of disease status, as they are influenced by numerous external and behavioral confounders. Step count can fluctuate with weather, social routines, or comorbidities like musculoskeletal pain; respiratory rate can rise with stress, fever, or anxiety [17, 28]. Inability to distinguish these confounders from

true exacerbations produces false alerts that cause unnecessary patient anxiety and avoidable clinical interventions. All of this highlights the need for robust clinical validation and standardization of these emerging digital biomarkers in real-world settings, which are often proprietary and opaque in many consumer algorithms [28, 29, 35].

In summary, wearables fulfill two roles in pulmonology: a pragmatic, evidence-based application of consumer devices to promote long-term stability, adherence and behaviour change in rehabilitation programmes [17,18]; And another frontier was the development of high-fidelity, sensor-driven systems that could detect and even predict acute respiratory distress in real time [19]. At the intersection of these approaches, respiratory care may change from episodic management to continuous prevention - mirroring the paradigm shift in cardiology. But realizing this promise will require overcoming the challenges of validation, data integration and equitable access that characterize this rapidly evolving field. Pulmonology wearable devices enable long-term activity tracking and early detection of respiratory deterioration in chronic lung diseases such as COPD. These tools facilitate rehabilitation adherence & provide predictive insights but are susceptible to confounding noise and limited clinical validation. Work should continue on standardizing digital biomarkers, algorithm transparency, and accessibility in healthcare settings.

Objective Monitoring in Neurology: The Case of Parkinson's Disease

In neurology, especially in the management of neurodegenerative disorders like Parkinson's disease (PD), wearable technology addresses one of the field's most persistent limitations - the use of subjective, episodic clinical assessments. The traditional "gold standard," the Unified Parkinson's Disease Rating Scale (UPDRS), although clinically validated, captures only brief clinical snapshots and is prone to recall bias. Thus, it fails to reflect patient experience - particularly the unpredictable motor fluctuations characteristic of the disease - those abrupt transitions between "on" periods of good mobility and "off" periods of rigidity and immobility - which profoundly affect quality of life. Early systematic reviews, such as the one published in 2016, suggested that wearable sensors could one day capture these cardinal motor symptoms - tremor, bradykinesia, dyskinesia - and gait irregularities in continuous, objective monitoring beyond the clinic [20].

Since then, the field has evolved from exploratory feasibility studies to the rigorous development of validated digital biomarkers - objective, quantifiable, and clinically interpretable metrics derived from continuous sensor data. A 2024 review, which was published in Advances in Clinical Chemistry documented this evolution, describing how accelerometer and gyroscope information are being reinterpreted into clinically meaningful indicators for monitoring therapeutic response, motor symptom burden and disease progression with unprecedented resolution. [21]. This maturation marks a paradigm shift from simple data collection toward the establishment of standardized, regulatory-grade digital biomarkers that can be incorporated into clinical trials and real-world care.

Equally crucial is the dimension of patient acceptance and usability. A 2025 qualitative meta-synthesis exploring the experiences of individuals with PD revealed a nuanced picture of engagement with wearable devices [22]. On one side, patients reported feeling more empowered and reassured by the objective feedback and increased self-awareness these devices provided. Unfortunately, on the other hand, they noted concerns regarding comfort, device intrusiveness, privacy risks and psychological exhaustion from constant self-monitoring. This ambivalence reveals an essential fact about digital health: technologic sophistication has to match human-centered design to maintain adherence and ensure that the technology supports, not burdens the lived experience of the patient. [22].

Thus, the role of wearables in Parkinson’s disease has progressed from a proof-of-concept tool for objective measurement [20] to a maturing ecosystem at the intersection of biomedical engineering, clinical neuroscience, and patient-centered care [21,22]. The ultimate goal is clear, to harness continuous, multimodal data streams to deliver truly personalized, adaptive therapy, allowing clinicians to adjust medication timing and dosage in near real-time to minimize “off” episodes and optimize quality of life.

Yet the road to clinical translation remains complex. Problems include data standard fragmentation and a lack of universally accepted digital biomarkers. Complex algorithms developed by many research groups are proprietary and device-specific, creating a "digital Tower of Babel" that prevents replication, meta-analysis and regulatory approval [21,28]. Similarly, integration of wearable-derived data into electronic health records (EHRs) is limited without standardised frameworks for clinical interpretation or workflow integration [22,27]. Without such integration, these data risk remaining isolated within research silos and producing technically compelling but clinically inert insights. Those challenges require not only technical innovation but also coordinated efforts in standardization, regulatory alignment, clinician education so that the next generation of

neurological care is data-driven but human-centric. In neurology, wearables have enabled objective, continuous measurement of motor symptoms beyond clinic visits - particularly for Parkinson's disease. These enrol patients and provide valuable biomarkers for disease monitoring, but data fragmentation, device heterogeneity and lack of interoperability still prevent routine use. Establishing standardized digital biomarkers and integrating wearable data into electronic health records will be key to translating this technology into daily neurological care.

Enhancing Medication Adherence Through Wearable Technology

Effective pharmacotherapy remains a cornerstone of chronic disease management, but one major challenge remains: access to care. poor medication adherence. This issue, which continues to burden healthcare systems worldwide, is due to a complex interplay between simple forgetfulness, the cognitive strain of managing polypharmacy and low patient engagement or understanding of therapeutic benefits. Wearable/mobile health technologies are well-positioned to address these multiple barriers, moving beyond simple reminder systems to rich, interactive ecosystems that integrate behavioral, cognitive, and physiological feedback.

Recent data support these digital interventions as clinically effective interventions. One major 2025 meta-analysis combining data from 38 randomized controlled trials quantified their impact - mobile health tools increased adherence by 77% compared to standard care (Odds Ratio = 1.77) [24]. Most importantly, the analysis showed that multi-component interventions combining reminders with educational content, behavioral feedback and monitoring features were most effective. This shows that success requires more than just prompting patients; it requires engaging and informing them through feedback-driven reinforcement.

These findings follow a broader technological evolution described in recent scoping reviews [23]. The simplest smartwatches are reminder devices that send haptic feedback and visual alerts. More sophisticated applications combine wearables with smart pill bottles which register each use to produce an objective digital adherence record for patient and clinician. This makes adherence a objective clinical metric rather than a subjective self-report. Despite these advances, heterogeneity in study design, short follow-up durations, and reliance on self-reported adherence measures continue to limit the generalizability of current evidence [24].

Perhaps the most sophisticated frontier of this evolution is the closed-loop biofeedback system, a psychological breakthrough in adherence science. In this case, the wearable's function goes beyond passive monitoring; it continuously tracks physiological markers to deliver instantaneous, palpable evidence of therapeutic efficacy. A patient with hypertension, for instance, might witness in real time how their blood pressure stabilizes after taking their medication, thereby confirming the causal relationship between adherence and favorable results. This direct, data-driven feedback changes medication-taking from a passive obligation to an active health behavior.

But this constant data flow also creates psychosocial risks. While many patients describe feeling more empowered and involved, continuous monitoring can trigger "digital health anxiety" - compulsive self-tracking, misinterpretation of benign fluctuations and psychological stress over "perfect" metrics. Recent qualitative studies document this paradoxical dual nature: digital tools simultaneously increase control and increase anxiety [22, 27]. This illustrates how human-centered systems must balance feedback with reassurance to ensure behavioral engagement without cognitive overload.

In essence, these technologies are redefining medication management as a memory-dependent, error-prone process within a dynamic, data-driven and behaviorally reinforced therapeutic loop. These address one of the most persistent and expensive barriers to care - forgetfulness, regimen complexity, and disengagement [23,24]. Looking forward, wearable adherence data integration with electronic health records and pharmacovigilance infrastructures may enable a holistic synthesis of patient behavior, clinical outcomes, and therapeutic optimization within a single intelligent ecosystem.

Wearable / mobile health technologies are turning passive reminder systems into interactive / feedback-driven tools for medication adherence. Evidence shows better adherence and engagement with multi-component interventions, but sustained use can induce digital fatigue or anxiety. The next designs must combine automation with user trust and incorporate adherence data directly into clinical decision-making for real therapeutic impact.

Navigating the Barriers: Technical, Ethical, and Economic Challenges

Wearable technologies have enormous potential, but their safe, effective and equitable introduction into routine healthcare is shaped by several large and interconnected challenges. Deep technical obstacles, systemic inertia, and complicated ethical and privacy realities temper the promises of ongoing, personalized health monitoring. Determining informed consent in a time when passive data collection is commonplace is the main ethical conundrum. Conventional consent models are not suitable for continuous data collection because they were created for discrete clinical events. This creates a gap between regulatory requirements and technological practice - as evidenced by studies that even Institutional Review Board (IRB) members, the formal gatekeepers of research ethics, feel uncertain about how to assess and approve protocols involving such new technologies [25].

It is exacerbated as wearables transition from research tools to mainstream products, with attendant privacy and governance issues. The "datafication" of health produces enormous longitudinal streams of private information. Regulatory frameworks such as GDPR offer some protection, but data volumes and granularity remain vulnerable, as the healthcare sector recorded over 700 major data breaches in a single year [26]. Human factors studies show how this tension affects people. Almost 80% of users report moderate to high data security concerns in some populations, highlighting a difficult trade-off between perceived benefits and personal privacy risk [27].

Beyond these human-centered concerns, there are several profound technical obstacles that separate clinically validated instruments from consumer-grade devices. It remains methodologically challenging and resource-intensive to convert unprocessed, high-frequency sensor data into trustworthy digital biomarkers. Gigabytes of raw data, mostly motion artifacts and ambient noise, can be generated daily by a single user. As shown in a recent framework from NPJ Digital Medicine, turning this data stream into a validated biomarker requires signal filtering, feature extraction and clinical validation against established gold standards [28]. Algorithmic transparency adds to this difficulty. A 2024 systematic review showed that many advanced machine learning models in wearable analytics remain "black boxes" [29]. This opacity prevents clinical adoption, as healthcare providers cannot be expected to assume medico-legal responsibility for decisions based on models they cannot interpret. Building trust thus requires explainable, interpretable and transparent algorithms.

Even when a technology is proven accurate, interpretable and ethically sound, real-world adoption depends on economic feasibility and systemic readiness. A 2024 Mayo Clinic review illustrated these pragmatic challenges - device costs often exceeding USD 500 are prohibitive for many users and reimbursement structures are dated [30]. Clinicians are rarely paid for the extra time they spend reviewing continuous data streams, even though specific use cases are beginning to receive their own reimbursement codes. Therefore, there is a risk that innovations intended to democratize healthcare will actually exacerbate inequality by restricting access for well-funded systems or wealthy groups. Addressing these disparities requires rational reimbursement policies, logically priced device design, and digital literacy campaigns to ensure that the benefits of wearable health monitoring reach underprivileged populations.

Future Perspectives: From Reactive Care to Predictive, Personalized Medicine

The evolution of wearable technologies goes beyond incremental refinement. It's a paradigm shift to predictive/personalized healthcare. This transition will be driven by new-generation hardware, advanced artificial intelligence (AI), and a new patient-centric framework for clinical decision-making. It is based on a hardware revolution based on flexible bio-chips and advanced materials science to realize skin-conformable, nearly invisible sensors compatible with human physiology [31]. These platforms go beyond the capabilities of typical wrist-worn devices and permit continuous, non-invasive monitoring of biochemical and physiological parameters. So they turn the body's biological signals into a continuous, clinically interpretable data stream.

This flood of high-fidelity data provides the foundation for the next transformative leap: AI-driven predictive analytics. Emerging evidence shows that the fusion of AI and wearable systems is gradually shifting the focus of care from passive monitoring of existing conditions to active prediction and prevention of future disease [32, 33]. The most advanced example of this vision would be the Digital Twin: an extremely accurate in silico model of an individual that is updated with real-life data from wearables, electronic health records, and multi-omic datasets [34,35]. These models capture retrospective trends and simulate individualized health trajectories to produce validated digital biomarkers for P4 medicine—predictive, preventive, personalized, and participatory care [36,37]. However, most current AI systems are opaque black boxes with limited explainability, which impair clinical

accountability, interpretability, and regulatory oversight. Many of these are still theoretical or pilot concepts, but early feasibility studies have shown their utility in selected clinical areas.

Despite this promise, there remains a substantial evidence gap between theory and practice. Hardware and analytical frameworks keep evolving rapidly, but even some of the most sophisticated applications lack long-term, large-scale randomized controlled trials with hard outcomes such as mortality, hospital stays, or healthcare costs. In particular, while numerous wearable-based pilots are now in place, very few studies report sustained improvements in morbidity or cost at the population level. Systematic reviews consistently state that patient engagement, behavioral outcomes, and surrogate markers are the strongest evidence, but validation against concrete clinical endpoints is in development [38]. This brings to light a significant issue: expectations have been implemented too soon because technology has advance faster than clinical validation. In order to bridge this gap, we require thorough multicenter studies that validate the clinical utility of these technologies using standardized methodologies and open reporting frameworks.

In addition, when they work, their deployment creates enormous ethical, regulatory and societal problems. It isn't about building powerful AI tools, but being honest, transparent, and equitable [39]. In a landmark 2019 study in Science, the cost of care was shown to be a proxy for clinical need, with algorithmic bias harming Black patients [40]. This demonstrates how digital health systems may exacerbate structural injustices rather than address them if intentional efforts are not made to improve data diversity, fairness, and explainability. Thus, strong governance and ethical frameworks are required for post-market surveillance, model certification, and data validation—principles that are also represented in the World Health Organization's Global Strategy on Digital Health [41]. The foundation of responsible and just deployment in parallel health data ecosystems will be data sovereignty, consent, and cross-border governance.

The challenge of equity extends globally as well. Wearable health technologies have a double potential: They can help countries with low and middle income overcome the current limitations of healthcare access by enabling remote diagnostics and continuous monitoring. But if such systems are developed and sold as premium consumer goods they will only serve to further globalize the health gap and deny predictive and personalized care to the affluent [42]. Fair results require inclusive design, affordability, and scalability - innovation must be about universal benefit, not selective privilege.

To realize this vision, a clear and coordinated research and policy agenda is essential. Priority should be given to:

- large, multicenter randomized controlled trials across diverse populations to establish clinical efficacy and cost-effectiveness;
- real-world implementation studies to evaluate workflow integration, usability, and clinician engagement;
- the creation of open interoperability standards to eliminate data silos;
- equity-centered deployment strategies that ensure wearable technologies reduce, rather than reinforce, health disparities.

The next decade will ultimately determine whether this digital transformation is capable of being more than a technical milestone: it can be the foundation for a trusted, ethical and participatory healthcare ecosystem. Technology, ethics, and inclusion will decide whether wearable systems become a truly global instrument of precision public health able to provide predictive and personalized medicine for all.

Conclusions

Far from being just a trend, wearable health technologies are proving to be a powerful catalyst in managing chronic diseases, as this review demonstrates. The way care is delivered is fundamentally changing – shifting from reactive visits to the clinic towards ongoing, personalized support informed by daily health data. Cardiology illustrates this impact well: arrhythmia screening is now within reach for many more people thanks to wearables, aiding early atrial fibrillation detection, and the technology shows exciting potential for precise, cuffless blood pressure measurement. Static, retrospective markers such as HbA1c have been replaced in diabetology by dynamic metrics such as Time in Range to enable responsive, informed self-management. In pulmonology and neurology, wearable systems provide objective, longitudinal insights into functional status and symptom variability, whereas in pharmacotherapy, they address one of medicine's most persistent problems - poor medication adherence - through feedback-driven behaviour reinforcement. These technologies also promote psychosocial well-being through patient engagement, self-efficacy and a sense of control over chronic conditions beyond measurable outcomes.

It is still difficult to translate technological potential into fair clinical reality, though. Iterative improvement and rigorous validation can easily overcome significant technical challenges like algorithmic transparency, signal variability, and data accuracy. Health disparities are growing as a result of low digital literacy risk, inconsistent reimbursement models, high device costs, and rapid innovation that have outpaced privacy, consent, and data ownership frameworks. And algorithmic bias risks embedding structural inequities into tools intended to advance equity. A similar problem is that wearable data is not unified with electronic health records, without which the clinical utility of these technologies is almost theoretical. Practical issues such as reduced CGM accuracy at hypoglycemic extremes or motion-induced artifacts in PPG-based sensors call for usability testing, especially in older or functionally limited populations.

Human-centered design, not sophisticated algorithms, will ultimately be the key to the success of wearable health technologies. Transparency, bias reduction, and the meaningful integration of continuous data into clinical workflows are all made possible by such a vision, which calls for tight cooperation between researchers, clinicians, technologists, and regulators. Only through such coordinated, ethical efforts can wearable systems deliver predictive, personalized medicine for all patients while upholding principles of justice, inclusion, and human dignity.

Disclosure

Authors' contribution:

Conceptualization: Mateusz Mierniczek, Maria Mierniczek, Aleksandra Mierniczek
Methodology: Jarosław Dudek, Kinga Kaczmarska, Kinga Rosołowska
Software: Mateusz Mierniczek, Maria Mierniczek, Aleksandra Mierniczek
Check: Jarosław Dudek, Kinga Kaczmarska, Kinga Rosołowska
Formal analysis: Mateusz Mierniczek, Maria Mierniczek
Investigation: Aleksandra Mierniczek, Kinga Rosołowska
Resources: Jarosław Dudek, Kinga Kaczmarska
Data curation: Jarosław Dudek, Kinga Kaczmarska
Writing - rough preparation: Aleksandra Mierniczek, Kinga Rosołowska
Writing - review and editing: Mateusz Mierniczek, Maria Mierniczek, Jarosław Dudek, Kinga Kaczmarska
Visualization: Mateusz Mierniczek, Maria Mierniczek, Aleksandra Mierniczek
Supervision: Maria Mierniczek
Project administration: Mateusz Mierniczek

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