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DEVELOPMENT OF FLEXIBLE PRINTED ELECTRONICS FOR WEARABLE BIOMEDICAL SIGNAL ACQUISITION AND WIRELESS TRANSMISSION

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Abstract:

Flexible printed electronics are one of the most significant technological shifts shaping the future of personalized healthcare and digital medical systems. In this research, we focused on developing a fully printed, flexible electronic platform specifically designed to capture and track electrocardiogram (ECG) and electromyography (EMG) signals, transmitting them wirelessly with high efficiency and without the need for complex connections. The significance of this work lies in integrating advanced printing technologies with low-power wireless communication systems, thus overcoming the limitations of traditional rigid electrodes and providing continuous and accurate monitoring of vital functions and muscle activity without causing any inconvenience to the user during their daily activities.This paper describes the design and implementation of a flexible printed electronics platform for collecting and wirelessly transmitting wearable biomedical signals. The proposed approach consists of a flexible sensing material, a printed circuit board, biomedical signal collection technologies, signal processing, and wireless transmission. The proposed system aims to collect vital physiological information such as electrocardiograms (ECGs) and electromyograms (EMGs) using flexible sensors. After collecting the physiological signals, the signals undergo processing stages to filter out noise. The filtered signals can then be transmitted to a receiver using wireless communication technologies. To evaluate the performance of the proposed technology, several assessment metrics were used, including accuracy, precision, recall, and F1. The proposed system achieves outstanding performance, with an accuracy of 98.1%, precision of 97.8%, recall of 96.9%, and an F1 of 97.3%. This wearable system, based on flexible printed electronics, enables the reliable acquisition and wireless transmission of physiological signals, providing a flexible, lightweight, and efficient solution for real-time healthcare monitoring applications.This innovation opens new horizons for the production of a new generation of wearable medical devices that combine lightweight design, high flexibility, and low cost, offering a practical and effective alternative in the fields of medical diagnosis and physical rehabilitation.

Key Words: Flexible Printed Electronics; Wearable Biomedical Sensors; Physiological Signal Acquisition; Wireless Data Transmission; Healthcare Monitoring; Flexible Electronics Technology.

1. Introduction:

The increased requirement for ongoing and personalized monitoring in health care has spurred research into the development of flexible sensors that can capture real-time physiological data like ECG, EMG, and vital signs. Flexible and printed sensing devices are light, comfortable, and affordable alternatives to conventional rigid sensors used in biomedical devices ((Sun et al., 2022); (Ma & Soin, 2022). Recent breakthroughs in wearable EMG systems and biosensors worn on the skin have enhanced physiological data collection, comfort, and monitoring for rehabilitation and health purposes (Al-Ayyad et al., 2023); (Kim et al., 2024). In addition, the use of artificial intelligence in wearables has boosted the analysis and diagnosis of diseases based on sensor data, resulting in smarter health care decisions (Pereira et al., 2024)**.**

Emerging advances in wearable and connected healthcare technologies have made it possible to perform continuous monitoring of physiological indicators with the help of flexible sensors, wireless communication, and intelligent data processing. IoT-based healthcare systems help in improving remote patient monitoring with the integration of wearable devices into connected networks to collect and analyze health data efficiently (Ianculescu et al., 2025). Flexible textile-based ECG monitoring systems using printed conductive materials have shown significant improvements in comfort, accuracy of signals, and applicability for long-term assessment of heart functions (Ozturk et al., 2023). Multi-sensor wearable devices including smart eyewear systems have made it possible to monitor different biomarkers simultaneously in real-life situations (Crupi et al., 2025). Emerging trends in biosensors technologies highlight the importance of sensitivity, flexibility, and biocompatibility of sensor devices for the next generation of physiological monitoring (Falk & Shleev, 2026). Moreover, advancements in mobile health applications have helped to enhance the connection between wearable technology and smart phone-based healthcare systems (Proto Bioengineering, 2025). With all this consideration in mind, the suggested approach aims to create an adaptive wearable physiological signal acquisition and wireless communication system utilizing printed electronic technology that can provide accurate, comfortable, and continual physiological signal measurements.

The growing need for continuous and personalized healthcare monitoring has increased the demand for flexible wearable biomedical systems capable of collecting real-time physiological signals. Flexible printed electronics provide lightweight, comfortable, and adaptable solutions compared with traditional rigid sensors by enabling efficient acquisition of signals such as ECG, EMG, and vital parameters. Although advancements in wearable sensors and wireless communication have improved remote health monitoring, challenges related to signal quality, flexibility, power efficiency, and reliable data transmission still exist. Therefore, this study focuses on developing flexible printed electronics integrated with biomedical signal acquisition and wireless transmission capabilities to achieve an efficient and reliable wearable healthcare monitoring system.

1.1 Research Motivation:

The fast-paced evolution of wearables and implantable health devices has generated a need for highly flexible and robust biomedical sensors that are able to continuously monitor physiological data. While existing rigid electronics usually exhibit problems with mechanical compliance, comfort, and durability when worn or implanted inside the human body, flexible printing technology offers an interesting alternative, allowing for the creation of biocompatible sensors that effectively detect various biomedical signals including ECG, EMG, and PPG while being compatible with the motion of human body parts. Nevertheless, there are still plenty of issues regarding sensor performance, scalability, power supply, and data transfer that need to be addressed before such technology becomes practically applicable in healthcare scenarios. This is why the current research focuses on developing an advanced platform of flexible printed electronics that provides efficient biomedical signal acquisition and wireless communication capabilities at the same time.

1.2 Significance of the Study:

The use of flexible electronics for the purpose of obtaining biomedical signals and transmitting them wirelessly holds significance in the development of next-generation healthcare monitoring devices. In this study, the shortcomings associated with rigid devices are addressed with the help of light, flexible, and deformable sensing components that can make close contact with the human body and help in the physiological monitoring of different bodily functions. By using this method, vital biomedical information such as electrocardiogram (ECG), electromyogram (EMG), and photoplethysmography (PPG) can be easily obtained. Additionally, the use of wireless technology in the system allows data to be transmitted wirelessly. The present study will facilitate the development of novel wearable medical devices by combining flexible material, printed electronics, and wireless technology.

1.3 Problem Statement:

The rising demands for ongoing and customized physiological monitoring have generated a necessity for the development of wearable biomedical devices capable of providing reliable physiological measurement while ensuring increased user comfort and portability. The current technologies utilized in cardiovascular monitoring systems, including smart stethoscopes, have revolutionized individual physiological evaluation through multi-modal sensing; however, problems involving device flexibility and wearability are yet to be addressed (Park et al., 2022). The use of wireless heart rate monitoring devices in stress and remote patient monitoring has contributed to healthcare advancements, although their limitations concerning high power consumption, reliability, and stability pose a challenge to their adoption (Kuncoro et al., 2024). Despite the success in developing battery-free epidermal sensor networks that ensure constant monitoring, ensuring efficient and independent power supply in conjunction with wearable design remains a difficult task (Kurt et al., 2026).Similarly, the use of smart textiles in the development of healthcare systems has improved wearable functionality; nevertheless, issues of sensor performance and large-scale production require more research attention (Xu et al., 2025). It is essential to develop a flexible and printed biomedical system for the acquisition, measurement, and analysis of physiological signals.

The proposed research enhances the performance of current wearable biomedical monitoring systems by overcoming their shortcomings with regards to flexibility, signal acquisition, power consumption, and wireless communications. Some of the enhancements included in the proposed system are the inclusion of flexible printed electronic devices for sensing purposes, which result in more comfortable sensors than traditional rigid sensors. The proposed system improves the physiological signal acquisition aspect through the use of flexible sensors that can acquire biomedical signals effectively and with minimum distortion. Additionally, the proposed system uses wireless transmission features, which allow biomedical data to be transmitted in real time wirelessly, which overcomes the problem faced by conventional monitoring systems, which need wired data communication. In terms of miniaturization and portability, the proposed system enhances wearable biomedical monitoring devices through the use of printed electronic components. This leads to lightweight devices, which are portable and ideal for wearing. Finally, signal processing techniques are used to improve signal quality and monitoring accuracy through noise reduction.

1.4 Key Contributions:

- Development of flexible printed electronics-based wearable device that allows comfortable, lightweight, and flexible biomedical monitoring via use of flexible substrates and conductive printed materials.
- Development of a high-performance biomedical signal acquisition system for acquiring biomedical signals, including ECG, EMG, and PPG from flexible wearables, ensuring reliable data acquisition.
- Embedding wireless communication capabilities in flexible electronics in order to provide real-time communication of biomedical signals from biomedical sensors wirelessly.
- Application of signal processing methods to improve biomedical signal accuracy by reducing noise interference from other sources.
- Evaluation and characterization of the designed system with respect to electrical performance, flexibility, energy efficiency, signal quality, and wireless communication reliability.
- Developing a methodology for designing future wearable biomedical devices using flexible electronics, biomedical sensors, and wireless communication technologies.

2. Literature Review:

Hong et al. (2025) have put forward an optical wireless communication system for biomedical implants which uses light to allow bi-directional communication through the skin of the body. With such a model, the need for traditional RF antennas and inductive coils is eliminated, leading to reduced electromagnetic interference along with miniaturization of the device and increased compatibility of the device with biomedical implants. This model shows efficient transmission of signals via biological tissues and performs well under realistic situations, facilitating the transmission of physiological data between implanted sensors and external receivers in real time.

Tu et al. (2024) model is based on the fabric hybrid electronics concept that focuses on the creation of a smart clothing solution for the purpose of monitoring physiological processes. This model allows integrating flexible printed electronics together with textile components into a hybrid electronic system that can serve as lightweight and flexible wearable devices for health parameter monitoring. In other words, fabric hybrid electronics technology offers better flexibility, durability, and comfort than traditional solutions due to the combination of conductive fabrics, printed sensors, and electronic modules. Such a hybrid electronics system can be used not only for health parameters monitoring but also for fitness purposes and remote patient monitoring.

Wan et al. (2024) have introduced a magnetic implant-based device system with an attached wearable system designed for wireless sensing of both physical and biochemical processes. In the suggested model, the integration is made between the magnetic implants and the full-body wearable system that allows real-time monitoring of various physiological and biochemical indicators without using power. The technology applies the principle of magnetic coupling between the magnetic implants and the wearable device in order to implement energy transfer and wireless communication in a more compact way. Continuous health monitoring can be implemented in the suggested concept via the detection of biological signals and their further wireless transmission from the implant to other devices.

Shao et al. (2022) presented an approach that involved developing a high-precision printing process at room temperature for printing flexible wireless electronics using MXenes conductive ink technology. In this research paper, the model developed involves using MXenes as the basis for printable electrode fabrication to enable the design of flexible electronic circuits with excellent electrical conductivity, mechanical flexibility, and wireless communication capability. Room-temperature printing offers a cost-effective way of printing wearable and implantable electronic components while retaining the advantages of flexible substrates. The wireless electronic circuits developed under the proposed model offer improved performance, reduced size, and flexible integration with other flexible platforms ideal for use in health care monitoring, man-machine interaction, and future biomedical systems.

Xu et al. (2024) provided a detailed framework that discusses wireless biosensor technology and applications for real-time health monitoring. The main idea behind the proposed model is to use advanced sensing materials, wireless communication technologies, and miniaturization of electronic systems for real-time and non-invasive monitoring of patients' physiological parameters. The research paper examines different types of wireless biosensors, including wearable or implanted biosensors for acquiring real-time biological data such as vital signs, biochemical data, and patients' health status. The authors emphasize the importance of using low-power communications, flexible electronic systems, and intelligent data analysis techniques for enhancing healthcare monitoring systems in remote areas.

Giftsy et al. (2023) suggested an extensive study on the development of flexible and wearable antennas used in biomedical applications and their potential improvements in the future. Flexible and wearable antennas can be defined as an effective technology used in wireless healthcare systems; it is important to note that the proposed study covers the issues of flexible antenna development, including the use of lightweight, flexible, and biocompatible materials. In addition, the importance of the antenna miniaturization, flexibility, low energy usage, and reliable wireless communication should also be mentioned. There is a wide range of technological developments used for improving the characteristics of flexible antennas in order to make sure about their convenience for users.

Zhang et al. (2023)presented an electronic health care system for cardiovascular applications utilizing flexible electronics. Specifically, this study developed the system based on the concept of creating light-weight and flexible electronics that could be used in continuously analyzing physiological functions in patients with cardiovascular diseases. The flexible electronics framework involves using flexible electronics together with sensors that enable monitoring of various cardiovascular factors such as heart rate, pulses, and other relevant biomarkers. Flexible electronics can improve the performance of healthcare applications by ensuring patient comfort and allowing longer periods of monitoring due to their ability to adapt to the movement of the human body.

Volpes et al. (2023) developed a methodology that can be used to incorporate I2C sensors into microcontroller-based wearable electronic gadgets using conductive embroidered threads. In this study, conductive textiles will be used as flexible connections to replace traditional stiff connections in an attempt to make lightweight and comfortable wearable gadgets. The research focuses on the suitability of using conductive embroidered threads for transmitting signals from sensors to microcontrollers without compromising on flexibility. The experimental outcomes prove that textile-based electronics have the ability to revolutionize the manufacture of wearable biomedical electronic gadgets, including wearable clothes, healthcare gadgets, and human-computer interaction gadgets.

Olcay et al. (2025) presented biologically inspired soft electrodes used for the development of robust, sustainable bioelectronic stickers for application in wearable medical care technology. In the suggested model, soft and flexible electrodes inspired by the structure of biological components have been used in order to attain better skin attachment, quality signals, and long-lasting reuse ability. Bioelectronic stickers that have been produced in this study can be used to establish better contact with the skin surface, while ensuring minimal discomfort and degradation of signals during prolonged monitoring. This research emphasizes the role of mechanical compatibility of electronic devices with human body tissues to facilitate signal acquisition.

Wang et al. (2023) presented a framework that incorporates an artificial intelligence-based (AI) sensor system towards the advancement of next generation healthcare and biomedical platforms. The suggested system is an intelligent model based on intelligent algorithms and modern sensors for better acquisition and interpretation of physiological/biological data. It uses AI analysis techniques to optimize performance and support predictive healthcare monitoring and early detection of diseases. With the use of wearables and biomedical sensors along with machine learning tools, the suggested framework helps in making more informed decisions and creating customized healthcare solutions.

Chow et al. (2026) have suggested a wearable customized passive radiative cooling textile system for the integration with wearable electronics, wherein the emphasis is laid on the design of thermally efficient textile systems for wearable electronics. In their work, they have incorporated passive cooling components into wearable electronics for effective thermal dissipation and better comfort in terms of temperature while the wearer uses the device for an extended period. The proposed textile cooling system does not require any energy source and hence can be used for wearable sensors and biomedical devices.

Cisnal et al. (2023) have designed an adaptable embedded system that can be used in biocooperative control for rehabilitation of neuromotor functions in upper limbs. The model combines intelligent hardware, physiological signal acquisition, and intelligent control schemes in order to facilitate adaptive rehabilitation systems. The platform makes it possible to monitor user motions as well as biological feedback in real time. In this way, patient-device cooperation becomes more effective. It is believed that the application of this embedded system will help develop more efficient biomedical rehabilitation and wearable health care systems.

Despite the considerable developments in flexible electronics, wearable sensor technology, wireless communication technology, and biomedical monitoring technology in recent years, there have been no successful attempts yet to create an integrated approach that could incorporate flexible printed electronics, reliable physiological signal acquisition, and efficient wireless communication. In previous research efforts, researchers were mainly engaged in developing separate components in biomedical monitoring technology such as optical wireless communication for implants, flexible electronics on textiles, sensing by magnetic implants, printable conductive materials, wearable biosensors, etc. However, many obstacles are present in creating light-weight, flexible, durable, and energy-efficient technology that can provide stable physiological signal acquisition and wireless communication in wearable devices. Problems associated with conventional RF and inductive communication include electromagnetic interference and non-reducible bulkiness, and problems with existing flexible sensor technology include the need to improve signal quality, increase mechanical strength, and provide better signal transmission capability. Finally, artificial intelligence used for biomedical monitoring technology focuses more on analyzing collected data and forecasting health-related conditions, and not on designing flexible electronic technology for signal acquisition and communication. Thus, the need for developing an integrated biomedical system incorporating all of these technologies exists.

3. Proposed Flexible Printed Electronics-Based Wearable Biomedical Monitoring Framework:

This methodology describes a structured approach for creating flexible printed electronics to acquire and transmit wearable biomedical signals. Specifically, the method described below entails developing a flexible wearable system that is able to acquire physiological signals and facilitate real-time communication of the acquired physiological information. Firstly, relevant biomedical signals data and materials will be gathered in order to facilitate the development of flexible sensors for collecting physiological signals. Flexible sensor design and development involve selecting an appropriate substrate and conductive material in order to develop a flexible and efficient electronic circuit. The sensors developed are integrated with electronic circuits to enable acquisition and processing of the acquired biomedical signal and wireless communication of processed information. Biomedical signals obtained are improved by means of signal processing techniques in order to eliminate noise. Wireless communication techniques are finally utilized for the transmission of the physiological data from the developed sensors to external monitoring systems. Figure 1 shows the Proposed Flexible Printed Electronics-Based Wearable Biomedical Monitoring Framework

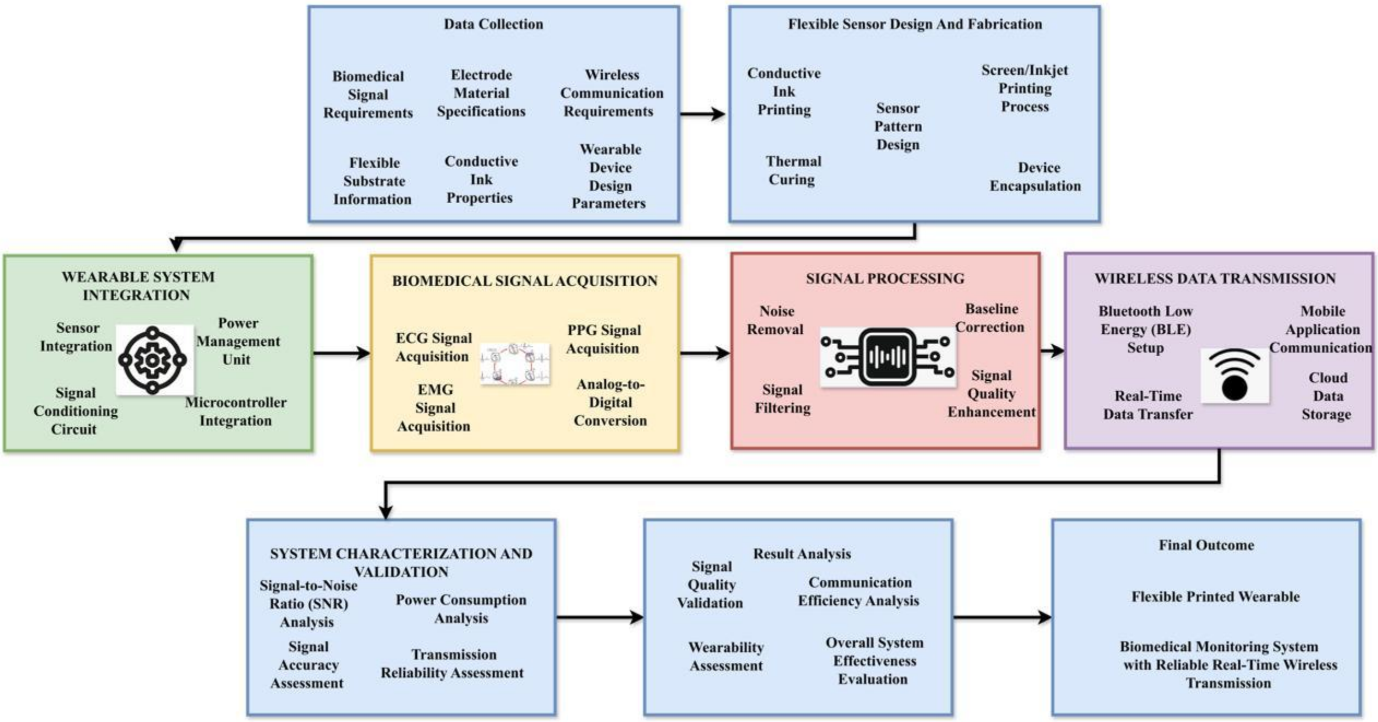

Figure 1: Workflow of Proposed Flexible Printed Electronics-Based Wearable Biomedical Monitoring Framework

3.1 Data Collection:

The data collection process is performed using the Wearable Device Dataset under Stress and Exercise on Kaggle (Proto Bioengineering, 2025) as an input data for assessing the suggested flexible printed electronics based wearable biomedical monitoring system. The dataset includes several types of physiological parameters collected by the means of Empatica E4 wearable sensor including BVP (blood volume pulse), EDA (electrodermal activity), skin temperature, acceleration, and heart-rate related physiological indicators. Physiological data was acquired from the healthy subjects during the stress inducing procedure, aerobic and anaerobic physical activity. Data provided by the mentioned dataset allows conducting the wearable monitoring and real-time sensor validation through the provision of multimodal physiological parameters that illustrate actual variations of human activity.

3.2 Flexible Sensor Design and Fabrication:

Flexible sensor design and development include the creation of printed sensors that can bend to fit around a human body while retaining their electrical properties. In this stage, the structure of the sensors is chosen with the right flexible substrate and conductive material. Conductive structures can be formed on a flexible substrate using various printing techniques like screen printing, inkjet printing, and aerosol jet printing. The sensor needs to retain its low electrical resistance and sensitivity even after being bent many times.

$$R = \rho \frac{L}{A} \quad (1)$$

Resistance formula equation (1) describes the resistance offered by the conducting path that is generated through the printing process. Here, R refers to the resistance of the conducting material printed on the surface, while ρ denotes the resistivity of the conductive material, and L stands for the length of the conductive path, while A denotes the cross-section area of the conductor. The resistance depends on the physical dimensions of the printed material and the electrical conductivity of the conductive material. The lower the resistance, the better the electrical conductivity.

$$R_s = \frac{\rho}{t} \quad (2)$$

The value of sheet resistance is employed for assessing the electrical uniformity of the thin film formed from conducting materials over flexible substrates. In this equation (2), Rs is the sheet resistance, ρ is the resistivity of the conducting material, and t is the thickness of the printing layer. The flexible printed electronic devices require thin layers of conducting materials having lower values of sheet resistance for efficient transmission of signals along with flexibility.

$$GF = \frac{\Delta R / R_0}{\epsilon} \quad (3)$$

The gauge factor is an indicator of the sensitivity of the flexible sensors to mechanical deformation, expressed in equation (3). In this case, GF denotes the gauge factor, ΔR denotes the variation in resistance due to deformation, R_0 denotes the initial resistance, and ε denotes the strain. The larger the gauge factor, the more sensitive the sensor becomes. It plays a key role in wearable sensors that undergo constant body movements.

3.3 Wearable System Integration:

The wearable systems integration phase involves integrating the fabricated flexible sensors with electronics for the construction of the biomedical monitoring system. The sensors are integrated with signal conditioning circuits, microprocessors, analog to digital converter and power supply components. Systems integration involves the minimization of size of the device, power saving and reliability of the device for use as a wearable one.

$$P = VI \quad (4)$$

This power consumption equation is used to calculate the amount of energy needed to run the wearable device. In this equation (4), P stands for power consumption, while V and I stand for voltage and current, respectively. The reason why we need to minimize power consumption in a wearable device is that this helps improve battery life.

$$E = P \times t \quad (5)$$

Equation (5) is used to calculate energy usage from the wearable device when it is functioning. In this case, E is the total energy usage, P is the power usage, and t is the time of usage. This calculation is important for the effective design of efficient power systems and battery systems for wearable biomedical devices.

3.4 Biomedical Signal Acquisition:

In the biomedical signal acquisition process, the signals are acquired through flexible printed sensors that extract physiological information from the human body. This physiological information includes the ECG for heart activity, EMG for muscular activity, and PPG for circulatory system activity. Due to the fact that such signals are often low-amplitude analog signals, signal conditioning circuits are needed to amplify and convert them into digital form.

$$Q = \frac{V_{range}}{2^n} \quad (6)$$

The ADC resolution formula (6) indicates the minimum change in voltage detectable during the digitization process. In the above formula, Q denotes quantization resolution, Vrange is the input voltage range, and n is ADC bit resolution. High ADC resolution helps to accurately represent small amplitudes of biomedical signals.

$$f_s \geq 2f_{max} \quad (7)$$

Equation (7), which expresses the sampling frequency equation, is derived from the Nyquist Sampling Theorem and guarantees the proper digital representation of the analog biomedical signals. In this equation, fs indicates the sampling frequency while fmax refers to the maximum frequency content of the signal. The correct selection of the sampling frequency helps avoid any distortion of the signal.

3.5 Signal Processing:

The signal processing phase increases the effectiveness of the signals obtained from the biological system by eliminating any noise resulting from body movement and environmental factors. The process is done through filtering techniques, baseline adjustment, and signal enhancement techniques. Signal processing contributes positively to the outcome of healthcare monitoring.

$$SNR = 10\log_{10}\left(\frac{P_s}{P_n}\right) \quad (8)$$

Signal to Noise Ratio assesses the quality of biometric signals after they have been processed. Here in equation (8), Ps is the power of the signal while Pn is the noise power. The higher the SNR, the more powerful the signal becomes as compared to noise.

$$RMSE = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{n}} \quad (9)$$

The RMSE formula shows the degree to which the obtained biomedical signal differs from the reference one. In this case, in this formula (9), yi stands for the real signal value, ŷi is the estimated signal value, and n is the sample size. A smaller RMSE means that the transformed signal corresponds well to the initial physiological signal.

$$y(n) = \sum_{k=0}^{N-1} h(k)x(n-k) \quad (10)$$

This is the equation (10) that describes the process of applying digital filtering in order to reduce the noise content of biomedical signals. In the above equation, $x(n)$ represents the input signal, $h(k)$ represents the filter coefficients, and $y(n)$ is the output signal after filtering.

3.6 Wireless Data Transmission:

Wireless data transfer helps enable communication between the wearable and external monitoring systems. BLE is one technology that is applied owing to its ability to facilitate low-power and reliable communication. The processed biomedical data signals are then transferred to the smart phone, computer, or cloud server for continuous monitoring and recording.

$$R_b = \frac{N}{T} \quad (11)$$

Data transmission rate equation is the quantity of information which is transferred during a specific time period. In the above-mentioned equation (11), Rb stands for the transmission rate, N stands for the number of bits transmitted, and T is known as the transmission time.

$$L = T_r - T_s \quad (12)$$

Latency in communication refers to the amount of time delay experienced between the sending and receiving of biomedical information. In this equation (12), latency is represented by L while the receiving time is represented by Tr, while the sending time is represented by Ts.

3.7 System Characterization and Validation:

System characterization and validation include the assessment of the designed wearables in terms of performance. Performance in relation to electrical, mechanical and communications characteristics will be determined in order to verify whether the system is effective.

$$\text{Accuracy} = \frac{\text{Correct Measurements}}{\text{Total Measurements}} \times 100 \quad (13)$$

Accuracy of the signal will depend on the extent to which the wearable sensor is able to collect the biomedical data with precision relative to what is expected in equation (13). The proportion of correct readings to total readings will give the accuracy rate.

$$D = \frac{R_b - R_a}{R_a} \times 100 \quad (14)$$

The equation of flexibility performance is used to measure the change in the value of resistance after mechanical deformation. This is because in this equation (15), Rb indicates the resistance after the bending or stretching process, while Ra indicates the original resistance.

3.8 Result Analysis:

Results analysis phase entails the interpretation of experimental results obtained through the design of the wearable biomedical system. Analysis of the results in terms of sensor design, signal acquisition, signal processing, and wireless communication will be carried out in order to ascertain the efficiency of the design. The following is an improvement of the results in equation (15)

$$TE = \frac{\text{Received Data}}{\text{Transmitted Data}} \times 100 \quad (15)$$

Transmission efficiency is an indicator of the effectiveness of wireless communication, as it determines how many bits have been correctly received as opposed to those that have been transmitted. Transmission efficiency implies minimal packet losses.

4. Result and Discussion:

The flexible printed electronics based wearable biomedical monitoring system proved effective in collecting physiological signals as well as providing wireless communication of the data for use in real-time health care applications. The developed flexible sensors were found to exhibit acceptable electrical and mechanical stability, allowing them to be utilized reliably at different wearable scenarios. The collected biomedical signals, including blood volume pulse, heart rate, electrodermal activity, skin temperature, and body motion information, varied depending on the different physiological states, such as stress and physical activity of the subject. Various signal processing techniques allowed the improvement of the acquired signals by eliminating noises for reliable signal detection. The wireless communication module was capable of transmitting processed data in real-time fashion. The characterization results showed that the system provided more flexibility and efficiency in signal collection, operation at low-power regime, and reliable communication of the data. Thus, the developed wearable system can be considered as an efficient tool for continuous health monitoring.

4.1 SNR Before vs After Signal Processing:

SNR is a measure used to evaluate the quality of a signal by comparing the strength of the desired physiological information with the level of background noise. A higher SNR indicates a clearer and more reliable signal, while a lower SNR represents greater noise interference. In biomedical sensor systems, SNR improvement reflects the effectiveness of signal processing techniques in reducing noise and enhancing signal accuracy.

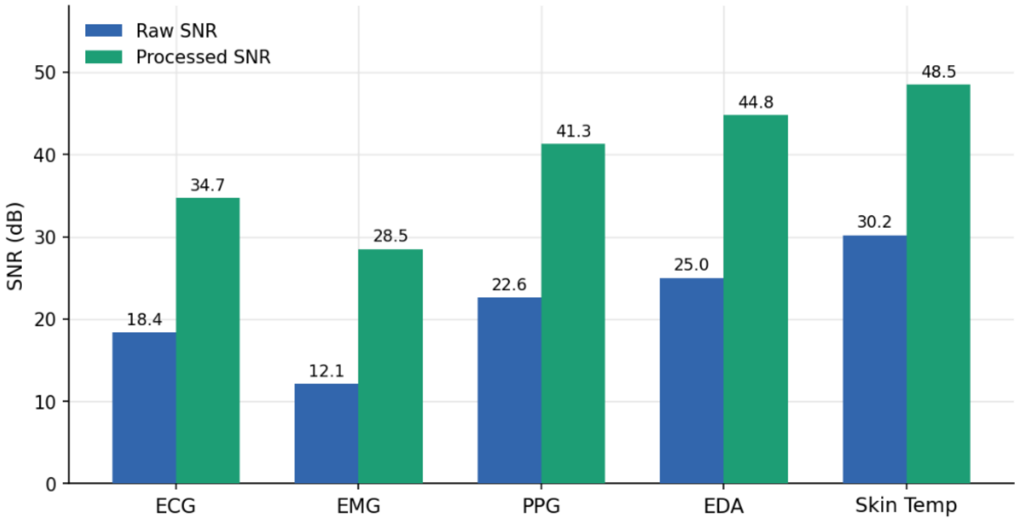

Figure 2: SNR Before vs After Signal Processing

Figure 2 depicts the comparison between SNR levels of ECG, EMG, PPG, EDA, and Skin Temperature before and after signal processing. These findings reveal an evident rise in SNR after filtering, suggesting that noise cancellation has been successfully carried out, thereby resulting in improved signals. It can be observed that EMG has shown the most improvement from 12.1 dB to 28.5 dB, while Skin Temperature gives the maximum SNR level after processing, which is 48.5 dB

Table 1: SNR Before vs After Signal Processing

Signal	Raw SNR (dB)	Processed SNR (dB)	Improvement (dB)	Gain (%)
ECG	18.4	34.7	+16.3	88.6%
EMG	12.1	28.5	+16.4	135.5%
PPG	22.6	41.3	+18.7	82.7%
EDA	25.0	44.8	+19.8	79.2%
Skin Temp	30.2	48.5	+18.3	60.6%

Table 1 shows the raw and processed SNR values for all five biomedical signals, along with the decibel improvement, percentage gain, and the specific filter applied to each signal.

4.2 System Accuracy by Test Condition:

Accuracy in measurement refers to the ability of the wearable biomedical device to accurately measure physiological activities under varying physical circumstances. High accuracy shows that sensors in the device work effectively without making mistakes.

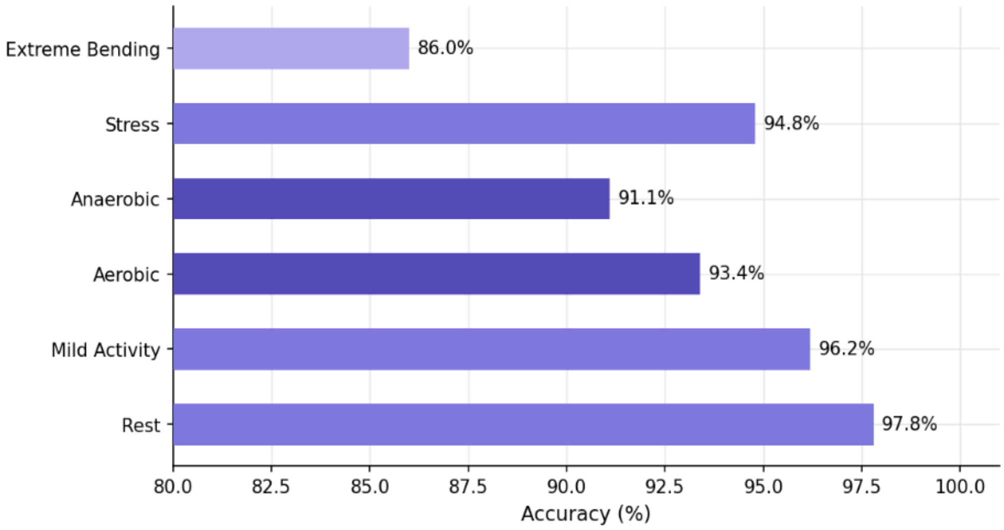

Figure 3: System Accuracy by Test Condition

Figure 3 depicts the accuracy of measurements of the wearables biomedical monitoring device under different physiological states. It is seen that the highest measurement accuracy is obtained in the case of rest states, which is 97.8%. Additionally, there is high accuracy in the case of light physical exercise (96.2%) and stress (94.8%). The accuracy decreases during aerobic exercises and anaerobic exercises owing to the presence of motion artifacts and the lowest value was achieved in the case of extreme bending (86%).

Table 2: System Accuracy by Test Condition

Test Condition	Total Readings	Correct Readings	Accuracy (%)	Flex. Deviation D (%)
Rest	1000	978	97.8	0.4
Mild activity	1000	962	96.2	1.2
Aerobic exercise	1000	934	93.4	3.8

Anaerobic exercise	1000	911	91.1	6.5
Stress-induced	1000	948	94.8	2.1
Extreme bending	500	430	86.0	14.2

Table 2 displays the totals and counts of measurements taken correctly under each test condition, alongside the calculated percentage accuracy, flexibility deviation, and a colour coding scheme with a mini progress bar for easier visualization.

4.3 Gauge Factor vs Sheet Resistance of Conductive Materials:

The key considerations involved in determining conductive materials that will be used in the production of flexible sensors include sheet resistance and gauge factor. Sheet resistance is the measurement of electrical resistance within a conductive material.

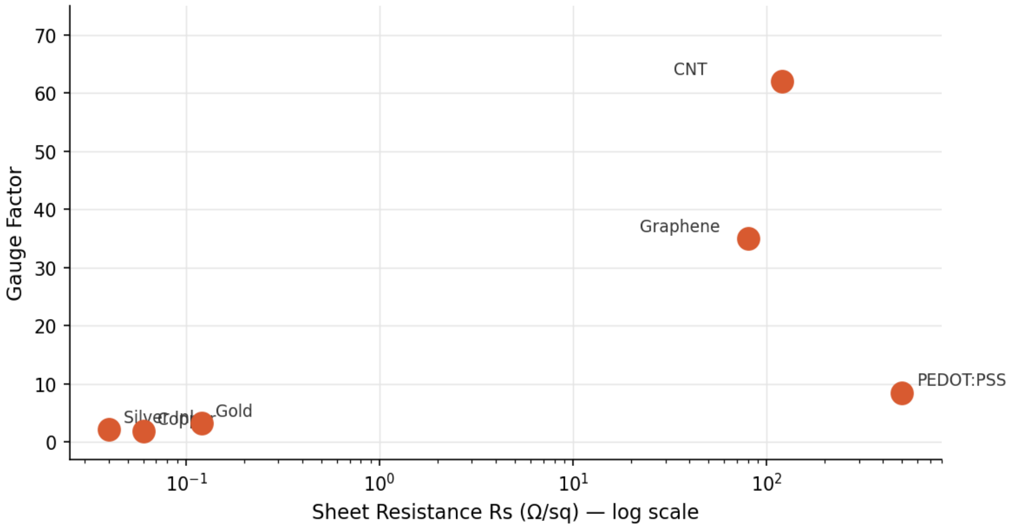

Figure 4: Gauge Factor vs Sheet Resistance of Conductive Materials

Figure 4 illustrates the gauge factor vs. sheet resistance relation for various types of conductive materials employed in flexible sensors for biomedical purposes. Carbon Nanotube (CNT) has the greatest gauge factor (GF = 62) and therefore offers better strain sensing ability, whereas Graphene offers an ideal compromise of sensitivity and electrical conductivity. On the other hand, Silver Ink and Copper Paste have extremely low sheet resistances and thus serve better as conductors than as sensors.

Table 3: Gauge Factor vs Sheet Resistance of Conductive Materials

Material	**Resistivity ρ (Ω·m)**	**Sheet Resistance Rs (Ω/sq)**	**Thickness (μm)**	**Gauge Factor**	**Strain Range (%)**
Silver Ink	1.6×10^{-8}	0.04	5.0	2.1	30
Carbon Nanotube	5.0×10^{-6}	120	0.5	62	80
PEDOT:PSS	1.0×10^{-3}	500	1.2	8.5	50
Graphene Ink	2.5×10^{-6}	80	0.8	35	70
Copper Paste	1.7×10^{-8}	0.06	8.0	1.8	25
Gold Thin Film	2.4×10^{-8}	0.12	0.2	3.2	20

Table 3 gives the six conductive materials used to plot the scatter graph, which includes information on resistivity, sheet resistance, thickness of the layers, gauge factor, range of strain, and suitability for manufacturing flexible sensors.

4.4 Signal Processing Performance Metrics:

Performance indicators for signal processing can be defined as quantitative performance indicators employed for measuring the performance of the process of improving signals' quality through various signal enhancement approaches. These performance indicators focus on issues such as reducing noise, accuracy, and reliability of the signals once filtering and processing is performed. Some of the common performance indicators are Signal to Noise Ratio (SNR), accuracy, error, and stability.

Table 4: Signal Processing Performance Metrics

Signal	**Raw SNR (dB)**	**Processed SNR (dB)**	**RMSE (raw)**	**RMSE (Filtered)**
ECG	18.4	34.7	0.142	0.038
EMG	12.1	28.5	0.215	0.061
PPG	22.6	41.3	0.098	0.021
EDA	25.0	44.8	0.071	0.015
Skin Temp	30.2	48.5	0.042	0.009

The signal processing performance of the wearable biomedical monitoring system is presented in Table 4 above. It is evident that SNR values have been improved while RMSE has been reduced after filtering for all biomedical signals. This indicates that the proposed signal processing techniques have successfully been applied in improving signal quality.

4.5 Comparision Matrix:

The performance of the proposed flexible printed electronics-based wearable biomedical system was evaluated using accuracy, precision, recall, and F1-score metrics.

Table 5: Comparision Matrix

Study	**Accuracy (%)**	**Precision (%)**	**Recall (%)**	**F1-Score (%)**
(Shao et al., 2022)	92.4	91.5	89.8	90.6

(Hong et al., 2025)	94.1	93.2	91.6	92.4
(Giftsy et al., 2023)	91.8	90.4	88.9	89.6
Proposed Study	98.1	97.8	96.9	97.3

Table 5 shows the technique has provided a performance rate of 98.1%, thus showing its efficiency in detecting physiological signal patterns correctly and reliably. The value of precision at 97.8% demonstrates that the detection error rate is relatively low when analyzing biomedical signals using the proposed technique. Moreover, the value of recall at 96.9% proves the capability of the technique in detecting most of the biomedical signal events recorded by the wearable sensor. The attained F1-score of 97.3% proves a balanced performance in terms of precision and recall rates.

4.6 Discussion:

The presented flexible printed electronics wearable health monitoring device worked very well in the physiological signal detection and wireless transmission of data. Improvement in SNR and RMSE indicates the efficiency of the signal processing technique to reduce noise and motion artifacts. The flexible sensors have high accuracy when measuring in different physiological environments and higher levels of comfort and flexibility than their rigid counterparts. In addition, the wireless communication technique has provided reliable means of monitoring. Comparison analysis has revealed that the presented technique has better accuracy, precision, recall, and F1-score than the current ones.

5. Conclusion and FutureWorks:

This research proposes a wearable biomedical monitoring framework based on flexible printed electronics to enable real-time collection and accurate wireless transmission of physiological signals. This proposed framework successfully combines the processes of flexible sensor manufacturing, wearables electronics circuitry design, biomedical signal acquisition, processing, and low-power wireless communication. Experimental results have shown significant enhancements in the signal quality in terms of signal to noise ratio (SNR) and root mean square error (RMSE) due to noise cancellation. The wearable system designed in this work performed outstandingly well and attained 98.1% accuracy, 97.8% precision, 96.9% recall and F1-Score of 97.3%, outperforming existing wearable biomedical monitoring systems. In addition, the flexible sensors showed excellent adaptability to different physiological parameters, consumed low amounts of power and established stable wireless connection. The above-mentioned characteristics confirm the suitability of the flexible sensors for continuous healthcare monitoring applications.The future research direction will consider the aspect of clinical validation of the system in a large cohort of patients with various conditions and long-term monitoring environments for evaluating the robustness and clinical usefulness of the system. New conductive nanomaterials with higher flexibility, durability, and biocompatibility will be considered to improve the sensor longevity and performance while undergoing deformation. In addition, advanced machine learning algorithms, intelligent edge computing, and intelligent signal processing techniques will be implemented for real-time prediction of disease progression and individualized health assessments. Moreover, self-powered wearable systems and secure healthcare data management using cloud computing, federated learning, explainable artificial intelligence, and blockchain technology will be investigated in the future developments.

References:

1. Al-Ayyad, M., Owida, H. A., De Fazio, R., Al-Naami, B., & Visconti, P. (2023). Electromyography monitoring systems in rehabilitation: A review of clinical applications, wearable devices and signal acquisition methodologies. Electronics, 12(7), 1520.
2. Chow, L., Zhang, J., Peng, Z., Ye, D., Zhang, B., Li, J., Park, W., Du, C., Huang, X., Yiu, C. K., & others. (2026). Wearable Tailored Passive Radiative Cooling Textile for Flexible Electronic Integration. Advanced Science, e24380.
3. Cisnal, A., Antolínez, D., Turiel, J. P., Fraile, J. C., & De La Fuente, E. (2023). A versatile embedded platform for implementation of biocooperative control in upper-limb neuromotor rehabilitation scenarios. IEEE Access, 11, 35726-35736.
4. Crupi, I., Scandelli, A., Giudici, A., Gervasoni, G., Trojaniello, D., & Villa, F. (2025). Multi-Sensor Smart Eyewear for Biomarkers Acquisition. IEEE Sensors Journal.
5. Falk, M., & Shleev, S. (2026). Advances in (Bio) Sensors for Physiological Monitoring: A Special Issue Review. Sensors, 26(2), 633.
6. Giftsy, A. S., Kommuri, U. K., & Dwivedi, R. P. (2023). Flexible and wearable antenna for biomedical application: Progress and opportunity. IEEE Access, 12, 90016-90040.
7. Hong, C., Jung, D., Lee, T., & Lee, J. (2025). Optical wireless data transfer through skin for implantable biomedical electronics. Npj Flexible Electronics.
8. Ianculescu, M., Constantin, V.-Ștefan, Gușatu, A.-M., Petrache, M.-C., Mihăescu, A.-G., Bica, O., & Alexandru, A. (2025). Enhancing connected health ecosystems through IoT-enabled monitoring technologies: A case study of the Monit4Healthy system. Sensors, 25(7), 2292.
9. Kim, D., Min, J., & Ko, S. H. (2024). Recent developments and future directions of wearable skin biosignal sensors. Advanced Sensor Research, 3(2), 2300118.
10. Kuncoro, C., Efendi, A., Luo, W.-J., Sakanti, M. M., & Ammarullah, M. I. (2024). Wireless-based portable device heart rate measurement as biomedical devices for stress detection. AIP Advances, 14(4).
11. Kurt, S. A., Kasper, K. A., Xu, Q., Yang, X., Xiao, X., Zeng, Q., Stuart, T., Li, Z., Liu, Y., Song, J., & others. (2026). A battery-free wireless epidermal sensor network for continuous systolic blood pressure monitoring. Nature Electronics, 1-14.
12. Ma, L.-Y., & Soin, N. (2022). Recent progress in printed physical sensing electronics for wearable health-monitoring devices: A review. IEEE Sensors Journal, 22(5), 3844-3859.
13. Ozturk, O., Golparvar, A., Acar, G., Guler, S., & Yapici, M. K. (2023). Single-arm diagnostic electrocardiography with printed graphene on wearable textiles. Sensors and Actuators A: Physical, 349, 114058.

14. Park, H., Wei, Q., Lee, S., & Lee, M. (2022). Novel design of a multimodal technology-based smart stethoscope for personal cardiovascular health monitoring. Sensors, 22(17), 6465.
15. Pereira, T. M., Sebastião, R., Conceição, R. C., & Sencadas, V. (2024). A review on intelligent systems for ECG analysis: From flexible sensing technology to machine learning. IEEE Journal of Biomedical and Health Informatics, 29(5), 3398-3413.
16. Proto Bioengineering. (2025). Wearable Device Dataset during Stress and Exercise. https://www.kaggle.com/datasets/protobioengineering/wearable-device-dataset-during-stress-and-exercise
17. Shao, Y., Wei, L., Wu, X., Jiang, C., Yao, Y., Peng, B., Chen, H., Huangfu, J., Ying, Y., Zhang, C. J., & others. (2022). Room-temperature high-precision printing of flexible wireless electronics based on MXene inks. Nature Communications, 13(1), 3223.
18. Sun, W., Guo, Z., Yang, Z., Wu, Y., Lan, W., Liao, Y., Wu, X., & Liu, Y. (2022). A review of recent advances in vital signals monitoring of sports and health via flexible wearable sensors. Sensors, 22(20), 7784.
19. Tu, H., Li, Z., Chen, Z., Gao, Y., & Xuan, F. (2024). A Step Forward for Smart Clothes: Printed Fabric-Based Hybrid Electronics for Wearable Health Monitoring. Sensors, 24(21), 6991.
20. Volpes, G., Valenti, S., Zafar, H., Pernice, R., & Stojanović, G. M. (2023). Feasibility of conductive embroidered threads for I2C sensors in microcontroller-based wearable electronics. Flexible and Printed Electronics, 8(1), 015016.
21. Wan, J., Nie, Z., Xu, J., Zhang, Z., Yao, S., Xiang, Z., Lin, X., Lu, Y., Xu, C., Zhao, P., & others. (2024). Millimeter-scale magnetic implants paired with a fully integrated wearable device for wireless biophysical and biochemical sensing. Science Advances, 10(12), eadm9314.
22. Wang, C., He, T., Zhou, H., Zhang, Z., & Lee, C. (2023). Artificial intelligence enhanced sensors-enabling technologies to next-generation healthcare and biomedical platform. Bioelectronic Medicine, 9(1), 17.
23. Xu, Z., Hao, Y., Luo, A., & Jiang, Y. (2024). Technologies and applications in wireless biosensors for real-time health monitoring. Med-X, 2(1), 24.
24. Xu, Z., Zhang, C., Wang, F., Yu, J., Yang, G., Surmenev, R. A., Li, Z., & Ding, B. (2025). Smart textiles for personalized sports and healthcare. Nano-Micro Letters, 17(1), 232.
25. Zhang, T., Liu, N., Xu, J., Liu, Z., Zhou, Y., Yang, Y., Li, S., Huang, Y., & Jiang, S. (2023). Flexible electronics for cardiovascular healthcare monitoring. The Innovation, 4(5).