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Review

Wearable Sensors for Health Monitoring

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Abstract

Growing global populations and the rapid increase in older adults are driving healthcare costs upward. In response, the healthcare system is shifting toward models that allow for continuous monitoring of individuals without requiring hospital admission. Advances in sensing technologies, embedded systems, wireless communication, nanotechnology, and device miniaturization have made it possible to develop smart systems that continuously track human activity. Wearable sensors can monitor physiological indicators and other symptoms, helping to detect unusual or unexpected events. This enables timely assistance when it is needed most. This paper outlines these challenges and reviews recent developments in wearable sensor–based human activity monitoring systems. The focus is on health monitoring applications, including relevant biomarkers, wearable and implantable sensors, established sensor technologies currently used in healthcare, and the future prospects and challenges involved in researching, developing, and applying these sensors to support widespread use in human health monitoring.

Keywords: health monitoring; wearable sensors; implantable sensors; biomarkers; sensors; biochemical monitoring; body fluid analysis; screening and early diagnostics

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1. Introduction

Over the past several decades, the rapid evolution of sensing technologies, flexible electronics, and wireless communication has transformed the way physiological signals can be measured and interpreted. Among these advancements, wearable sensors have emerged as powerful tools capable of continuously monitoring key health indicators in real time. Their increasing popularity across security, entertainment, commercial, and especially medical domains reflects a broader shift toward decentralized, personalized, and preventive healthcare models. As global populations age and chronic diseases become more prevalent, the demand for systems that enable unobtrusive, long-term monitoring outside of clinical settings continues to grow.

In the medical field, wearable and implantable sensors offer unique opportunities to assess human activity and physiological function with high temporal resolution. These devices can non-invasively measure vital parameters—including cardiovascular signals, body temperature, biochemical markers, and metabolic indicators—providing insights that were previously accessible only through hospital-based equipment. By capturing dynamic physiological changes, wearable sensors help detect early signs of illness, monitor disease progression, and support timely interventions, thereby improving quality of life and reducing healthcare costs.

Recent advancements in materials science, nanotechnology, and printed electronics have enabled the fabrication of highly flexible, stretchable, and biocompatible sensing platforms that closely conform to the human body. Such technologies are now capable of measuring complex biochemical analytes in sweat or interstitial fluid, tracking motion and posture, or continuously monitoring heart rate, blood pressure, and temperature. At the same time, progress in miniature power systems and wireless data transmission supports seamless integration into everyday life.

This review presents an overview of the state of the art in wearable and implantable sensors for health monitoring. It highlights key physiological signals and biomarkers, discusses major sensing mechanisms and materials, and examines recent developments in device design and fabrication. Furthermore, it outlines current challenges and emerging prospects for translating these technologies into robust, user-friendly systems suitable for widespread adoption in healthcare.

2. Wearable and Implantable Health Monitoring Sensors

2.1. Wearable Sensors

Wearable sensors are the primary tools for detecting physiological signals from the human body. These devices can measure a range of parameters, including blood glucose levels, heart rate, respiratory rate, and body motion [1]. Each parameter provides essential information about health and bodily function, and the sensors used to detect them operate through different underlying mechanisms.

2.1.1. Physiological Sensors

2.1.1.1. Cardiovascular Monitoring System

Continuous monitoring of heart rate and pulse is essential for both the prevention and diagnosis of cardiovascular diseases (CVDs). The heart's primary function is to pump blood throughout the body, maintaining tissue perfusion, recycling venous blood, and enabling metabolic exchange processes [2]. Heart rate reflects the frequency of cardiac cycles, and in clinical settings, both heart rate and pulse serve as fundamental indicators of cardiac function [3,4].

CVD remains one of the leading causes of mortality worldwide, responsible for more than 17 million deaths annually—approximately 31% of global deaths [5]. This number is projected to rise to 23.6 million by 2030 [6]. Despite this high mortality rate, up to 90% of CVD cases are preventable through early detection [7]. Heart rate and pulse provide vital information that supports timely prevention and treatment of cardiovascular conditions [8]. Although CVDs are typically asymptomatic in their early stages, they already affect arterial pulse characteristics, influence blood pressure, and alter wrist pulse waveforms [9].

Traditional cuff-based sphygmomanometers are still widely used in clinical practice to measure systolic and diastolic blood pressure [10,11]. However, this indirect method does not enable continuous monitoring. To overcome this limitation, authors have proposed a flexible blood pressure sensor based on ultrathin, lightweight graphene tattoo sheets [12].

When placed over a wrist artery, a small electrical current is applied to the skin to measure bioimpedance, and machine learning models correlate fluctuations in this signal with blood pressure to enable continuous monitoring. Another study introduced a flexible blood pressure sensor based on piezoelectric composite ultrasonic technology, representing a significant departure from conventional approaches [13]. In this design, PDMS and conductive silver nanowires were integrated using a dice-and-fill technique, yielding a highly flexible sensor.

The electrical activity of the heart is commonly assessed using the electrocardiogram (ECG), which provides essential insights into cardiovascular health. Because ECG signals are periodic, heart rate can be derived from R-to-R (RR) intervals [2]. Traditional ECG monitoring typically relies on gel-assisted Ag/AgCl electrodes, but their use can be inconvenient [14]. Skin-contact ECG sensors, by contrast, allow users to more easily monitor cardiac health and detect early signs of serious conditions such as cardiomyopathy, arrhythmias, and hypertension [15,16]. However, Ag/AgCl electrodes may cause skin irritation [14,17], which has driven increasing interest in flexible dry electrodes. One reported example is a flexible, wearable electrode in which highly conductive silver was deposited onto cowhide via plasma sputtering [18]. Tests on six subjects showed that the resulting ECG signal quality was comparable to that obtained using standard Ag/AgCl electrodes.

Plethysmography and ultrasound are also widely used to monitor pulse and heart rate [19], but the bulkiness of the equipment and difficulties maintaining accuracy during long-term measurements limit their suitability for wearable systems [20,21]. To address these limitations, a flexible strain sensor for real-time pulse monitoring was recently introduced [22]. This patch-type device employs highly sensitive, flexible polyaniline to detect pressure variations generated by blood flow, enabling the analysis of pulse characteristics for clinical applications. Further developments led to the creation of a flexible pressure sensor capable of simultaneously monitoring three pulse positions [23]. This device integrates traditional Chinese pulse diagnosis with modern sensor technology. Ionogel-based pressure sensor arrays were fabricated on PET substrates, converting arterial pressure fluctuations into changes in electrical resistance. A notable advantage of this system is its ability to generate three-dimensional pulse maps that present key information—including pulse strength and waveform—closely mimicking a physician's tactile assessment.

Another successful example of a flexible pulse sensor is based on poly(vinylidene fluoride-co-trifluoroethylene) (PVDF-TrFE) [24]. This device integrates analog amplification circuitry and sensing components onto a flexible substrate capable of detecting low pressures (down to 10 kPa) and increasing electrical signal strength tenfold. These characteristics make it highly effective for monitoring human pulse signals.

2.1.1.2. Activity Monitoring System

Motion or activity monitoring of moving objects is a widely studied topic in the field of wearable electronics. Most wearable motion-detection systems rely on strain sensors, in which variations in baseline resistance serve as indicators of motion-related activities [25,26]. Motion detection is particularly valuable for prosthetic limbs, soft robotics, and for individuals with physical impairments or elderly persons who require continuous remote activity monitoring [27,28]. However, many state-of-the-art sensors and systems suffer from significant drawbacks—including bulkiness, rigidity, limited wearability, and excessive weight—which make continuous monitoring difficult [27,28]. Consequently, substantial research efforts have focused on developing lightweight wearable systems using thin-film electronics and sensors printed directly onto flexible polymeric or textile substrates [29]. These wearable platforms—often referred to as electronic skins—are equipped with various sensors designed to mimic the sensory functions of human skin [30,31]. Different strategies have been explored to create such sensors, including the use of discrete sensing elements distributed across multiple body regions or fully integrated systems embedded within a connected wearable suit [28,32]. Soft motion-sensing suits typically incorporate sensors positioned at joints that articulate during movement, thereby activating the sensing elements. One example is human gait monitoring, where strain sensors embedded in a wearable suit capture motion patterns [33]. In another development, strain sensors made from liquid metal embedded in elastomers were placed on the hip, knee, and ankle joints to measure bending angles [27].

Nanoscale materials play a significant role in designing motion-detection sensors, either in their pure form or as composites mixed with elastomeric polymers. Embedding conductive fillers into rubber-based matrices is especially advantageous due to their high stretchability and ease of integration onto non-planar surfaces. For instance, natural rubber infused with liquid-exfoliated graphene has been used to form a conductive composite [34]. This structure exhibited a 10^4-fold increase in resistance at strains up to 800%, demonstrating high sensitivity and a dynamic response suitable for continuous motion monitoring when mounted on joints or other moving body parts. Silver nanowires printed using Ecoplex as a dielectric layer have also been utilized to fabricate capacitive sensors for multifunctional wearable applications [35]. These sensors were capable of detecting strain, pressure, temperature, and touch under various physiological conditions.

Another notable approach employed a double-helical carbon nanotube (CNT) array to create a strain sensor for hand-motion detection [36]. This design enabled strain measurements up to 410% with low hysteresis and high sensitivity to subtle movements. Additionally, CNT/Ecoflex nanocomposites have been used to produce ultra-stretchable, skin-mountable strain sensors for motion monitoring [37]. In these composites, the CNT percolation network forms conductive pathways, while the Ecoflex matrix accommodates the large deformations associated with joint or muscle motion, resulting in resistance changes corresponding to expansion levels.

Further work has explored 3D printing of CNT/polyurethane nanocomposites in which thin extruded filaments serve as strain sensors [38]. Similarly, CNT/PDMS nanocomposites have shown strong potential for wearable, strain-based motion detection [39–41]. The capability of 3D printing enables precise control over CNT/polyurethane mixing ratios and viscosities, facilitating the fabrication of composites optimized for percolation and ideal for strain-sensing applications. In another development, a multifunctional sensing device was printed on a flexible substrate, incorporating Ag, CNTs, PEDOT:PSS, and ZnO to detect multiple physiological signals in real time [42]. These sensor patches comprised both disposable and non-disposable components: the disposable component adhered to the skin and integrated printed sensors for tracking temperature, acceleration, and ECG signals, and included kirigami structures to accommodate skin deformation.

Recent advances also include the development of a novel composite consisting of a conductive sponge made from carbon black impregnated into a shear-thickening gel and polyurethane [25]. This sensor provided effective impact protection—reducing applied forces by 44%—while simultaneously monitoring human motion. Additionally, strain sensors based on liquid metals and conductive iono-elastomers have garnered considerable interest for their ability to detect large deformations with high sensitivity [43,44].

2.1.1.3. Body Temperature Monitoring System

Wearable temperature sensors have been widely studied, with significant exploration of diverse sensing materials and printing technologies. In wearable applications, temperature sensors serve two primary purposes: continuous monitoring of human body temperature and measurement of ambient temperature. For body-temperature monitoring, sensors are typically mounted directly on the epidermis or maintained in close contact with the skin as detachable components of wearable devices [45]. Continuous body-temperature tracking is particularly important for patients with chronic illnesses, individuals who are unconscious or injured, people undergoing anesthesia or surgical procedures, and workers exposed to extreme environmental conditions. Wearable temperature sensors are also crucial in electronic-skin technologies and are frequently investigated alongside other sensing systems aimed at advancing industrial and social robotics [46,47].

Printed thermal sensors generally operate by measuring resistance changes in metallic structures as temperature increases, with thermal coefficient of resistance (TCR) values used to quantify their response [48]. In recent years, numerous thermal sensors have been developed using intrinsically conductive materials and nanocomposites engineered into geometries optimized for flexibility and minimal bending constraints [49,50].

Fully printed fabrication methods simplify manufacturing and reduce cost, enabling the creation of single-layer patterned conductive lines in various geometries such as meanders, spirals, and circles. In one example, a polymeric blend containing SWCNTs was used to simultaneously detect temperature and CO_2 gas [51]. Direct attachment of sensors to the epidermis requires substrates with skin-like properties—biocompatibility, breathability, oxygen permeability, and waterproofing—yet meeting all these requirements remains challenging. To address this, breathable and stretchable temperature sensors inspired by human skin have been developed [52]. Additional work includes transfer-printed copper strips on semi-permeable polyurethane films and an inkjet-printed graphene/PEDOT:PSS temperature sensor fabricated on a skin-conformable polyurethane substrate, eliminating the need for photolithography [53].

Skin-mounted biosensors capable of simultaneously detecting sweat metabolites, electrolytes, and temperature have been integrated into a single wearable patch designed for prolonged use during exercise [54]. A related approach enabled concurrent measurement of sweat pH using an ion-selective field-effect transistor (ISFET) and skin temperature using an embedded temperature sensor

[55]. Silver-based interconnects were printed, and PEDOT:PSS served as the temperature-sensing material. Real-time testing was performed by attaching the patch to a subject’s neck during exercise.

Recent advances have also investigated the printing and performance of nanoscale sensing materials. Resistance variations in sensing layers connected by conductive pastes were evaluated under temperature changes. A comparative study of carbonaceous materials—including rGO, SWCNTs, and MWCNTs—assessed responsivity and long-term stability [56]. Reduced graphene oxide (rGO) displayed strong and stable performance under varying environmental conditions, including humidity, pressure, and gas exposure, and remained responsive even when coated with protective insulating layers. Graphene nanowells exhibited exceptionally high TCR values (up to 180% K^{-1}), making them strong candidates for human-body temperature monitoring [57].

A biocompatible conductive “green” electrolyte composed of aliphatic diol–calcium chloride ($CaCl_2$) complexes was also identified as a promising material for *in vivo* and *in vitro* temperature sensing, showing consistent resistance changes with temperature [50]. A customizable 3D-printed sensor capable of monitoring both temperature and pressure was developed using a skin-toned substrate for direct visual readout [58]. Through multilayer 3D integration, pressure and temperature sensors were merged into a single flexible patch. Furthermore, an innovative self-adhesive mechanism inspired by octopus suction cups was created using PDMS microstructures to ensure robust adhesion to the skin [59].

A resistance-based temperature sensor was developed using a nanocomposite of poly(N-isopropylacrylamide) (pNIPAM) hydrogel, PEDOT:PSS, and CNTs, exhibiting a strong thermal response of 2.6% $°C^{-1}$ within the human-temperature range (25–40 °C). A highly stretchable and self-healing thermistor based on a polyacrylamide/carrageenan double-network (DN) hydrogel also demonstrated stretchability up to 330% strain and a sensitivity of 2.6% $°C^{-1}$ at high strain levels [60], making it suitable for placement on joints or irregular surfaces and closely mimicking the self-healing behavior of human skin.

Precise temperature feedback is essential for monitoring active heating in applications such as heat therapy, perioperative care, and controlled transdermal drug delivery. Integrated wearable temperature sensors have been employed for these purposes [61]. Stretchable aluminum heaters combined with gold-based resistance temperature detectors (RTDs) were implemented in a tattoo-like wearable patch fabricated using a cut-and-paste method, enabling conformal attachment to any body area without restricting movement [60]. Collectively, these developments highlight the strong and growing interest in advancing wearable temperature-sensing technologies across diverse application domains.

2.1.1.5. Blood Oxygen Saturation (SpO_2) Monitoring System

Blood oxygen saturation (SpO_2) is a critical vital sign that reflects the percentage of oxygen-bound hemoglobin in arterial blood. Continuous SpO_2 monitoring is essential for managing respiratory diseases, cardiovascular conditions, sleep disorders, and critical care [62]. Wearable SpO_2 technologies—integrated into smartwatches, rings, earbuds, and skin patches—have rapidly evolved from traditional clinical pulse oximeters to compact, low-power platforms capable of long-term, non-invasive physiological tracking. This evolution has been driven by advances in optical sensing, noise-reduction algorithms, flexible electronics, and wireless connectivity.

These wearable systems enable real-world physiological assessment, offering trend-based insights into conditions such as sleep apnea, chronic obstructive pulmonary disease (COPD), and silent hypoxemia. During the COVID-19 pandemic, wearable oximeters became widely used for remote patient monitoring, underscoring their clinical relevance [62]. Beyond conventional fingertip devices, modern wearable oximeters provide continuous and unobtrusive monitoring of blood oxygenation across multiple form factors.

Despite significant progress, accuracy challenges persist—particularly under high-motion conditions, in individuals with darker skin tones, and in low-perfusion states. Ensuring equitable performance, lowering energy consumption, and improving calibration strategies remain important goals for future development. As these technologies continue to advance, wearable SpO_2 systems are poised to play an increasingly important role in telemedicine, chronic disease management, sleep diagnostics, and personalized health monitoring.

2.1.2. Biological Fluid Based Sensors

2.1.2.1. Glucose Sensors

Diabetes is a widespread chronic disease that poses serious global health risks. Millions of individuals are affected worldwide, and it remains one of the leading causes of mortality each year according to the World Health Organization (WHO) [63,64]. The primary cause of diabetes is the dysfunction or depletion of insulin production, which leads to irregular glucose levels; therefore, frequent monitoring of glucose concentration is essential to prevent severe complications. Glucose biosensors have undergone extensive development since the first-generation device was introduced in 1962 by Clark and Lyons at Cincinnati Children's Hospital [65]. A variety of human physiological fluids—including blood, urine, sweat, saliva, interstitial fluid, ocular fluid, and breath—contain glucose biomarkers suitable for diagnostic purposes [66,67].

Enzymatic sensing, particularly using glucose oxidase (GOx), remains the most widely adopted method for selective glucose detection [67]. In this approach, redox reactions at the sensor interface generate measurable decreases in oxygen concentration and release hydrogen peroxide (H_2O_2), both proportional to glucose levels. Initially developed for laboratory-based blood analyses, glucose monitoring technologies have rapidly evolved into handheld devices for rapid point-of-care testing. Modern glucometers typically rely on disposable enzyme-activated electrode strips [67]. Comprehensive reviews of glucose sensors and recent advancements in portable detection systems are provided elsewhere [66–69].

With the rapid growth of microelectronics on unconventional substrates—especially wearable and conformable materials—glucose sensors have attracted substantial research interest [70]. Wearable and implantable glucose sensors enable *in vivo* measurements that allow continuous, real-time glucose tracking and improved self-management of diabetes [71].

Emerging technologies such as the Internet of Things (IoT) enable clinicians to monitor patient data remotely through cloud-based systems [72]. Several recent proof-of-concept devices have demonstrated practical real-time glucose-monitoring capabilities. One example is an all-printed, tattoo-based glucose sensor designed for noninvasive glycemic monitoring [73]. This device operates through epidermal sensing by combining reverse iontophoretic extraction of interstitial glucose with enzyme-based amperometric detection. Screen printing was used to fabricate the electrodes: silver (Ag) and silver chloride (AgCl) served as the reference and counter electrodes on a Papilio transfer-paper substrate, while conductive carbon ink formed the working electrode. Comparative in vitro and on-body measurements demonstrated strong potential for detecting micromolar glucose concentrations.

Another innovative development is a wearable sensor array for multiplexed perspiration analysis [74]. This fully integrated platform simultaneously monitored multiple sweat biomarkers—including glucose, lactate, sodium, and potassium ions—along with skin temperature. Electrochemical glucose and lactate sensors employed Ag/AgCl electrodes, and ion-selective membranes were drop-cast for electrolyte detection. Tests performed during indoor and outdoor physical activities confirmed the system's effectiveness for personalized diagnostics and real-time health monitoring.

Functional nanoscale materials—including nanowires, nanoribbons, and nanotubes—are increasingly important for designing conformable wearable sensors. For instance, In_2O_3 nanoribbons were used to fabricate field-effect transistor (FET) sensors on PDMS substrates [75]. After lamination onto the skin, these sensors successfully detected glucose in sweat, tears, and saliva at concentrations as low as 10 nM. Another system integrated a sweat-based glucose sensor with a closed-loop transdermal drug-delivery module, enabling accurate glucose measurement with real-time correction for pH, temperature, and humidity variations [76]. These miniaturized devices were fabricated via clean-room processes and transfer-printed onto PDMS for skin-conformable operation.

Additional wearable sensing platforms include cotton fabrics printed with carbon graphite, Ag, and AgCl electrodes for lactate detection [77]. In another example, a spray-printed reduced graphene oxide (rGO) working electrode was integrated into a wrist-mounted sensor, yielding excellent amperometric responses for *in vivo* glucose detection in the 0–2.4 mM range [78]. A robust non-enzymatic wearable sensor patch, incorporating integrated signal-processing and wireless-communication modules, was also developed on flexible stainless steel [71]. Implanted into subcutaneous tissue, these sensors continuously monitored interstitial glucose levels.

Organic-material-based biosensors have likewise shown promise due to their compatibility with low-temperature fabrication and inherent biocompatibility. One such device used a PEDOT (poly(3,4-ethylenedioxythiophene))–glucose oxidase cross-linked film for amperometric glucose sensing [72]. A three-electrode system was patterned on a PET substrate and paired with front-end electronics to enable remote glucose monitoring.

Together, these advances in sensing materials, device architectures, and fabrication methods illustrate a rapidly progressing field, with wearable glucose-monitoring technologies poised for industrial-scale production in the near future.

2.1.2.2. Lactate Sensors

Lactate is a key metabolite in the human body, produced in muscle tissue during the anaerobic metabolism of glucose. Continuous lactate monitoring is particularly important during physical activity—especially for athletes—to prevent cell acidosis, which can severely impair muscle performance [79,80]. Several human body fluids contain measurable lactate concentrations. For example, blood typically contains 0.5–1.5 mM lactate in healthy individuals at rest, with levels rising to approximately 12 mM during intense exercise 81. Other fluids—such as tears, saliva, and sweat—exhibit distinct lactate concentrations [79,81,82]. For practical wearable applications, lactate sensors should be noninvasive and ideally operate using sweat or interstitial fluid analysis [83,84].

Selectivity is essential because body fluids contain numerous other metabolites. Consequently, most wearable electrochemical lactate sensors employ enzymes such as lactate oxidase for selective detection, although non-enzymatic approaches have also been explored [85]. Redox mediators are sometimes incorporated to enhance catalytic activity and improve sensing performance.

A printable, tattoo-based electrochemical biosensor was developed for real-time lactate monitoring during exercise [80]. This device used Ag/AgCl electrodes and functionalized multi-walled carbon nanotubes (MWCNTs) in a three-electrode configuration. It exhibited strong chemical selectivity for lactate, demonstrated linear detection up to 20 mM, and maintained stable performance under continuous mechanical deformation. A multiplexed sensor array capable of simultaneously measuring multiple metabolites, electrolytes, and skin temperature was also demonstrated on a soft, flexible substrate [86]. This fully integrated wearable patch could be comfortably worn on the wrist or as a headband.

Hybrid sensing systems that combine biochemical and electrophysiological monitoring represent an advanced approach to wearable health tracking [87]. In one such system, Ag/AgCl electrodes were screen-printed and lactate oxidase was used as the selective enzyme. When mounted on the skin, the patch enabled simultaneous measurement of both electrical and chemical signals without cross-interference. A non-enzymatic lactate sensor was also fabricated using screen printing, in which the working electrode was electropolymerized with 3-aminophenylboronic acid (3-APBA) imprinted with lactate [85]. This device achieved a detection range of 3–100 mM, a detection limit of 1.5 mM, and a response time of 2–3 minutes.

Textile-based printed amperometric biosensors have additionally been demonstrated for lactate monitoring [88]. Carbon graphite and Ag/AgCl inks were deposited onto cotton fabric as the working, reference, and counter electrodes, respectively. After immobilization with lactate oxidase, these sensors achieved a detection range of 0.05–1.5 mM within five minutes. A tube-shaped painted biosensor also showed strong potential as a portable and user-friendly biochemical sensing platform [84]. Its interior surface was printed with carbon graphite and Ag/AgCl to form an electrochemical cell suitable for lactate detection.

Furthermore, graphene nanowells were printed alongside Ag/AgCl electrodes to create an electrochemical biosensor capable of real-time lactate detection [89]. Testing in fluids such as deionized water and phosphate-buffered saline demonstrated a wide detection range from 1.0 μM to 10 mM, accommodating conditions that mimic diverse physiological environments.

Lactate sensing remains a major research focus in wearable electronics. Rapid progress in sensing materials, device integration, and fabrication techniques points toward strong potential for commercial adoption in the near future.

2.1.2.3. pH Sensors

pH represents the measure of acidity or alkalinity—the caustic or basic characteristics—of a target solution. Accurate pH measurement is fundamental across numerous environmental, biological, and chemical processes, and a wide range of detection methods has been developed over time [90]. Traditional pH sensing relies on potentiometric, chemiresistive, optical, mass-based, and capacitive techniques. Conventionally, pH is measured using glass electrodes or ion-selective field-effect transistors (ISFETs). However, mechanical rigidity, the need for a reference electrode, and the risk of electrolyte leakage present challenges for miniaturization and for wearable applications on irregular surfaces [91].

As a result, newer strategies—particularly chemiresistive sensing—have gained prominence as low-cost, miniaturizable approaches suitable for wearable devices with minimal signal degradation. Monitoring pH in various physiological fluids, especially sweat, has received increasing attention because pH correlates directly with multiple health conditions. For example, patients with type II diabetes or kidney stones often exhibit lower pH levels than healthy individuals [92], and many skin disorders are also associated with abnormal pH values. Therefore, skin-mounted, noninvasive, *in vivo*, real-time pH monitoring is expected to play a crucial role in the early diagnosis of several medical conditions [93]. Human skin itself reflects changes in body pH, making it an excellent site for continuous monitoring.

Hydrated skin tends to be more acidic, whereas dehydrated skin becomes slightly more basic. Current research therefore focuses on developing sensors capable of distinguishing between such physiological states. One example is an electrochemical device integrated with data-acquisition and signal-conditioning circuits for continuous, real-time monitoring of pH and calcium concentrations in body fluids [92]. The sensing results were validated using spectrometry and commercial pH meters, demonstrating high repeatability and selectivity. A capsule-sized implantable pH sensor prototype was also developed for gastroesophageal reflux monitoring [94]. This system used interdigital electrodes for impedance and pH detection, operating wirelessly through external transponders.

Wearable and textile-based approaches have also been explored. Cotton-yarn-based conductive wire electrodes were proposed for detecting pH and other analytes in the human body [95]. Carbon nanotubes (CNTs) served as the conductive filler and were coated with a polymeric membrane to form ion-selective electrodes. Functionalization plays a critical role in CNT-based sensing: biofunctionalized, inkjet-printed CNTs were demonstrated for pH detection [96], where the sensing mechanism relied on doping and dedoping of CNTs by hydronium and hydroxide ions. Multiple printing cycles improved conductivity and ensured reproducible sensitivity and fast response times.

Screen-printed thick films of Ag/AgCl/KCl electrodes have also been developed for simultaneous pH and temperature sensing [97]. Metal-oxide-based printed layers, such as screen-printed TiO_2 thick films, were investigated for pH measurement and water-quality analysis [90]. In these devices, screen-printed interdigitated electrodes (IDEs) paired with TiO_2 sensing layers exhibited impedance changes strongly correlated with pH variations. More recently, high-resolution aerosol-jet printing has been employed to fabricate CNT-based serpentine sensing layers with Ag electrodes [91]. The resulting miniaturized sensors exhibited rapid response times, high sensitivity, and promising biocompatibility for potential live-cell applications.

Overall, extensive research progress—from simple, scalable fabrication techniques on flexible substrates to advanced nanomaterials and robust real-time detection mechanisms—highlights the strong momentum toward future adoption of wearable pH-sensing devices. Table 1 summarizes the sensing approaches, materials, substrates, and mechanisms used in fluid-based pH sensing systems.

Table 1. Summary of representative materials, substrates, sensing mechanisms, and fabrication procedures used in fluidic-based sensor systems [98].

Sensor type	Materials	Substrates	Mechanism	Fabrication	References
Glucose sensors	Ag/AgCl	Polyurethane	Iontophoresis	Screen printing	[64]
	Cr/Au, Cr/Pt	PI / PDMS	Electrochemical	Transfer printing	[99]
	In2O3	PET	Transconductance by using FET	Shadow masking	[75]
	Ag/AgCl	PET	Chronoamperometric	Lithography	[70]
	nPt	Flexible stainless steel	Electrochemical	Electroplating	[65]
	Ag/AgCl, PEDOT-PSS	PET	Amperometric	Vacuum deposition	[100]
	Graphene oxide, Au, Pt	PI	Amperometric	E-beam evaporation	[78]
Lactate sensors	Carbon, Ag/AgCl	Textile (cotton)	Amperometric	Screen printing	[88]
	Carbon, Ag/AgCl	Polymeric tubes	Amperometric	Manual printing	[84]
	Graphene oxide, Ag/AgCl		Electrochemical	Screen printing	[80]
	MWCNTs, Ag/AgCl	Paper (Papilio)	Electrochemical	Screen printing	[73]
	Ag/AgCl	PET	Electrochemical (chronoamperometric)	Lithography	[70]
	Carbon, Ag/AgCl	PET	Electrochemical	Screen printing	[83]
	3-aminophenylboronicacid (3-APBA)	PET	Impedimetric	Screen printing	[81]
pH sensors	Au, Polyaniline, CNT	PDMS	Electrochemical	Layer by layer (LBL)	[93]
	CNT, Ag	PI	Conductimetric	Aerosol jet printing	[87]
	SWCTs	Liquid crystal polymer	Conductimetric	Inkjet, Screen printing	[92]
	Ag/AgCl, KCl, RuO2	Glass	Electrochemical	Screen printing	[95]
	TiO2	Alumina	Electrochemical	Screen printing	[85]
	PVB-Ag/AgCl,PANI	PET	Electrochemical	Electrochemical deposition	[89]

2.1.2.4. Cholesterol Sensors

Cholesterol monitoring is essential for maintaining human health, as elevated serum cholesterol levels are strongly correlated with increased risks of cardiovascular and cerebrovascular diseases, including heart disease, stroke, hypertension, coronary artery disease, arteriosclerosis, and cerebral thrombosis [101]. Accordingly, substantial research efforts have focused on developing highly sensitive cholesterol biosensors employing a range of detection mechanisms. Recent advances in strategies to enhance the selectivity and sensitivity of enzymatic cholesterol sensors have been comprehensively reviewed elsewhere [102].

An integrated array of field-effect transistors (i-FETs) has been demonstrated for the simultaneous and selective detection of multiple analytes—specifically cholesterol, glucose, and urea [101]. In this system, ZnO nanorods serve as the functional sensing elements, improving device stability and enabling rapid, multi-analyte analysis. Despite such progress, comparatively limited work has addressed the fabrication of cholesterol sensors on polymeric substrates using printing-based manufacturing approaches. Wearable cholesterol-monitoring platforms remain in an early stage of development and require substantially more research, particularly with respect to material selection and the optimization of detection mechanisms.

2.2. Implantable Sensors

Implantable prototypes for healthcare applications constitute the second major class of wearable sensing systems. These devices are inserted into the human body to detect physiological abnormalities or administer micro-doses of therapeutic agents. Implantable sensors enable continuous, real-time monitoring of internal biochemical variations, providing a direct interface for molecular transport and physiological signal tracking. Among implantable technologies, two primary categories—neural sensors and drug-delivery systems—have been extensively investigated. The most widely adopted examples are invasive glucose-monitoring devices, including Blood Glucose Monitoring (BGM) and Continuous Glucose Monitoring (CGM) systems. Several minimally invasive commercial CGM platforms, such as Abbott's FreeStyle Libre 2 and Dexcom's G6, quantify glucose levels in the subcutaneous interstitial fluid (ISF). Despite their clinical utility, these devices can still cause discomfort or pain during application.

Self-Monitoring of Blood Glucose (SMBG) remains a common approach for point-of-care glucose assessment. This method requires a small blood sample obtained via finger prick, which is applied to a reagent strip containing enzyme-based components—typically glucose oxidase. The enzymatic reaction generates an electrical signal that is subsequently processed by the SMBG device to yield an accurate glucose concentration. SMBG systems are valued for their simplicity, reliability, and utility in daily glucose management. Nonetheless, they provide only single-time-point measurements and therefore fail to capture the full spectrum of glucose fluctuations occurring over a 24-hour period. Moreover, repeated finger pricking can cause discomfort and reduce patient adherence to regular monitoring [103]. A representative example is Abbott's FreeStyle Precision Neo meter—a compact device capable of analyzing extremely small blood volumes within seconds and equipped with integrated data storage and trend-analysis features.

Continuous Glucose Monitoring (CGM) systems offer a more advanced solution, employing a subcutaneous sensor to deliver real-time glucose data at frequent intervals. This continuous data stream provides users with a comprehensive view of diurnal glucose dynamics, enabling earlier detection of hyperglycemic or hypoglycemic events. CGM is particularly beneficial in individuals with highly variable glycemic profiles, offering substantially more information than SMBG. However, adoption remains limited by high cost, and device accuracy may decline during rapid glucose fluctuations, potentially influencing clinical decision-making [104]. The Dexcom G6 system exemplifies current CGM technology, featuring a subcutaneous sensor with a functional lifespan of up to 10 days and wireless transmission of real-time glucose readings to smartphones or other devices. Despite these advantages, accessibility and affordability remain significant challenges, underscoring the need for further innovation.

Although invasive approaches such as SMBG and CGM serve as the clinical gold standard, they exhibit several drawbacks. Frequent skin penetration or prolonged sensor implantation may cause pain, irritation, or user fatigue. Additionally, improper sterilization, reuse of lancets, or sharing of monitoring equipment can increase the risk of transmitting blood-borne pathogens, particularly in environments with limited availability of disposable medical supplies [105]. These limitations have intensified interest in developing non-invasive glucose-sensing technologies capable of providing accurate, continuous measurements without causing physical harm. Such innovations would substantially enhance patient comfort while mitigating safety risks associated with traditional

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invasive methods. Over recent decades, significant research efforts have been directed toward advancing a range of non-invasive strategies for continuous glucose monitoring.

3. Mature Applications of Health Monitoring Sensors

Several health-monitoring sensor technologies can be considered mature, stable, and widely adopted, with extensive validation and routine use at scale in clinical and consumer settings. These mature applications are listed in Tables 2 and 3.

Cardiovascular monitoring constitutes one of the oldest and most reliable application areas. Electrocardiography and heart-rate monitoring, implemented through Holter monitors, chest straps, and smartwatches, are well established for both diagnostic and longitudinal monitoring purposes. Blood pressure monitoring using oscillometric cuffs remains the clinical reference standard, while some cuff-less blood pressure measurement methods have now reached a sufficient level of maturity and validation for broader deployment. Pulse oximeters measuring peripheral oxygen saturation (SpO_2) are extensively used in hospital environments and are increasingly integrated into wearable devices.

Glucose monitoring represents another domain with highly mature sensor technologies. Continuous Glucose Monitors (CGM), such as those developed by Dexcom and Abbott FreeStyle Libre, are FDA-approved and widely used in diabetes management. These systems enable continuous measurement of glucose levels and have become integral to modern clinical practice for both type 1 and type 2 diabetes.

Activity and motion tracking technologies based on accelerometers and gyroscopes are also well established. These sensors are routinely used for step counting, fall detection, sleep monitoring, and sedentary behavior tracking. They are commonly embedded in fitness bands and smartwatches, as well as in medical-grade wearables used for clinical monitoring and functional assessment.

Respiratory monitoring has a long history in clinical care and has expanded into wearable formats. Respiration rate sensors based on impedance measurements and chest-worn bands are widely used, while capnography remains a standard technique in clinical settings, particularly in anesthesia and intensive care. Wearable respiratory belts are now deployed both at home and in hospitals for continuous respiratory monitoring.

Temperature monitoring technologies are similarly mature. Digital skin temperature sensors and ingestible temperature sensors have long been used in clinical and research settings. More recently, continuous temperature patches have been introduced and are applied in fever tracking, fertility applications, and longitudinal physiological monitoring.

Sleep monitoring is a well-established field with both clinical and consumer applications. Polysomnography, incorporating electroencephalography (EEG), electromyography (EMG), airflow sensors, SpO_2 measurement, and thoracic effort sensors, is fully mature and remains the clinical gold standard. In parallel, wearable sleep trackers, including devices such as Fitbit and Oura, have reached a reasonable level of maturity and are widely used for sleep monitoring outside clinical laboratories.

Implantable sensors represent some of the most mature health-monitoring technologies. Cardiac pacemakers and implantable cardiac monitors have decades of proven clinical use, providing continuous cardiac sensing and therapy. Cochlear implants similarly represent a long-established class of implantable sensor systems with extensive clinical validation.

Gait and rehabilitation monitoring has also benefited from mature sensing solutions. Inertial Measurement Units (IMUs) are widely used for gait analysis and for tracking physical therapy and rehabilitation progress, with broad adoption in sports medicine and rehabilitation settings.

Finally, environmental and physiological stress sensors have achieved stable commercial deployment. Skin conductance sensors measuring electrodermal activity (EDA) are used for stress monitoring in mature products such as the Empatica E4, while UV exposure sensors are increasingly integrated into wearable devices to monitor environmental exposure.

Together, these applications represent a set of health-monitoring sensor technologies that are characterized by technical stability, clinical validation, regulatory acceptance, and large-scale use in both clinical practice and consumer health monitoring.

Table 2. Mature Health-Sensor Applications with Example Devices.

Sensor / Application	Wellness Devices	Clinical Devices
Heart rate / ECG	e.g. Samsung Galaxy Fit 3: a fitness tracker that monitors heart rate, steps, sleep, general activity	Clinical ambulatory ECG monitors (patches or Holter devices) for rhythm monitoring
Blood Oxygen (SpO_2)	e.g. One Medical Oxy One Pro: a fingertip pulse oximeter available to general consumers	Hospital-grade pulse oximeters used for respiratory monitoring
Activity / Steps / Movement	e.g. Amazfit Helio Strap: wearable tracker for steps, activity, sleep, daily movement	Clinical-grade activity/rehabilitation trackers (e.g. inertial measurement units in gait labs) for rehab, mobility assessment
Sleep Tracking	Many smartwatches or fitness bands (e.g. via accelerometer + heart-rate) for general sleep patterns	Clinical-grade sleep monitoring systems (polysomnography) for sleep disorders diagnosis
Blood Pressure (Home Monitoring)	Some smartwatches / wrist devices attempt BP estimation (requires calibration)	Dedicated home blood-pressure monitors (arm cuffs) or clinic sphygmomanometers - standard medical devices
Continuous Glucose Monitoring (CGM)	Consumer-grade CGM still limited	Dexcom CGM - widely used by people with diabetes to continuously monitor interstitial glucose
Respiratory Rate / Oxygenation (for sleep apnea, COPD, lung disease)	Some wearables attempt estimation of breathing rate, but with limited accuracy	Clinical respiratory monitors, pulse oximeters, capnography used in hospitals or at-home under supervision
Skin Temperature / Body Temperature	Smart thermometers or wearable “wellness” patches (non-invasive)	Medical-grade temperature monitors for fever tracking/hospital use. (Often part of vital-sign monitoring devices.)
Fall Detection / Emergency Alert	Smart bracelets/watches with accelerometer + gyroscope + fall detection features	Clinical alert systems (sometimes combined with ECG/SpO_2 monitors) for elderly care or chronic disease management
ECG Holter / Extended Cardiac Monitoring	Some “semi-consumer” portable ECG devices (more for wellness or preliminary screening)	Full Holter monitors, ambulatory ECG patches - gold standard for arrhythmia diagnosis
Remote Patient Monitoring (multi-parametric: HR, SpO_2, ECG, etc.)	Limited - some connected wearables with several sensors, but generally non-medical	Hospital-at-home devices, “vital-sign monitors” used in telemedicine / home care settings
Smart Clothing / Textile Sensors	Emerging: sensor-embedded garments for activity, basic vital signs (accelerometer, PPG, etc.)	Smart textile systems used in clinical monitoring or rehabilitation for continuous monitoring

4. Prospects and Challenges

Wearable sensors—such as photoplethysmography (PPG) watches, inertial measurement units (IMUs), ECG patches, smart textiles, and biochemical sensors—have become central to modern digital health. Their rapid development has been driven by advances in miniaturized electronics, wireless communication, ultra-low-power systems, and AI-based analytics. The literature widely recognizes their potential for continuous health monitoring, remote patient management, and preventive medicine, while also emphasizing significant methodological, regulatory, and ethical challenges.

Wearables enable persistent monitoring of physiological and behavioral parameters, including heart rate, respiration, physical activity, and sleep, beyond traditional clinical environments. Continuous data acquisition supports longitudinal tracking and the early detection of physiological deviations, enabling earlier intervention compared with episodic clinical measurements [106,107]. Machine-learning methods applied to wearable sensor data have demonstrated the ability to identify subtle trends predictive of disease onset, including cardiac arrhythmias, sleep disorders, metabolic dysregulation, and stress-related conditions [108,109].

Wearable technologies have shown clinical utility in the management of chronic diseases, including diabetes through continuous glucose monitoring, hypertension via connected blood-pressure cuffs, chronic obstructive pulmonary disease through oxygen monitoring, and cardiac arrhythmias using ECG-based devices [110,111]. Furthermore, AI-driven data fusion techniques can integrate multimodal sensor streams to derive personalized risk scores and digital biomarkers that capture individual physiological trajectories [112,113]. Clinical-grade wearables also support decentralized healthcare models by enabling home-based monitoring, reducing hospital burden, and facilitating remote clinical decision-making [114,115].

Despite these advantages, several limitations remain. Consumer-grade wearables are often affected by motion artifacts, variable skin perfusion, optical interference, and algorithmic inconsistencies, resulting in reduced accuracy compared with gold-standard clinical equipment [116,117]. A recurring challenge is the heterogeneity across devices in sensing modalities, signal-processing algorithms, calibration procedures, and data formats, which limits interoperability, reproducibility, and large-scale data aggregation [118,119].

Wearables generate intimate, high-resolution biometric data, raising concerns related to re-identification risks, cybersecurity vulnerabilities, algorithmic bias, and the potential misuse of health data by employers or insurers [120,121]. From an engineering perspective, trade-offs between user comfort, sampling frequency, sensor quality, and battery capacity remain a major constraint. Long-term user adherence is often low, and data accuracy depends heavily on correct device placement and maintenance [122,123].

From a regulatory standpoint, medical-grade wearables must undergo rigorous evaluation under FDA or CE frameworks, which can significantly slow innovation and market adoption. In contrast, most consumer devices lack medical certification and cannot be relied upon for clinical decision-making [124]. Additionally, clinicians face challenges in integrating high-volume wearable data into electronic health record systems without contributing to alert fatigue or increased cognitive burden [125].

Overall, the literature agrees that wearable sensors hold transformative potential to shift healthcare from a reactive model toward one that is preventive, continuous, and personalized. Their ability to generate rich longitudinal datasets is unmatched by traditional clinical tools. However, challenges related to accuracy, standardization, privacy, regulation, and clinical integration must be addressed to enable their safe and effective adoption in mainstream healthcare.

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Abbreviations

The following abbreviations are used in this manuscript:

Ag/AgCl	Silver / Silver Chloride
BGM	Blood Glucose Monitoring
CNT	Carbon Nanotube
COPD	Chronic Obstructive Pulmonary Disease
CVD	Cardiovascular Disease
DN	Double Network
ECG	Electrocardiogram
FP	Follicular Phase
IMU	Inertial Measurement Unit
ISF	Interstitial Fluid
LBL	Layer By Layer
LP	Luteal Phase
PDMS	Polydimethylsiloxane
PPG	Photoplethysmography
PVDF-TrFE	Poly(vinylidene fluoride-co-trifluoroethylene)
RR	R-to-R interval
SMBG	Self-Monitoring of Blood Glucose
SpO_2	Blood Oxygen Saturation
SWCNT	Single-Walled Carbon Nanotube
TCR	Thermal Coefficient of Resistance
WHO	World Health Organization

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