An examination of wearable technology in the field of biomedical engineering: A review

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Abstract A wearable device is a piece of technology that can be worn on the body, designed to be portable, lightweight and equipped with various sensors or features for specific functions. As a game-changer in the field of biomedical engineering, wearable technology provides innovative approaches to illness management, individualized healthcare and health monitoring. This review looks at wearable technology as it stands in the field of biomedical engineering, emphasizing its uses, difficulties and potential. The research examines a wide variety of wearable wireless biosensors, sensor patches, wristwatches, wearable face masks and multi-sensor smart clothing, emphasizing their potential to measure physiological parameters, including blood pressure, heart rate and sleep patterns. This study demonstrates the need for intelligent wearable devices for high-quality signal capture, processing and continuous monitoring of critical parameters. The creation of smart wearables that meet the specified design standards enables the creator of a wearable with reduced power consumption that can be used to monitor the health of patients. This study offers a thorough analysis of wearable technology's present state, obstacles and potential applications in the field of biomedical engineering. It will be of great use to investigators, medical professionals and developers of technology.

Keywords: biomedical engineering, wearable devices, physiological parameters, monitoring, healthcare

1. Introduction

1.1. Biomedical engineering

The field of biomedical engineering (BME) contributes engineering principles with biological, medical along with health systems research including the use of technology to enhance health and quality of life require a foundation in the physical, mathematics as well as biological sciences. BME is one of the engineering specialties with the greatest rate of growth in the globe; in 2015, there were 117,935 biomedical engineers in 129 countries. BME specialists are engaged by national regulatory authorities, hospitals coupled with other healthcare facilities, universities, government agencies, the health technology and healthcare sectors (Mousavi et al 2020). In the early 2000s, wearable sensor technology saw a noticeable increase in use, mostly in the healthcare industry. These sensors keep an eye on a number of physiological indicators, including blood pressure, heart rate, respiration rate, skin temperature, mobility and brain activity (Iqbal et al 2021). When combined with systems for biotelemetry, they build bodily sensor networks (BSNs) with intelligence that use wireless connections to offer users access to real-time environmental or physiological data (Seçkin et al 2023). A new generation of sensors has been made possible by developments in printed electronics, miniaturization, smart textiles and intelligent fabrics. According to Vijayan et al (2021), these sensors offer a “wear-and-forget” feature despite compromising the user’s convenience or interfering with daily routines. Figure 1 depicts the different wearable devices developed in biomedical (Mäkynen et al 2022).

Real-time health monitoring, diagnosis, prevention and possibly even extension of human lifespan are made possible by wearable electronics coupled with biomedical devices like drug delivery systems, glucose monitoring sensors, wearable pressure sensors, pulse oximetry sensors as well as electrocardiography (ECG) monitoring sensors (Cicha et al 2022).

1.2. The Integration of Wearable Technology in Biomedical Engineering

Conventional batteries are used to power these gadgets and they either need to be recharged or changed on a regular basis. The primary use of first-generation wearable biosensors was biophysical monitoring, which involves recording
physiological parameters, including body temperature, heart rate and physical activity (Pham et al 2020). These gadgets take the shape of shoes, headphones, or watches. Invasive techniques like injectable devices and microneedles are used in second-generation wearable biosensors. To incorporate biosensor technology into the body, this category comprises contact lenses, tattoos, on-skin patches and films placed on teeth. The sensor’s sensitivity represents the minimum threshold for detection of the apparatus or the measurable and perceivable strength of the signal (Koydemir and Ozcan 2018). The reaction time and relaxation time are connected to the wearable device’s capacity for quick and real-time response, while the range of detection relates to the applicable sensor signal. The wearable device’s applicability and sensing capabilities are determined by these critical criteria. Furthermore, the biocompatibility, cycle stability and durability of the sensor are essential for the long-term, steady functioning of wearable technology (Cheng et al 2021).

Figure 1 Various wearable devices.
Source: https://doi.org/10.1007/s10389-023-01893-6

1.3. Wearable Technologies in the Biomedical Engineering Realm

Montesinos et al (2022) suggested creating new learning opportunities inside an analytical course on biological signals and systems by using blended learning spaces. This will increase students’ motivation, enthusiasm and comprehension of the content covered. They designed an educational program that leverages wearable technology and cloud-based collaborative creation platforms to enable students to transform ordinary situations into immersive learning settings. Compared to artificial neural networks (ANN) and long short-term memory (LSTM) models, they have shown that the suggested method yields the greatest results when utilizing a statistical learning technique known as moving average with autoregressive integration. Since these metrics indicate the variation between the measurement and the value real or accurate value, they have utilized the mean squared error (MSE), root mean square error (RMSE) and mean absolute error (MAE) values to analyze the linear models and gauge the effectiveness of the framework (Ganesan et al 2021). Vos et al (2023) examined the models constructed on datasets with a limited number of individuals, documented in a single research procedure, can generalize. The next suggests and assesses techniques to merge these datasets into one big dataset to examine the machine learning models constructed on bigger datasets can generalize. Finally, to quantify prediction capacity on fresh, unknown data, they propose and assess the usage of ensemble approaches by combining gradient boosting with an ANN. The wearable constructions of stiff, soft and textile-based wearable biomedical devices were examined (Seckin et al 2023).

1.4. Wearable Technologies in various applications

As technology advances, it will be feasible to get sensors from the textile surface to provide measures that are more pleasant, precise and superior. The most common fundamental sensor types in health research include resistive, capacitive, piezoelectric, optical, semiconductor, galvanic skin response and inertial measurement units. Information on the kinds of sensors utilized in health applications was provided (Smida et al 2020). For wearable biomedical telemetry applications, this research provides a semi-flexible, low-profile, wideband antenna. High efficiency (93% at 2.4 GHz) and gain (2.50 dB) are maintained by the suggested antenna. Simulations and experimental studies demonstrate that the antenna’s bending has no influence at all on the bandwidth, efficiency, gain and reflection coefficient. Additionally, excellent performance is shown when the antenna is simulated and tested experimentally close to the human body. A viable option for small, wearable biomedical equipment is the suggested wide band antenna. Makynen et al (2022) provided the most prevalent cardiac arrhythmia is atrial fibrillation (AF) worldwide. For many years, researchers have researched arrhythmias and the techniques used to treat them.

https://www.malque.pub/ojs/index.php/mr
Professionals everywhere are trying to raise the standard of care. Wearable technology is one cutting-edge innovation that has potential applications. Electrocardiogram (ECG) and photoplethysmogram (PPG) recordings are the two most used types of recordings from these devices. These gadgets will become important pieces of technology as they become more affordable since they can be used for monitoring, enhancing sensitivity and supporting the quality of therapy. This is crucial since AF can be difficult to identify beforehand, particularly when using home monitoring. Javaid et al (2023) observed biomedical engineering's importance in the medical field. The research and innovation components of BME in the healthcare sector are covered in this study. The study went on to list and go over important uses of BME in healthcare. BME is an exciting area of life science that has the potential to revolutionize healthcare that pave the way for new innovations in prosthetics, diagnostic tools, imaging and other fields.

Hasan et al (2021) provided an extensive overview of the categorization of energy harvesters (EHs), including triboelectric nanogenerators (TENGs), piezoelectric generators (PEGs) and thermoelectric generators (TEGs), which enable the operation of a broad range of devices. The working ethics, optimization parameters, innovative parts and technology architecture of the EHs are reviewed since they impact their operational efficiency. Additionally, each of the above-mentioned EHs' breakthrough performance is emphasized. Di Rienzo et al (2020) examined how wearable technology for biomedical applications uses Near Field Communication (NFC) to provide ultra-low power communication. Verifying if NFC hardware can accommodate the diverse needs of various use cases in biomedicine is the primary goal. They will supply an overview of the latest developments in NFC-enabled systems at this time to achieve the goal. Subsequently, they will assess NFC capabilities using a series of tests using available devices. To assess if creating battery-free gadgets is feasible, they will pay close attention to energy-collecting capabilities. Chen et al (2020) provided an overview of recent advancements in electronic skin technology for medical gadgets of the future that can detect many physiological parameters of the body of a person. An in-depth discussion is given to the essential e-skin features that must be achieved for them to be used in medical applications. The article delineates the comprehensive uses of these sensors in the fields of interventional, wearable and implanted medicine. It highlights the ways in which these gadgets track the health condition of individuals and might potentially supplant conventional clinical instruments.

2. The Process of Choosing and Manufacturing Flexible Materials

The performance of the sensors can be impacted by the choice and construction of the materials. The materials' flexibility, conductivity and durability are essential for biomedically focused sensor systems. Polymethylsiloxane (PDMS), polyethylene naphthalate (PEN), polyethylene terephthalate (PET), polyimide (PI) and polyvinyl alcohol (PVA) are examples of current flexible materials (Zhao et al 2022).

PET has good mechanical strength and it is used in flexible printed circuit boards. PET can be utilized to encapsulate devices and offers good electrical insulating qualities at the same time. PET has the ability to transmit light and can be used as an optical sensor shield. PVA is utilized in synthetic fibers and device adhesives due to its exceptional hydrophilicity. PVA is used in the production of disposable products because of its superior film-forming qualities and ease of degradation. The most utilized flexible substance is PDMS. In situations with high and low temperatures, it is a superb force-sensitive material with exceptional flexibility. Furthermore, PDMS is a suitable medium for pressure sensors and has strong dielectric characteristics. PDMS is utilized in flexible wearable, pressure sensing and device packaging. It has a certain degree of air permeability. Capacitor films and flexible printed circuit boards (PCBs) are two typical applications of PEN. It is a film-based device material that has advantages over PET in terms of durability and resistance to heat. It works well to prevent water and gas as well as it can be used to package electronic gadgets.

3. Evaluation of wearable devices in biomedical

The mobility, user-approachability and environmental flexibility of wearable technology set them apart from current medical gadgets. Tiny sensors have made it possible to create implanted devices for illness diagnostics due to advancements in electronics, biocompatibility and nanomaterials. Physiological sign identification is made easier by the development of flexible and skin-attachable electronic gadgets. The multifunctionality of today's wearables allows them to work as a microcomputer, allowing data processing and collection as well as external interaction authorization for the systems as a whole. Through wireless technologies like Bluetooth, WiFi, LoRa protocol, radio-frequency identification (RFID) and near-field communication (NFC), these devices can connect with other devices. With the help of wearable technology and the Internet of Things (IoT), it is used in households along with the healthcare sector for continuous, remote monitoring. Large, traditional devices are employed in the medical field to gather data and forecast illness (Guk et al 2019). The portable electronics are categorized according to how they connect to the body and come in a variety of designs. They are divided into three categories: headgear, which includes helmets, mouth-guards, glasses, as well as apparel, which includes jackets, singlets, jeans and belts. Wrist-worn items include watches, rings, bracelets and gloves. Figure 2 presents the evaluation of wearable devices.

4. Wearable devices in biomedical
4.1. Sensor patch

Hua et al (2022) addressed the viable solution to these challenges in health monitoring is the use of skin-attachable sensors. With skin-attachable sensors, they can monitor heart rate, respiratory rate, human motion, lung, glucose, blood oxygen saturation, heart sound and biomarkers in biological contexts. These sensors are made possible by their high signal-to-noise ratio and good comfort. They can be used for long-term, household and real-time detection of weak physiological signals. Chakraborty et al (2023) looked into sticky hydrogel patches, which have become a popular and effective bioactive multipurpose substitute. Hydrogels are three-dimensional, polymeric materials that can expand in water and have a structure very similar to that of natural tissue. Hydrogels’ physicochemical characteristics are easily modifiable, making them appropriate for a wide range of biological applications. Hydrogels can be given sticky qualities by physicochemical manipulations, which make them perfect substitutes or additions to conventional sticking plaster.

![Figure 2 Increase in wearable technology in the biomedical.](image)

4.2. Wearable wireless biosensor

Biomarkers found in human biofluids like interstitial fluid, tears, sweat, as well as saliva”. Wang et al (2022) looked into Non-intrusive, wearable biological sensors for ongoing observation. Sweat Erdem et al (2023) examined the benefits of wearable biosensors, showing that wireless devices enable the effective simultaneous non-invasive measurement of several analytes in a sensitive and selective manner without requiring time-consuming and tedious stages. Numerous physiological signals can be monitored in real-time, such as pathological variables like “dopamine, ions, glucose, including biophysical signals like blood pressure, temperature and pulse, along with numerous other metabolites. These biosensors can identify a small number of analysts at high enough concentrations, during intense activity, to produce an adequate amount of biofluid. The biosensor is made up of graphene electrodes that are capable of recovering in location. It is functioning with redox-active reporter nanoparticles and metabolite-specific molecularly imprinted polymers. The modules for micro-fluidic sweat sampling, signal processing, calibration, iontophoresis-based sweat induction and wireless communication are integrated into the biosensor.

4.3. Wristwatch

Kheirkhahan et al (2019) explored that the real-time healthcare data transfer and tracking for patients and research participants is altered by smartphone and wearable technologies. A wide range of interactive healthcare applications that can adjust to the participant’s changing surroundings is enabled by adaptable, two-way and immediate interaction controls. Furthermore, a range of sensors on smartwatches are appropriate for gathering information about location and physical activity. Since smartwatches are becoming more and more popular and well-liked by users, they are perfect for maintaining long-term records of actions to study patterns of exercise when living conditions independently and how these patterns relate to illnesses that appear to happen at random.

4.4. Wearable face mask

Hyysalo et al (2022) proposed the Smart Mask, an ecosystem and platform powered by the IOT that aims to stop the spread of other respiratory viruses, such as COVID-19. Wireless, IoT, sensing materials, software integration and AI will provide real-time health data collection along with event detection connected to health based on the user’s environment. A personal health trajectory can be created by comparing personal data to extensive public data sets. On a broader scale, AI-based analysis of health data can be used to forecast and reduce medical expenditures with correct diagnosis and strategies for therapy.
Maintaining one’s own health and stopping the spread of disease can be aided by a smart face mask that monitors breath information. Before such technologies can be used in real life, a few issues must be resolved. Creating a pressure sensor with outstanding stability, electrical and mechanical qualities as well as ease of activation at low pressure is one of the main challenges. Zhong et al (2022) suggested a standard face mask is combined with a tiny, self-contained readout and a pressure sensor circuit to create a wireless smart face mask.

4.5. Multi-sensor smart garment

Wearable and inconspicuous gadgets are becoming increasingly popular for the ongoing tracking of physiological markers. Among the five vital signs, respiration rate is the most useful in identifying changes in health status and physiological disorders. (Massaroni et al 2019) Examined how well multi-sensor intelligent clothing estimated the FR while running and walking. To capture the movements of the chest wall brought by breathing, piezo-resistive sensor components have, among other things, been included in bands or clothing. This has made it possible to track respiratory activity indirectly. Smart textiles, or clothes with non-invasive sensor integration, are innovative approaches to remote healthcare monitoring. The potential for intelligent decision-making is increased when Artificial Intelligence (AI) algorithms are integrated with Polymer Optical Fiber (POF) sensors, which offer appealing advantages for smart textile technology. To assess the system’s performance on the activity categorization of several participants, this research describes the creation of completely transportable photonic intelligent clothing with 30 multiplexing POF sensors and AI techniques (Avellar et al 2022). The developments in big data, artificial intelligence, wearable technology, mobile communication and the IoT are transforming people’s lifestyles. Because of their rigidity and bulkiness, conventional wearable devices pose several obstacles to the ongoing tracking issues with human health. Since e-textiles have advanced recently and small electrical devices have been incorporated into textiles, smart clothing systems for remote health monitoring have become mainstream. Ahsan et al (2022) evaluated the structure of health monitoring systems using smart clothes is provided. For the creation of smart clothes, this framework offers design guidelines, appropriate sensors and textile materials. This will enable uninterrupted long-term monitoring of the gadget. While designing the wearable gadget, incorporating several wireless technologies is essential. The physiological signal is provided over a network of wireless communications to the doctors or to them. It is monitored and these devices are very useful to the biomedical and healthcare systems. Table 1 denotes the various wearable gadgets created for observation and their applications.

<table>
<thead>
<tr>
<th>S. No</th>
<th>Device developed</th>
<th>Physiological parameter</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Wrist-worn personal fitness tracker</td>
<td>Heart rate (HR)</td>
<td>A mechanism of early warning to detect clinical decline in the intensive care unit</td>
</tr>
<tr>
<td>2.</td>
<td>Smart helmet</td>
<td>HR, HRV, evoked potential and Auditory steady-state response</td>
<td>Decrease the number of road accidents</td>
</tr>
<tr>
<td>3.</td>
<td>T-shirt with textile electrode</td>
<td>QRS complex, R peak, P and T waves and the pre-and post-RR intervals</td>
<td>Essential indicators are continuously monitored</td>
</tr>
<tr>
<td>4.</td>
<td>Wearable sleep care kit</td>
<td>HR, (S_pO_2), sleep quality of the patient</td>
<td>To decrease the severity of obstructive sleep apnea</td>
</tr>
<tr>
<td>5.</td>
<td>Wristwatch</td>
<td>Conversation and interpersonal interactions</td>
<td>Tracking of mental health</td>
</tr>
<tr>
<td>6.</td>
<td>Wrist-worn PPG sensors</td>
<td>HR</td>
<td>Essential sign monitoring for medical purposes</td>
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<tr>
<td>7.</td>
<td>Fiber Bragg grating sensor</td>
<td>BP</td>
<td>Estimating Arteriosclerosis</td>
</tr>
<tr>
<td>8.</td>
<td>Smart clothing with several sensors</td>
<td>Rate of respiration</td>
<td>Observing physical activity</td>
</tr>
<tr>
<td>9.</td>
<td>Wearable face mask</td>
<td>Parameters for breathing (S_pO_2) and (S_pO_2) and blood pressure in systolic form, Body temperature, RR and HR</td>
<td>Monitoring respiration to assess lung function</td>
</tr>
<tr>
<td>10.</td>
<td>Wearable wireless biosensor</td>
<td>HR, BP, body temperature</td>
<td>Continuous patient observation</td>
</tr>
<tr>
<td>11.</td>
<td>Sensor patch</td>
<td>HR, BP, body temperature</td>
<td>Applications in healthcare</td>
</tr>
</tbody>
</table>

5. Challenges in wearable devices

5.1. Battery life
Battery life is a common worry among wearable devices since many items in this field suffer from poor battery longevity. Users usually face the difficulty of regular recharge or limited use times, which limits the usefulness and accessibility of such gadgets Mirtaheri and Li (2019). The necessity for frequent charging can have an impact on user pleasure and overall wearable use, spurring continuous industry attempts to increase battery life and investigate novel power-saving solutions.

5.2. Security issues

Wearable gadgets raise security problems owing to the capture and storage of sensitive information. The recorded information, which includes personal health indicators and location data, is a possible subject for cyber assaults and hackers (Pirbhulal et al 2018). The susceptibility of smartwatches to hacking attempts creates worries regarding the confidentiality and safety of user data, underlining the importance of robust safety precautions for avoiding unintentional use and possible abuse of stored data.

5.3. Device breakage

Device breaking is a significant worry with wearable electronics because of its location on the body. The fragility of wearables varies according to their placement since certain regions are more vulnerable to impact or stress. For example, gadgets worn around the wrist can be subjected to inadvertent bumps or falls, increasing the chance of damage. This vulnerability emphasizes the significance of careful attention while determining the location of wearable devices, as well as the requirement for sturdy materials in their manufacture to maximize lifetime and reduce the chance of damage.

5.4. Power management

Wearable gadgets need regular recharging therefore power management is an important consideration. Wearables have a limited battery lifespan, necessitating effective power management solutions to increase battery life and improve user experience. This includes refining hardware as well as software components to reduce energy consumption, adopting power-saving modes and investigating novel charging ways to solve the issue of frequent charging (Yousri et al 2021). Effective power management means that wearable gadgets can work for extended periods of time between charges, increasing their practicality and utility in everyday life.

6. Final considerations

In the field of biomedical engineering, wearable technology has become a game-changer, providing unheard-of chances for data-driven insights, continuous monitoring and individualized treatment. Through the integration of wearable technology, advances in illness monitoring, rehabilitation and general well-being have been made possible by new avenues for understanding and controlling physiological data. In this review study, we investigate the various wearable devices’ technology and their materials in biomedical engineering. This study highlights the value of various wearable smart devices for tracking people’s physiological characteristics. The information presented in this study assists designers in determining the necessary conditions for creating biomedical smart devices. In the future, should examine how wearable can be used to monitor and identify infectious illnesses early. Potentially offering real-time data on vital signs and other pertinent factors, wearable technology might help to detect epidemics early and enable prompt public health actions.

Ethical Considerations

Not Applicable.

Conflict of Interest

The authors declare no conflict of interest.

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