Review Article

Wearable Biosensors for Real-Time Health Monitoring and Disease Prediction: Integrating Biology with Digital Health

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ABSTRACT

Introduction and Aim: Wearable biosensors represent a new era in digital health and biotechnology, offering non-invasive, continuous, and real-time monitoring of physiological and biochemical parameters. This review discusses their classification, applications, technological development, and future potential in disease prediction and personalized medicine.

Materials and Methods: Relevant literature on past, present, and emerging wearable biosensors was analyzed, covering sensor types, operational principles, connectivity (wired and wireless), and integration with advanced technologies such as artificial intelligence (AI), cloud computing, and next-generation wireless communication. Sources were selected based on their relevance to real-time health monitoring and disease prediction.

Results: Wearable biosensors are broadly divided into biophysiological sensors, which measure parameters such as heart rate, temperature, and motion, and biochemical sensors, which detect bioanalytes in biological fluids like sweat, saliva, and interstitial fluid. Major applications include blood glucose monitoring, cardiovascular assessment, pulmonary function tracking, and evaluation of mental health and sleep patterns. The combination of AI, cloud systems, and wireless networks enhances diagnostic precision and predictive accuracy. Market reports project the wearable biosensor industry to surpass USD 60 billion by 2030, with an annual growth rate exceeding 12%, indicating expanding research and adoption.

Conclusion: Wearable biosensors are transforming healthcare by enabling proactive, personalized, and remote medical management. Despite challenges in biocompatibility, stability, data security, and regulation, advances in flexible materials, energy-efficient designs, and AI-based systems continue to drive their evolution and clinical integration.

Keywords: Wearable biosensors, Real-time health monitoring, Disease prediction, Biochemical sensors, Personalized medicine.

1. INTRODUCTION

Wearable biosensors are non-invasive, portable and miniature devices that can continuously and immediately measure multiple physiological and biochemical parameters at rest and during exercise. The biological sensors built into electronic-based systems generate information relating to health and are capable of gathering, processing and reporting their results to remote devices or cloud systems where their results could be remotely analyzed and interpreted [1]. The value of these biosensors is that they can provide customized and data-driven health-care interventions that out-reach any earlier epistemic and clinic based health-care evaluations that existed before. Such health watching perceived as on-going and immediate has been on the rise in the modern world in the face of the global escalations of the incidence of chronic health issues such as diabetes mellitus, cardiovascular disease, respiratory disease and mental illness. Many of these present chronic diseases are progressive in nature and consequently it is significant that early detection of disease progression is possible. This is essential in order to minimize the complications linked to these diseases and enhance the quality of life as well as lowering health care costs. According to World Health Organization (WHO 2024) [2], non-communicable disease (NCD's) has an annual burden of approximately 43 million deaths nowadays, representing approximately 75 percent of all deaths worldwide, and not related to pandemics. These deaths amount to approximately 19 million deaths annually due to cardiovascular disease, 10 million deaths annually due to cancers, 4 million deaths annually due to chronic respiratory diseases and more than 2 million deaths annually due to diabetes and kidney disease. Also, nearly 1.8 billion adults in the global population (31 percent of adults) do not achieve the current recommended physical activity levels that cause their high rates of diseases like chronic illness [2-5]. Moreover, Monaghan *et al.*, 2024 [6] affirm that there is also a high impetus of the demand of the remote health monitoring technologies since these can reduce the need of travelling to hospitals by patients and consequently also reduces the need of utilization of the traditional hospital-based clinics under the current global health crisis conditions of the current COVID-19 pandemic.

One of the most significant changes in the healthcare sector is the transition between reactive (care after symptoms) and predictive and preventive care. This transformation comes about because biosensor technologies are being used in wearables to detect slight shifts in physiology to enable early diagnosis and preventive health care [7, 8]. Therefore, these machines play a crucial part in the receipt of real time feedback of the patients and in gathering of longitudinal data in the conditions of health across the globe. They are essential to the creation of precision medicine and the overall digital health agenda [9, 10]. Continuous risk analysis with platform technology related to artificial intelligence and big data, relevance considering the perspective of personalized therapy, and population health analytics are also possible [11, 12].

2. Types of Wearable Biosensors

Biosensors fall into two categories: those which depend on the nature of the signal (e.g. physical or chemical) and those which depend on the shape of the sensor, which can be flexible electronics, textile-based systems and implantable devices, to name a few. All forms of sensor support various diagnostic or monitoring needs, and therefore provide customized context based health measurements.

2.1 Biophysical Sensors

Here are described biophysical sensors of the physical parameters of the human system under study such as heart rate, electrocardiogram (ECG), electroencephalogram (EEG), respiration rate, body temperature and body movements. These sensors usually rely on physical transduction, like optical, electric, piezoelectric or mechanical transduction, to cause measurement of physiological changes in terms of a measurable electrical effect. Examples of these sensors are photoplethysmography (PPG) wrist sensors, ECG chest sensors, and accelerator sensors that give measurements of movements experienced by a sensor [13, 14]. Wearable ECG monitors have been authenticated to detect arrhythmia in real-time making them a significant device in clinical and home applications [15]. Head devices based on EEG are considered an efficient way of identifying brain-wave patterns in the treatment of epilepsy, sleep disorders, and mental health issues, especially in combination with artificial intelligence etc., in the analysis stage of the signals of the sensors [16, 17].

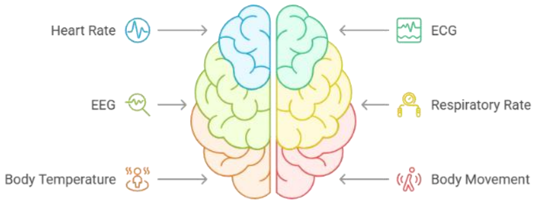

Fig 1. Biophysical Sensors

2.2 Biochemical Sensors

Biochemical biosensors concentrate on the concentration of molecular biomarkers in various biological fluids including sweat, saliva, interstitial fluid and tears. Such sensor devices are imperative to non-invasive observation of potential metabolic rates and hormonal concentrations. The order of analytes is glucose, lactate, cortisol, electrolytes (Na+, K+, Cl-), alcohol and urea [18]. To illustrate, according to sweat, biosensors are being developed to monitor blood sugar of diabetic patients continuously, and to monitor electrolyte balance and hydration of sportsmen [19]. According to tears, the glucose sensors built on contact lenses are highly patient-friendly and are set to provide non-invasive management of diabetes [20]. Moreover, recently emerged salivatory sensors have a future in monitoring stress biomarkers, cancer biomarkers and immunity status [21].

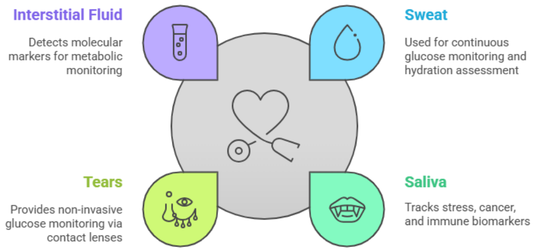

Fig 2. Biochemical Biosensors

2.3 Flexible and Stretchable Electronics

The current wearable sensors make use of flexible, stretchable, and skin-conforming substances that include graphene, polydimethylsiloxane (PDMS), polyimide, and liquid metal conductors. The mechanical compatibility of such materials with human skin reduces discomfort and increases the signal quality during movement [22, 23]. There are recent developments of textile-based sensors, temporary tattoo sensors and microfluidic patches, which can interface with skin, enabling long-term health monitoring without disturbing physical activity. These sensors are particularly flexible and pediatric, geriatric, and athletic applications are well possible [24].

2.4 Implantable vs. Non-Invasive Devices

The invasiveness of wearable biosensors is also a classification criterion. The consumer market is dominated by non-invasive biosensing devices, including smartwatches, wristbands, patches, and headbands, as they are user-friendly and not harmful to health. Non-invasive biosensors are ideally placed to monitor health on a routine or continuous basis, fitness or exercise and behavior [25]. Implantable biosensors give access to the biological markers present in tissues and fluids within the body. They are more accurate and stable and are more suited to intensive care and chronic conditions than their non-invasive counterparts. These include implantable glucose monitors, pressure sensors that will be placed on patients with heart failure, and feedback systems which will involve the delivery of the drug. These systems also continuously wirelessly communicate with other devices to transfer data and provide feedback to patients [26, 27].

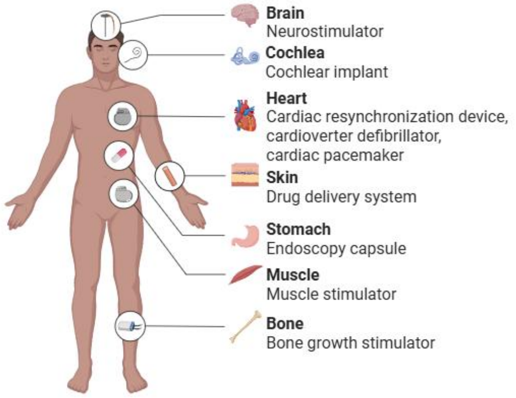

Fig 3. Wearable biosensor-based implantable and non-invasive devices for physiological and biochemical health monitoring

3. Mechanism of Action and Signal Processing

Wearable biosensors operate through the complex combination of biological detectors, signal transduction, and data processing systems. Their mechanism of action usually consists of four consecutive steps: bio-recognition, transduction, signal processing and data transmission. These stages collaborate to lay groundwork to surveillance of remote and real-time monitoring of physiological or biochemical parameters.

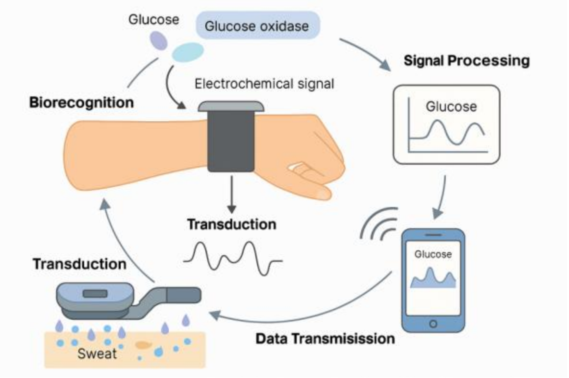

Fig 4. Mechanism of Sweat-Based Wearable Glucose Biosensors

3.1 Signal Detection and Conversion

This is the step that converts the signal into a digital form which the computer understands. The fundamental component of any biosensor is a bio-recognition component, which may be an enzyme (e.g., glucose oxidase), antibody, DNA aptamer or molecularly imprinted polymer, specifically recognizing the analyte of interest. When recognized, this binding event triggers a physicochemical event, be it electrochemical, optical, piezoelectric or thermal, which is sensed by a transducer. In the case of electrochemical biosensors, the variation of potential or current caused by redox reaction is measured and can be used to detect glucose or lactate [28, 29]. Optical biosensors use fluorescence, absorbance or surface plasmon resonance (SPR) to detect molecular interactions. The approaches offer label free, exceptionally sensitive detection and thus suit continuous monitoring of hormones and biomarkers [29]. Additional transduction methods are piezoelectric crystals, which provide detection of a mass change during an analyte-binding reaction, and thermometric sensors, which detect a change in heat when a biochemical reaction occurs [30].

3.2 Data Acquisition and Transmission

After the signal has been produced it is then subjected to signal conditioning- e.g. filtering and amplification- and then analog to digital conversion (ADC) to prepare the signal to be processed digitally. The generated data will be sent to external receivers through wireless communication protocols such as Bluetooth Low Energy (BLE), Wi-Fi, ZigBee, or Near Field Communication (NFC) [16, 31]. The related connectivity makes biosensors transmit data to smartphones, wearables, or cloud servers to be analyzed in real-time, assessed remotely, or alarmed in case of an emergency. Connection to the Internet of Things (IoT) architectures will enable continuous data transmission, central storage, and longitudinal health record development [17, 32]. Furthermore, data communication and edge computing are energy efficient to reduce battery use and decrease latency in real-time feedback frameworks.

3.3 Role of Artificial Intelligence and Machine Learning

Recent wearable biosensors produce large datasets of multivariate, continuous, and noisy time-series data. Intelligent filtering, pattern recognition, and health trend prediction are achieved by the integration of artificial intelligence (AI) and machine learning (ML) algorithms [18, 33]. Support vector machines (SVM), deep learning, random forests, and convolutional neural networks (CNNs) become more commonly used techniques to detect anomalies in ECG signals, diagnose patterns of stress based on the sweat composition, and solve glucose spikes [34, 35]. Also, adaptive learning systems allow biosensors to adapt to changes in the user physiological variation with time in the baseline thresholds to improve specificity and decrease false alarms. On-the-edge AI (computing at the hardware) and cloud-based analytics enhance the response time and enable offline or low bandwidth functionality [19, 36].

3.4 Security and Data Integrity

A more severe but frequently neglected factor of signal processing is data privacy and cybersecurity. As wearable biosensors gather sensitive health data, secure transmission and storage is necessary, and this is guaranteed by encryption, authentication mechanisms, and blockchain-based environments [37]. New discoveries in biometric encryption, employing physiological indicators (e.g., heartbeat or brainwave pattern) as cryptographic keys, have also been considered to strengthen user data protection [38].

3.5 Feedback and Actuation

More advanced wearable systems may include feedback loops, and information triggered triggers prompt therapy. As an illustration, closed-loop biosensor-actuator systems can be smart insulin pumps that regulate insulin dose according to real-time glucose measurements [39, 40]. Future developments can involve the addition of microneedle arrays, drug-impregnated patches and neural stimulation modules which are self-responsive in response to biosensor data.

4. Applications in Health Monitoring

Wearable biosensors have transformed the current health care system by helping to constantly monitor physiological and biochemical indicators in real time. Among the most serious applications is in the health management of diabetes, where biosensors help in the non-invasive monitoring of glucose in the sweat, interstitial fluid, or tears. Smartwatches, patches, and contact lenses can now measure the glucose level without having to take regular fingerpricks, significantly enhancing the compliance and comfort of patients [20, 41]. They have improved glycemic control and decreased the occurrence of hypoglycemia by generating real-time alerts and by being integrated with smartphone applications [42].

Wearable biosensors have broad application in cardiovascular health in measuring heart rate, blood pressure, and electrocardiogram (ECG) signals. Arrhythmias, including atrial fibrillation, can be identified by smartwatches and ECG patches based on AI algorithms, which forecast cardiovascular events prior to clinical symptoms onset [21, 43]. These features facilitate early diagnosis and medical intervention in good time, which is essential in alleviating the burden of heart disease. Moreover, the accuracy of cardiovascular risk assessments can be improved with the help of machine learning models that analyze the measurements taken with photoplethysmography (PPG) and other wearable-based sensors [44].

Wearable biosensors are also being used in mental health monitoring, and these can monitor physiological parameters like heart rate variability (HRV), galvanic skin response (GSR), and cortisol levels. These parameters are used as proxies of psychological stress, anxiety, and depression. Biosensors can give personalized feedback and assist in behavioral interventions when used alongside mobile applications to foster mental well-being [23, 45]. They can also identify underlying mental health problems by monitoring electrodermal activity and sleep disruptions, allowing to conduct more extensive psychological testing [46].

These devices are used to measure the hours of sleep, sleep phases, and apnea episodes, as well as fatigue, helping to diagnose insomnia and sleep apnea [24, 47]. Also, motion sensors on clothing are common in the monitoring of physical activity, gait, posture, and risk of falls, especially among elderly or rehabilitating patients. This information is essential to both post-surgery care and to the encouragement of healthy motility among at-risk groups [48]. Greater attention has been paid to respiratory health particularly following the COVID-19 pandemic. The remote monitoring of respiratory rate, oxygen saturation (SpO2), and airflow patterns in patients with asthma, chronic obstructive pulmonary disease (COPD), or post-viral complications is now possible through wearable biosensors [25, 49]. These systems lessen hospitalization as they enable early recognition of respiratory deterioration and ease remote patient care via telemedicine systems.

Wearable biosensors continue to gain importance in the field of public health due to their capacity to help detect and monitor infectious diseases at an early stage. They are using sensors to measure parameters like fever, cough frequency, and oxygen desaturation to screen COVID-19. Certain devices also detect biomarkers of inflammation, such as C-reactive protein (CRP) and interleukin levels, which are very important in predicting outbreaks and epidemiological surveillance [50]. Wearable biosensors in maternal and neonatal care are utilized to monitor the heart rate of the fetus, vital signs of the mother, and the activity in the womb. These are used as skin-interfaced, wireless gadgets that provide superior precision in monitoring yet reduce discomfort especially in neonatal intensive care units [51]. Biosensors monitor hydration and mobility trends as well as signs of cognitive impairment in geriatric care, helping elderly patients to remain independent and minimize hospital admissions [52].

Athletic performance monitoring is a fast developing discipline. Biosensors are wearable devices that measure hydration, accumulated lactic acid, and movement of the muscles to optimize training and recovery among athletes. Such sensors are also used in rehabilitation to measure joint motion, muscle activity, and physical progress during therapy [41, 53, 54]. New wearable biosensors are being developed in the field of oncology to measure the following: cancer biomarkers, the toxicity of chemotherapy, and radiation exposure. Though these technologies are experimental, they can potentially facilitate home-based management of cancer and real-time tracking of treatment responses [55].

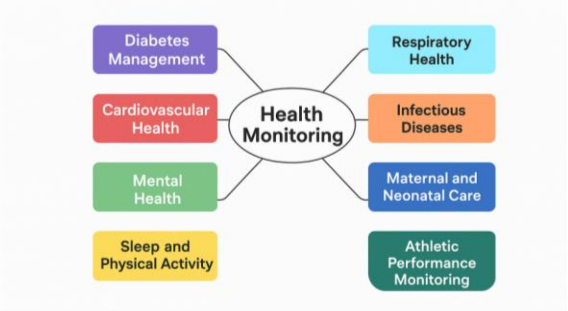

Fig 5. Applications of wearable biosensors in health monitoring

5. Disease Prediction and Early Diagnosis

The combination of predictive analytics and wearable biosensors is changing the disease prevention and early diagnosis sphere. Wearable biosensors produce vast amounts of personalized real-time health information through continuous measurement of physiological and biochemical parameters (heart rate, skin temperature, respiratory rate, and metabolic biomarkers, etc.). The patterns in these continuous data streams are then identified by sophisticated machine learning algorithms and statistical models and can be used to predict such chronic conditions as hypertension, type 2 diabetes, and cardiovascular events long before they occur [26, 56]. As an illustration, wearable technology along with artificial intelligence (AI) can approximate heart rate variation and blood pressure trends to predict hypertensive episodes or identify indicators of metabolic syndrome [57].

Wearable biosensors have been used in the acute care setting as highly efficient tools in the early detection of life threatening events like seizures, myocardial infarction, stroke, and cardiac arrhythmias. Multimodal biosensors, incorporating ECG, acceleration, SpO2, and electrodermal activity sensors, have the capability of identifying seizure antecedents, ischemic events, and oxygen desaturation [27, 58]. Another important use of these devices is remote patient monitoring. They offer live notifications that can aid in the timely provision of medical care, particularly when it comes to high-risk patients and those with poor access to emergency services. One of the notable improvements in this regard is the invention of customized notification systems. Such systems compare historical health data of a user to develop personalized baselines and send warnings to the user when they fall outside the normal physiological range of the specific individual. Alerts are relayed straight to patients, caregivers or healthcare providers through mobile applications, SMS or cloud-based dashboards. These systems combined with telemedicine platforms can facilitate remote diagnosis, triage, and management as well, thus closing the divide between patients and providers, especially in rural and underserved areas [28, 59]. These early interventions do not only minimise hospital hospitalisation, but also enable their patients to actively participate in their own health care.

Wearable biosensors are greatly increasing surveillance and control of diseases by detecting non-normal physiological modalities in populations. As an example, wearable real-time data was utilized in the COVID-19 pandemic to forecast infection danger through alterations in temperature, heart rate, and respiratory rate prior to PCR confirmation [60]. The same methods can be tailored to new outbreaks and allow government healthcare representatives to react promptly and effectively to new challenges. Wearable sensors are currently explored in the context of oncology as the primary method of detecting tumor biomarkers or physiological changes linked with malignancy at an early stage. Even in its research stage, biosensors to monitor variations in volatile organic compounds (VOCs), interleukin levels, or the presence of circulating tumor DNA in body fluids are being developed [61, 62]. These technologies can transform the current cancer screening by providing non-invasive home-based early diagnostics. Biosensor-based predictive models are also useful in neurodegenerative diseases like Parkinson and Alzheimer. Early warning signs can be subtle gait, tremor, facial expression, or speech associated with wearable motion sensors and acoustic biosensors that can become apparent before the overt manifestation of the condition [63, 64]. Deep learning can be applied to longitudinal data to estimate disease progression and propose the most appropriate intervention plans.

Wearable biosensors are currently being developed to track cytokine efflorescence and interstitial fluid or sweat inflammation in autoimmune and inflammatory diseases. Such early alerts are especially useful in situations like rheumatoid arthritis and lupus, where the exacerbations occur without prior notice [65]. Combination with on-the-edge computing and cloud-based AI systems makes it possible to perform on-device analytics and assess the risk in real-time. Moreover, biosensor systems are improving maternal health by measuring blood pressure, changes in heart rate, uterine contractions, and biochemical concentrations in sweat or urine, which indicate gestational diabetes, preeclampsia, and preterm birth [66]. Biosensors are used in fetal care to give early alert on distress or unusual fetal heart rate, which are used to prompt obstetric interventions. It is important to note that the progress of flexible electronics and skin-integrated biosensors has enhanced the comfort and wearability of users, which leads to better adherence to the monitoring regimens in the long run [67]. Together with pattern recognition using AI, these devices have unimaginable prospects to transform the clinical paradigm by transforming reactive treatment into predictive, personalized, and preventive (P4) healthcare.

Finally, massive health experiments are being conducted to confirm the use of wearable biosensor systems as early disease predictors in natural environments. Other programs, including the All of Us Research Program and the UK Biobank, have started to include wearable information to investigate the relationship between lifestyle, environment, and the development of disease [68-70]. Such initiatives are crating the basis of population-wide, precision-driven disease prediction models that can help enormously alleviate the global burden of chronic and acute diseases.

6. Current Commercial Devices for Real-Time Health Monitoring

The latest innovations in wearable technology resulted in the appearance of various commercially available devices used to track health status in real-time and predict diseases. These devices are fitted with sensors to monitor physiological parameters that include heart rate, ECG, SpO^2, glucose levels and physical activity.

Table 1. Summary of Key Wearable and Diagnostic Biosensor Devices

Device / product	**Core biosensing technology**	**Regulatory status**	**Primary application domain**	**Reference**
Apple Watch (Apple Inc., USA)	Optical heart rate (PPG), ECG, SpO_2, motion and temperature sensors	US FDA cleared (ECG), CE marked	Cardiac, activity, and wellness monitoring	[70]
Fitbit Sense / Charge (Google, USA)	PPG, EDA, skin temperature, accelerometer	CE marked, FDA cleared	Cardiac, stress, sleep, and activity monitoring	[71]
Oura Ring (Oura Health, Finland)	Optical PPG, temperature, accelerometer, gyroscope	CE marked	Sleep, recovery, and metabolic tracking	[72]
FreeStyle Libre (Abbott, USA)	Continuous glucose monitoring (enzyme-based electrochemical sensor)	US FDA and CE approved	Metabolic (diabetes management)	[73]
BioStamp nPoint (MC10 Inc., USA)	Flexible biopotential and motion sensors	US FDA cleared	Cardiac, muscular, and motion analysis	[74]
WHOOP Strap (WHOOP Inc., USA)	PPG and accelerometer-based physiological monitoring	CE marked	Fitness, recovery, and sleep analytics	[75]
Senseonics Eversense (USA)	Long-term implantable fluorescence-based glucose sensor	US FDA approved	Metabolic (diabetes management)	[76]
Samsung Galaxy Watch (Samsung, South Korea)	ECG, PPG, temperature, and bioimpedance sensors	CE and FDA cleared	Cardiac and general health monitoring	[77]
Garmin Wearables (Garmin Ltd., USA)	PPG, accelerometer, and pulse oximetry	CE marked	Fitness and wellness tracking	[78]
Withings ScanWatch (Withings, France)	ECG, SpO_2, and motion sensors	CE marked, FDA cleared	Cardiac and respiratory monitoring	[79]
SanketLife (Agatsa Pvt. Ltd., India)	Smartphone-integrated ECG biosensor	CDSCO and US FDA approved	Cardiac screening and remote diagnostics	[80]
DOSEE (SenseGiz Technologies, India)	Wireless ECG, heart rate, SpO_2, and respiration monitoring	Indian FDA and IEC 60601 compliant	Cardiac and respiratory health	[81]

Dozee® (Turtle Shell Technologies, India)	Contactless piezoelectric sensor with AI analytics	Approved by Indian regulatory authorities	Vital signs, sleep, and step-down ICU monitoring	[82]
HealthCube XL / Rapid (HealthCube India)	Multi-parameter diagnostic platform (ECG, BP, Hb, glucose, SpO_2)	NABL validated, CDSCO approved	Point-of-care and primary care diagnostics	[83]
Niramai® Thermalytix (India)	Infrared thermography with machine learning algorithms	CDSCO approved, BIRAC recognized	Oncology (breast health)	[84, 85]

7. Challenges and Limitations

The swift development and implementation of wearable biosensors have not yet achieved widespread implementation in healthcare, as there are several challenges that persist in hindering their adoption in clinical settings. Sensor accuracy and calibration is one of the major issues. Most consumer-level biosensors are susceptible to motion artifact variability, environmental variation, or intermittent contact with the skin. These errors may impair clinical judgment, especially in a situation with high stakes, like cardiovascular monitoring or glucose sensing [34, 86]. Moreover, optical and electrochemical biosensors are affected by skin color, sweat composition, and temperature, which require advanced algorithms and adaptive calibration methods to ensure that their performance is accurate [87]. Moreover, sensor degradation in terms of biofouling, mechanical wear or environmental exposures questions long term reliability [88].

A significant drawback of wearable biosensors is that they need to be powered by small, light power sources. Standard wearable devices use miniature batteries that need to be often recharged or replaced, which diminishes user convenience and hinders long-term and constant monitoring [35, 89]. To counter this hurdle, scientists are looking at energy-harvesting devices, including thermoelectric, piezoelectric, or solar energy devices which can produce energy using body heat, motion or ambient light. Nonetheless, incorporating these systems into small, flexible and biocompatible wearables is still a major engineering difficulty [90].

esides power issues, data security and privacy are productively challenging to wearable biosensor systems. These mobile gadgets are always receiving and transmitting sensitive personal health data through wireless communication systems like Bluetooth or Wi-Fi, making them susceptible to cyberattacks, data hijacking, unauthorized access, and abuse [36, 91]. Weak encryption, poor authentication methods, and unsecured firmware updates are some of the common vulnerabilities. Wearable biosensors should adopt strong encryption protocols, multi-factor authentication, and adhere to the international data protection laws, including the General Data Protection Regulation (GDPR) and the Health Insurance Portability and Accountability Act (HIPAA) to guarantee a secure adoption.

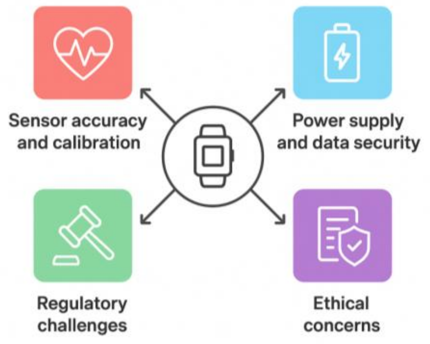

Fig 6. Challenges in Wearable Biosensors for Real-Time Health Monitoring

Secondly, the commercialization and approval of biosensors to use in medicine are also impeded by standardization and regulatory shortcomings. The absence of unified international guidelines to assess safety, efficacy and interoperability leads to fragmentation at the regional regulatory level and clinical approval stalemates [37, 92]. Furthermore, with the European Medical Device Regulation (MDR), numerous wearable medical products are currently placed into more risky categories that demand more comprehensive clinical testing and post-market monitoring [93]. Lastly, the ethical issues of data privacy, informed consent, and surveillance are becoming more extensively debated in the literature. Since biosensors constantly survey real-time physiological data, users might not even be aware of sharing intimate health information, which poses significant ethical and legal issues

[38, 94]. The risk of predictive analytics inferring sensitive conditions (e.g., mental health, reproductive health) based on biosensor measurements also brings up the issue of discrimination, insurance discrimination and abuse [95-97].

8. Application

Biosensors on wearables have captured a strong interest in biomedical and digital health studies because of its ability to measure physiological and biochemical signals in real-time, continuously, and without invasive intervention. These biosensors are successful in bridging the gap between biological data and electronic health platforms by incorporating biological recognition modules with transducers, microelectronics, and wireless systems. They are fundamental means of personalized medicine, preventive care, and prediction of disease. The next sections address the key fields of wearable biosensor implementation, such as cardiovascular, metabolic, respiratory, mental health, and lifestyle (sleep and activity) surveillance [98].

8.1 Cardiovascular Monitoring

Cardiovascular diseases (CVDs) are the principal cause of mortality worldwide, and constant supervision of cardiovascular parameters is vital to detect cardiovascular diseases in their initial phases and treat them. Wearable biosensors, including electrocardiogram (ECG) patches, photoplethysmography (PPG)-based biosensors, and smart watches, can be used to measure real-time heart rate and heart rate variability (HRV) pulse wave velocity, and blood pressure. Such devices are able to identify irregularities like arrhythmias and hypertension with high temporal precision, which allows remote cardiac evaluation and minimizes the number of hospital visits. Smart wearables have shown potential accuracy in cardiovascular anomalies when used with AI-based algorithms [99, 100]. Likewise, a 2023 American College of Cardiology report has underscored the increasing importance of consumer wearables in cardiovascular care alongside the necessity of standardized validation and algorithm disclosure.

8.2 Metabolic Monitoring

Non-invasive devices such as wearable biosensors have been developed to monitor the biochemical concentrations of glucose, lactate, cholesterol, and uric acid. As an example, biosensors relying on sweat use glucose oxidase (GOx) as the biorecognition component, which transforms glucose into electrochemical signals that can be measured. These AI-based wearable sweat-glucose are important in continuous glucose monitoring (CGM) to treat diabetes. The recent developments of laser-induced patches of graphene electrodes and microfluidics sensors improved sensor stability and selectivity to the analyte (Pennsylvania State University, 2023) [101]. In addition to glucose, lactate biosensors are also used in sports medicine to detect fatigue and metabolic strain that can be used to optimize training and recovery.

8.3 Respiratory Monitoring

Wearable respiratory biosensors are aimed at tracking the breathing rate, oxygen saturation (SpO2), and the airflow patterns, which are extremely important data to manage asthma, chronic obstructive lung disease (COPD), and sleep apnea. These sensors usually use piezoresistive or optical transduction modes built into smart fabrics, or belt chests, or even adhesive patches. Contactless and wearable respiratory devices have been advanced significantly in clinical and home practice. Also, new nanomaterial devices, including hexagonal boron nitride ink sensors, have shown rapid response and high sensitivity in the detection of subtle respiratory changes [102]. Although these developments have taken place, issues like motion artifacts, humidity sensitivity and user discomfort still restrict prolonged use.

8.4 Mental Health Monitoring

The use of wearable biosensors in mental health is a new area that aims at discovering physiological markers of stress, anxiety, and depression. Such gadgets track variables like heart rate variability (HRV), electrodermal activity (EDA), skin temperature, and cortisol concentration to deduce the emotional states. As artificial intelligence (AI) and machine learning are unified, biosensor data can be used to anticipate psychological distress and facilitate early interventions [103]. As an illustration, HRV and EDA multi-sensor platforms have been shown to be correlated with acute stress events allowing real-time mental state to be measured. Nevertheless, ethical issues, such as privacy of data, interpretability of the model, and long-term behavioral effects are still burning issues to clinical translation.

8.5 Sleep and Activity Monitoring

One of the most widely used technologies in commercial and clinical environments is wearable biosensors of sleep and physical activity. Gadgets that have accelerators, gyroscopes, and photoplethysmography (PPG) sensors track sleep time, sleep phases, and circadian cycles. More sophisticated devices also include wearable electroencephalography (EEG) and actigraphy in order to distinguish between sleep phases and identify disorders like insomnia and sleep apnea. Wearable EEG allows precise monitoring of sleep at home and helps to measure the quality and activity of sleep in older adults in inpatient conditions [104, 105]. Moreover, these sensors monitor daily steps, energy consumption, and sedentary habits and enable people to lead healthier lifestyles. Nonetheless, the differences between consumer-friendly wearables and clinical polysomnography are a current research dilemma [106, 107].

9. Future Perspectives

The future of wearable biosensors is to merge them with genomics, digital twins, and personalized medicine, which will open the door to highly personalized approaches to health care. Clinicians can use real-time physiological measurements provided by biosensors along with genomic and proteomic data to customize disease prevention, diagnostics, and treatment strategies according to the specific biology of a patient [39,108]. This methodology favors the idea of digital twins - virtual patient models that are constantly being updated with wearable measurements to model disease progression, predict treatment effects, and in silico test therapeutic interventions prior to their real-world implementation [109]. The pilot studies conducted in cardiovascular and oncology care recently have shown the promise of digital twins to optimize therapy, decrease adverse events, and allow the planning of adaptive therapy [110].

Smart tattoos, microneedle arrays, and epidermal electronics are some of the innovations that are changing the physical interface between machines and the human body. These highly conformal devices are ultra-thin, comfortable, allow all-time monitoring, and are biocompatible to be used long-term [40, 111]. As an example, electronic tattoos have been created on graphene to detect hydration level, electrolyte levels and lactate concentrations with great sensitivity, which opens the way to implants that are non-invasive and yet robust enough to perform clinically useful functions [41, 112]. Biosensors can be implanted into the microneedles, which can then monitor glucose, cortisol, or therapeutic drugs continuously in interstitial fluid, increasing the range of point-of-care diagnostics [113].

The combination of AI and self-diagnostic platforms is transforming the diagnostic options of wearable biosensors. Multivariate physiological signals can be combined using advanced machine learning and deep learning algorithms to detect subtle patterns, predict acute clinical events, and automatically institute triage or teleconsultations without clinical supervision [42, 114]. Furthermore, AI-based cloud services linked to wearables can be used to analyze disease trends at the population level and help detect ongoing outbreaks earlier and aid in making correct decisions in regard to the health of the population. Notably, the use of wearable biosensors in low-resource and rural areas has become an increasingly accepted aspect. Their portability, low power input, and the capability to operate without the need to have a permanent connection to the hospital infrastructure make them useful in telemedicine, maternal health monitoring, infectious disease surveillance, and chronic disease management in underserved populations [43].

The experience in deployments in far-flung locations in Africa and Southeast Asia has shown that mobile-linked biosensors can enhance antenatal care, identify early signs of sepsis and monitor vital signs in poorly served patients [115]. In the future, interdisciplinary efforts by materials scientists, AI engineers, and clinicians will be necessary to guarantee the reliability, affordability, and scalability of such innovations and eventually make them standard-of-care instruments [116].

10. Conclusion

With wearable biosensors, real-time health monitoring and disease prediction are quickly becoming groundbreaking as they offer unprecedented opportunities to personalized, preventive, and participatory healthcare. These devices allow timely intervention and better patient outcomes through early diagnosis due to the continuous and non-invasive monitoring of vital physiological and biochemical markers. Despite the limitations, especially sensor accuracy, long-term stability, data security, interoperability, and regulatory compliance, artificial intelligence, smart materials, and bioelectronic integration will be in a good position to address these issues. A collaborative, interdisciplinary approach involving biomedical engineers, materials scientists, clinicians, data scientists, industry stakeholders, and policymakers is the way forward. This type of collaboration is very necessary to make sure that future wearable biosensors are precise, trustworthy, safe, and cost-effective and also meet international regulatory and ethical requirements. Notably, the continued acquisition and creation of wearable biosensors must be in line with the World Health Organization Global Strategy on Digital Health (2023) and the United Nations Global Digital Compact, which both focus on providing equitable access, privacy of data, and interoperability in digital health systems. With these technical and social issues addressed, wearable biosensors can develop out of current innovations into essential instruments in most clinical care, eventually becoming parts of more fair, effective, and customized healthcare systems across the globe.

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