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WEARABLE MEDICAL DEVICES IN HEALTH CARE SYSTEM

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Abstract

The review emphasizes the growing significance of wearable technology in personalized healthcare, showcasing its ability to customize treatments by leveraging individual health data and predictive analytics to prevent diseases. Different types of wearable devices, such as skin-based, textile-based, and biofluidic-based wearables, play a crucial role in monitoring and managing a range of medical conditions, including cardiovascular diseases, hypertension, neurocognitive disorders, and muscle disorders. These technologies provide real-time, continuous monitoring of key health indicators, empowering both patients and healthcare providers to detect abnormalities early and intervene before conditions worsen. In addition to monitoring, wearable devices are evolving as platforms for drug delivery, further broadening their applications in the healthcare sector. This advancement positions wearables not only as tools for tracking health metrics but also as active participants in treatment, enabling timely therapeutic interventions. The widespread adoption of wearable technologies, including fitness trackers and biosensors, has fundamentally transformed traditional health monitoring systems by offering users the ability to continuously track vital signs such as heart rate, blood pressure, and blood glucose levels. This continuous monitoring facilitates a shift from a reactive to a proactive healthcare approach, where prevention and early intervention become key priorities. As technology continues to advance, wearable devices are expected to play an even more prominent role in personalizing healthcare, improving patient outcomes, and promoting a healthier population through early disease detection and management.

Keywords: Wearable devices, personalized health care, health monitoring, biosensors, wearable technology

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Introduction

With growing health concerns, the demand for real-time diagnostic tests is rising [1]. Wearable sensors play a crucial role in medical applications such as real-time monitoring, in vitro diagnosis, body composition analysis, and energy harvesting [2]. These devices provide detailed health data, aiding doctors in accurate and timely diagnoses while also reducing hospitalization costs and visits. They offer a convenient alternative for patients who may feel uneasy in hospital settings. Advances in engineering and electronic technology have expanded the capabilities of wearable healthcare devices, which typically consist of three key components: a substrate, an active element, and an electrode [3].

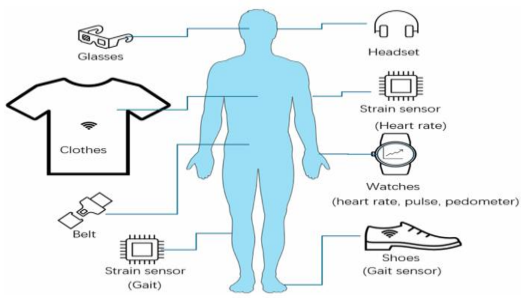


Figure:1 different types of wearable medical devices

Wearable devices can be placed on various body parts to monitor real-time health data, including heart rate, blood oxygen, and blood pressure. They track activities like step count, gestures, and swallowing. Some sensors can also be integrated into clothing for seamless health monitoring [4]. Wearable technologies, such as smartwatches, bracelets, armbands, and glasses, are becoming part of daily life. In healthcare, these portable devices help monitor, analyze, and regulate health conditions. They assist in disease management by collecting and processing real-time data. Advanced technologies like sensing, cloud services, and storage enhance their effectiveness [5]. Wearable healthcare devices have five key features: wireless mobility, intelligence, durability, ease of use, and portability. In modern medicine, their application aligns with the 4P model-preventive, predictive, personalized, and participatory-enhancing patient care and disease management [6].

Materials:

The production of flexible wearable sensors faces challenges due to material limitations and film thickness. Various printing technologies, such as inkjet and 3D printing, are commonly used to enhance their functionality. This review examines different materials, including polymers and liquid metals, along with emerging trends like biodegradable and self-healing materials. It also explores recent applications, challenges, and future prospects of wearable healthcare devices [7]. In general, the **materials of biosensors can be divided into:**

(1) inorganic materials based on metal, carbon, and oxide materials;

(2) organic mate rials such as polymers, small molecules, and natural biomaterials;

(3) compound/mixed material in order to realize the function and structure of complementary properties [8].

Inorganic materials lack flexibility, while organic materials face stability and safety concerns. Wearable biosensors using nanomaterials must prioritize biocompatibility to assess immune responses and dosage effects under different contact conditions. Key substrate materials include polymers like PDMS, PI, and PU, along with biodegradable and self-healing materials. Advancements in polymer technology have enabled the development of biosensors with enhanced flexibility, conductivity, and energy efficiency, categorized into thermoplastics, thermosetting polymers, elastomers, and composites etc.

•Elastomers:

Elastomers, known for their rubber-like elasticity, are widely used in wearable technology. PDMS, a commonly used elastomer, is applied in microfluidic chips, micropumps, electronic skin, and sensors due to its flexibility, chemical inertness, and stability across various temperatures. Its transparency and UV-responsive bonding capabilities make it ideal for integrating electronic materials with flexible substrates [9].

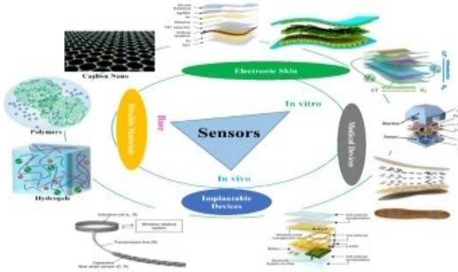


Figure: 2 flexible substrate

Thermosetting polymers

Thermosetting polymers undergo irreversible curing, making them highly durable. PI film, known for its thermal and chemical stability, serves as a strong base material for sensors. However, its poor blood compatibility and low oxygen permeability limit its use in wound healing. To address this, researchers modified PI surfaces using a waterborne dipping process, enhancing antibacterial properties while maintaining its physical integrity. Additionally, PI-based pH sensors incorporate Ag/AgCl electrodes and polyaniline, with modifications extending PI's applications in healthcare and sensing technologies.

Thermoplastic polymer

Thermoplastic polymers can transition between solid and liquid states reversibly. Thermoplastic PU (TPU) is valued for its elasticity, chemical stability, ease of processing, and cost-effectiveness [10-11]. Incorporating a porous, cracked bionic structure enhances TPU-based sensor sensitivity. Precision in structural design is crucial for optimizing sensor performance [12].

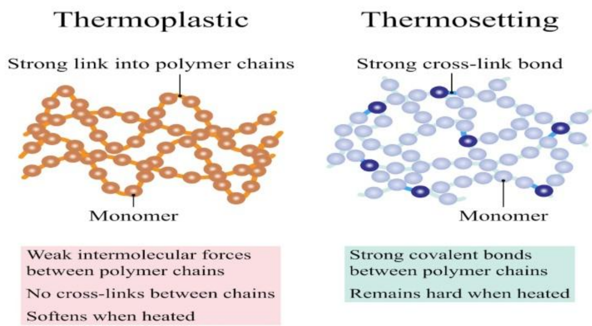


Figure: 3 differences between thermoplastic and thermosetting polymers

liquid crystalline polymers

Liquid crystalline polymers exhibit both liquid flow and solid anisotropy, forming stable mesophases under specific conditions. They can modulate light propagation under external stimuli, making them suitable for optical sensors in ionic, photon, and electronic skin applications. Additionally, polymer-dispersed liquid crystal (PDLC) devices hold potential for smart displays, as they can switch between transparent and opaque states with voltage stimulation [13].

Polymer gels

Polymer gels, first reported in 1978, are cross-linked networks that swell in solvents and respond to environmental changes like pH and temperature. Their responsiveness makes them valuable for wearable applications, including drug release, motion monitoring, and tissue adhesion modification. Additionally, combining gels with pressure-sensitive polymers enables the development of high-performance strain and pressure sensors **[**14].

Biodegradable materials

Biodegradable materials are gaining attention in wearable devices due to their eco-friendliness, transparency, and renewability. These materials, including degradable polymers, semiconductors, and hydrolyzed metals, break down under specific environmental conditions. Natural options like protein-based and polysaccharide polymers are widely used, while synthetic biodegradable materials offer customizable properties for large-scale production. Advanced processing methods such as electrospinning, 3D printing, and melt-spinning further enhance their applications [15].

Self-healing materials

Wearable medical devices often face durability challenges due to substrate or electrode wear from body movements, leading to reduced lifespan and resource waste. To address this, researchers are focusing on self-healing materials that mimic human skin, enhancing device longevity. Recent advancements in self-healing substrates have significantly extended wearable device usage.These materials function through extrinsic and intrinsic self-healing mechanisms.

Classification Of Wearable Devices

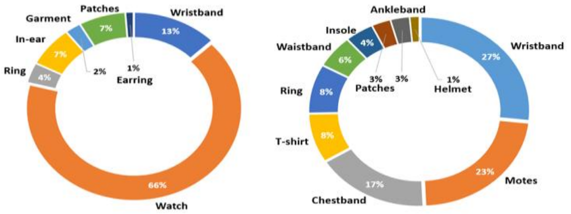
Wearable devices developed so far have been designed for use on all parts of the human body and are classified into 3 categories:

- Head
- Limb
- Torso wearable devices.

Head-worn wearable devices include glasses, helmets, headbands, hearing aids, earphones, earrings, and patches. Smart glasses like Google Glass offer features such as photography, video calls, and GPS tracking. With VR, AR, and mixed reality technology, these devices are increasingly used in telemedicine, medical education, and surgical navigation [16].

Limb wearable devices include accessories like smart watches and bracelets for the upper limbs, which monitor physiological parameters such as heart rate and UV exposure. Lower limb devices, such as smart shoes and socks, track movement for rehabilitation purposes.

Torso wearable's, including suits, belts, and underwear,



(a) Commercial wearables (b) Research wearables

integrate electronic textiles for biomedical applications. The development of internet-connected clothing by MIT in 2009 marked a significant advancement in smart textiles.

Impact on Patient Monitoring

Wearable technology has transformed patient monitoring by enabling real-time tracking of vital signs such as heart rate, blood pressure, and respiratory rate. Continuous data collection allows for early detection of health anomalies, improving the chances of timely medical intervention. Remote monitoring enhances healthcare accessibility, particularly for chronic patients and post-surgery recovery, reducing hospital readmissions and improving overall patient outcomes. Wearable devices enable remote monitoring, allowing early detection of health complications and reducing unnecessary hospital visits. They play a crucial role in managing chronic diseases like diabetes and hypertension by continuously tracking key health metrics. The real-time data from wearables helps personalize treatment plans, optimizing medications and lifestyle adjustments for improved patient care.

Enhancing Healthcare Outcome

Wearable devices support a healthier lifestyle by tracking physical activity, sleep, and nutrition, encouraging positive behavioral changes. They aid in preventive care by detecting early health abnormalities, allowing timely interventions. This proactive approach helps prevent chronic diseases and improves long-term health outcomes.

Diagnosis And Treatment Of Diseases

Wearable devices are of great significance in the changes in vital signs on a real-time basis

Neurological disorders

Early detection and intervention in the predementia phase of Alzheimer's can help delay its onset. Gait analysis using wearable devices offers a noninvasive method to assess cognitive function. These devices also hold promise for diagnosing other neurological disorders early [17].

Respiratory diseases

Wearable nocturnal breathing monitors enhance early diagnosis accuracy for obstructive sleep apnea and enable home use. A newly developed system offers long-term monitoring with high accuracy and energy efficiency.

Urinary diseases

A wearable artificial kidney has shown promise in treating end-stage renal disease by effectively clearing uremic solutes and maintaining balance. However, therapeutic applications of wearable devices still lag behind their monitoring functions. Advances in VR, AR, and remote technology have expanded their medical applications. These include medical education, surgical planning, intraoperative guidance, and remote consultations [19]

Chronic Diseases Management

Cardiovascular diseases

Cardiovascular diseases can be life-threatening and require early detection through continuous monitoring. Traditional methods include invasive and noninvasive techniques, with ECG and Doppler echocardiography being common. Wearable devices like Holter monitors provide dynamic tracking but have comfort and skin irritation issues. Innovations like the Apple Watch Series 4 and wearable defibrillators enhance home-based heart monitoring and emergency protection [19]

Pulmonary diseases

Early monitoring of COPD and asthma exacerbations can prevent severe complications and improve quality of life. Telehealth programs aid in early detection and self-management of these conditions. Affordable wearable devices track vital signs, cough, and breath sounds continuously. These signals support predictive analysis for early lung function deterioration [20].

Diabetes

Diabetes is a metabolic disorder caused by insulin dysfunction, leading to high blood sugar and potential organ damage. Effective self-monitoring and management help reduce complications and mortality. Available medical products include blood glucose monitors, injectable insulin, and implantable devices [21].

Hypertension

Hypertension is a chronic condition that increases the risk of cardiovascular and cerebrovascular diseases. Accurate blood pressure measurement is crucial, with methods classified as direct (invasive) or indirect (noninvasive). Traditional sphygmomanometers provide intermittent readings, while wearable devices enable continuous monitoring. These devices use various techniques, including artery tension, blood volume changes, pulse wave speed, and vibration measurement.

Limitations

Our review has some limitations, including potential omissions due to search term constraints. The diverse research designs included may also limit findings based on study methodologies. Despite efforts to reduce bias, some subjectivity in result analysis remains. As this is not a systematic review, broader research may reveal additional wearable device applications.

Applications of Wearable Devices in Medical Field

Wearable medical devices connect patients, doctors, and cloud systems to track health conditions and support disease management. They play a key role in monitoring, diagnosis, treatment, and rehabilitation. For Parkinson's patients, wearable sensors help adjust medication and assess drug efficacy. Photoplethysmography has shown high accuracy in detecting seizures in epilepsy patients. Blood-based diagnostics are invasive and unsuitable for real-time monitoring. Second-generation wearable biosensors use saliva, sweat, tears, and interstitial fluid as alternatives [21].

Challenges and Future Prospective

Wearable health devices (HWDs) effectively monitor physiological parameters but require improvements in stability, sensitivity, and privacy. Data accuracy is often affected by body motion, skin adhesion, and external noise. While widely used for monitoring, HWDs have limited diagnostic applications due to minimal integration with biological samples. Efforts are needed to enhance compatibility with blood, urine, and saliva for diagnostics. AI algorithms, such as supervised learning regression, can help track multiple health parameters for prognosis. Additionally, ensuring data security and protecting sensitive health information is crucial.

Secure communication protocols are crucial for protecting user data in wearable health devices (HWDs). A major challenge is maintaining a continuous power supply due to battery size limitations. Efficient energy harvesters like piezoelectric and triboelectric nanogenerators convert mechanical energy into electricity, enhancing device sustainability. HWDs are widely used for monitoring physiological conditions such as cardiovascular and muscle disorders, as well as glucose levels. However, their application in psychological diseases like Parkinson's and Alzheimer's remains limited. Expanding HWD use in mental health could provide significant future benefits.

Conclusion

Wearables are widely used in healthcare for monitoring and diagnostic purposes, because of the comfortability and daily care they provide to the wearer. This paper reviews recent efforts in the use of different HWDs for the monitoring of different disease conditions and have also highlighted recent commercially available HWDs. For this purpose, skin-based HWDs, biofluidic based HWDs, and other competing wearable technologies have been discussed. The relevant techniques for noninvasive and minimally invasive monitoring of different biological and chemical parameters including blood pressure, heart rate, and perspiration rate have been reviewed. Moreover, applications of HWDs for monitoring of different physiological and psychological para meters have also been discussed. Furthermore, this review also highlights the use of different materials for monitoring, diagnosing, and treating of different diseases, as well as the techniques for the application of HWDs as drug delivery systems including transdermal drug delivery systems and touch actuated systems. Inherent limitations with these wearable devices along with their future perspectives have also been discussed

Author Contributions

All authors are contributed equally

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Declaration of Competing Interest

The Authors have no Conflicts of Interest to Declare.

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