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Intelligent Polymer-Integrated Wearable Platforms for Sustainable IoT and Predictive Health Monitoring for Migraine Detection

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Abstract

Migraine is a neurological disorder, and its effect on the global workforce is resultantly significant. However, the fact of the matter is the absence of notable technological breakthroughs and the fact that the technology presently available is reactive, meaning it tackles the symptoms of the attack after the attack has occurred. The requirement for this paper is, therefore, the provision of an innovative approach, and this paper will describe the intelligent and wearable approach utilizing the predictions of the attack based on the stochastic nature of the biological signals. The proposed system monitors the essential pre-ictal physiological signal variations, which consist of the heart rate signal extracted from the photoplethysmography signal, Galvanic Skin Response, and the temperature of the skin. The essential physiological signal variations are processed through sophisticated machine learning techniques such as eXtreme Gradient Boosting *(XGBoost) and* Long Short-Term Memory *(LSTM) Networks, which have the precision to identify the minute trends among the patients prior to the onset of the migraine attacks. When the detection algorithm receives information about the potential onset of a migraine, it provides alert messages to the patients in the form of vibration messages and a polymer-based web interface. Development in the hardware arena also places importance on utilizing polymers/composites to their fullest extent. This technology can be employed in the development of wearable forms that should also exhibit biocompatibility, elasticity, lightness, and strength. Its applications also include future possibilities related to energy use. Based on the final prototype, the verification test of the prototype made it possible to establish the presence of the physiological pattern before the attack and attain an average prediction accuracy of the LSTM model of 88.9 percent. Generally, the results of the experiment underscore the huge potential for the use of AI technology in conjunction with the utilization of polymers in wearable technology for the prediction and prevention of neurology and Migraines.*

Keywords; eXtreme gradient boosting (XGBoost), long short-term memory (LSTM), pre-ictal, galvanic skin response

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INTRODUCTION

Migraine is a progressive and debilitating neurological disease that is defined by recurring bouts of headache, often with varying levels of severity from mild to severe, often with accompaniments of nausea, sensitivity to light, sound, cognitive disturbances, and brief bouts of neurological deficits. Current neuroscientific literature has redefined the pathophysiology of migraine as a disorder of brain function [5], with derangements of autonomic nervous system function rather than simply a vascular disease. Migraines are one of the major causes of disability in the world with more than one billion cases globally, predominantly in the most productive years of young individuals [4]. However, the major additional cost of migraine apart from the physical distress of pain is because of impaired productivity in the workplace with increased vulnerability of the individual to depression.

Notwithstanding a great deal of research, migraine underwent inadequate diagnosis as well as treatment based on current clinical practice. The difficulty level arises from episodic, unpredictable attacks that make it difficult to diagnose as well as treat effectively on time. The methods available for migraine are characterized as mainly acute, aimed at easing symptoms using drugs such as nonsteroidal anti-inflammatories as well as triptans when treatment begins after a migraine has already occurred. Even though these methods can decrease pain, there is a need for early prevention that has not been met by these methods based on current clinical practices.

Clinical and neurophysiological studies have shown that the migraine episodes are generally preceded by the existence of what is known as the prodromal phase, also known as the pre-ictal phase, and can happen hours before the actual occurrence of the migraine headache and even days before them [4]. Parameters for the existence of such phenomena as the potential pre-ictal state of the body, among others, include heart rate variability (HRV), electrodermal activity (EDA), skin temperature, and the level of physical activity that can be measured as potential signs of such pre-ictal physiological patterns. Recent advancements have been able to continuously and non-invasively monitor such parameters, thus allowing the early stages of the prodrome and impending attack of the migraine condition to be identified [1–3].

Prediction capabilities in migraine wearable systems have been largely improved by the application of both Machine Learning (ML) and Deep Learning (DL). Machine learning algorithms used in HRV signal analyses have shown good performance in identifying changes in the Autonomic Nervous System associated with neurological/neurodegenerative diseases, as well as cardiovascular diseases [6]. Moreover, architectures such as Long Short-Term Memory (LSTM) are particularly appropriate for HRV signal recording analyses, showing good performance in identifying pre-ictal states over long periods [7, 8]. Moreover, the application appropriateness of both Machine Learning algorithms/DL in wearable health technologies for the variety of biomedical signal analyses has been shown in many studies [9].

Similarly to the progress observed in data analytics solutions, the effectiveness of wearable health monitoring systems relies very much on the evolution of material platforms with high performance characteristics. Conductive polymers or polymer composites with flexibility and biocompatibility are found to be important enablers for the next generation of wearable sensors with a light structure and ability to be in prolonged skin contact for a prolonged period of time [10]. Graphene polymer nanocomposites have shown improved sensitivity, long durability, and lower power consumption ability with great suitability for biosignal sensing in wearable health monitoring systems [11].

The integration between wearable polymers and IoT platforms may aid or facilitate the transfer and analysis of data in a cloud-based setup and health monitoring by the individual. The use of wearable technologies based on the concept of IoT has been immensely studied for its use in remote healthcare support. It helps in effortless health monitoring of the wearer with health suggestions for the individual too [13, 14]. This will allow the use of the framework for predictive modeling with machine learning algorithms and deep learning algorithms for early warnings and proactive migraine control strategies. Scalable intelligent systems based on polymers have already been investigated for use in comparable predictive domains [12].

In this way, a promising path toward predictive migraine analysis is made possible by the clever integration of wearable polymer-based platforms with IoT connectivity and machine learning-driven analytics. By early detection of a pre-ictal physiological state, these technologies thus facilitate a paradigm shift from symptom-based reactive treatment to proactive and preventive care. Accurate prediction of migraine onset reduces the severity and frequency of the attack, improves the quality of life of the patients, and cuts down the overall clinical and socio-economic burden associated with migraine.

Problem Statement

Despite the progress made in the field of wearable health technology and migraine studies, there is an urgent need to fill the critical gap in the development of an effective, affordable, and practical wearable system that can potentially predict migraine attacks before the onset of the migraine. Migraine prediction today is restricted to the aftermath, as the existing wearable solutions are primarily focused on migraine management. Various studies in the past identified some biomarkers in the prodrome state that are linked to migraine, but that knowledge has not been applied effectively to develop wearable solutions.

Existing wearable technology is presently plagued by an inability to sense adequately, as it is reliant on a single or minimally integrated physiological measure indicative of migraine changes, but this is insufficient, as migraine is a function of multiple, contemporaneous changes in the autonomic function, electrodermal activity, thermoregulation, or cardiovascular function of the human body. Presently, these parameters simply cannot be adequately measured in a timely, comprehensive manner. Currently, early warning systems are insufficient.

Another significant limitation an epilepsy prediction system could have is in the computational framework of existing solutions. Many solutions rely heavily on cloud analytics, which has latency issues, increased power consumption, privacy issues, and hinder real-time response capabilities. There is no edge-based machine learning capability to enable real-time predictions and decision-making functions necessary in providing preliminary warnings during the pre-ictal stage Moreover, the existing prediction models have been designed and tested in an ideal and controlled lab environment that was not designed to bear real-world deployments.

From the point of view of hardware, there are a number of challenges due to material constraints and capability of wearing. Traditional rigid or semiflexible versions of electronics, when worn continuously for a long period of time, will definitely result in discomfort, poor skin contact, and motion artifacts. Even though polymer-based materials and composites show promising results in the development of flexible and stretchable sensors, their utilization in developing smart, low-power, and durable solutions specific to migraine is largely uninvestigated. Sustainability and accessibility add fuel to the fire. Currently, most of the existing wearable technologies for healthcare applications are either too expensive, inefficient, and battery-draining, thus limited for use in developing countries. Besides, the absence of sustainable architecture for IoT deployment is a significant constraint.

In order to overcome the above challenges, the design and development of a sustainable, robust, and intelligent polymer composite-based wearable platform integrating multimodal physiology sensor capabilities, edge-based machine learning, and IoT features for the early detection of migraines will be proposed. The proposed research has the ability to achieve comfortability, real-time pre-ictal detection, energy efficiency, and analytical prediction studies. Based on the potential of promoting the prevention of migraines through early warnings of attacks, the proposed research aims to contribute to the growth of wearable health care technology at the state-of-the-art frontier.

Proposed System

The proposed system links polymer-based wearable sensors with AI-driven predictive analytics. In this setup, real time prediction of migraine attacks is possible. It includes three major components: a wearable sensor platform, a data acquisition and pre-processing module, and an AI-based migraine prediction engine as presented in Figure 2.

The wearable sensing platform utilizes flexible, polymer-based materials in order to guarantee comfort, durability, and the reliable capture of physiological signals continuously. Multimodal sensors, such as PPG for heart rate and heart rate variability, galvanic skin response (GSR) sensors measuring the activity of the autonomic nervous system, and skin temperature sensors monitoring thermoregulation, are featured. Stable contact with the skin is maintained by conductive polymer composites and stretchable polymer electrodes while reducing motion artifacts. Lightweight, biocompatible, and anticorrosion properties of these polymer materials provide long-term daily use unimpairing the quality of the captured signal and comfort of the user [15–17].

- *Data acquisition and preprocessing:* The biological signals measured by the wearable sensing components are digitized by the low-noise analog-to-digital converters integrated into a low-power microcontroller unit. The digitized information is then transferred wirelessly by Bluetooth or Wi-Fi to a processing unit. The raw signal processing further comprises filtering, motion artifact correction, normalization, as well as signal synchronization for a multi-sensor. The critical features that have been extracted include HRV measures, GSR values on both amplitude and slope, as well as changes in skin temperature to improve the identification of biological patterns associated with the looming migraine attack.
- *AI-driven migraine forecasting engine:* The preprocessed multimodal data is further processed through the combination of Machine Learning algorithms and Deep Learning algorithms such as XGBoost and LSTM. The proposed LSTM algorithm is capable of recognizing the trend of the physiological signals that normally occur prior to a migraine. The XGBoost algorithm is the classifier that also determines the feature importance. The features obtained from the sensor data can be further processed through the context of the data such as the level of activity and the circadian rhythms to increase the confidence of the predictions. The algorithms are trained and checked on the labeled data of the migraine event to increase the predictability of the warnings and the warning time to reduce the chances of the warning being a false alarm. The real-life wearable implementation of the proposed system is illustrated in Figure 1.

MATERIALS AND METHODOLOGY

System Architecture

The proposed solution should have applications in being an efficient and portable solution for tracking those physiological signals that precede migraine prodromal activity. The proposed solution for designing the hardware involves combining photoplethysmography sensors, galvanic skin response sensors, and skin temperature sensors that can be integrated along with an ESP32 MCU. The use of these sensors has been deemed appropriate since they are relevant for tracking autonomic nervous activity along with temperatures that precede an event of migraine.

Figure 1. Real life wearable band for migraine detection.

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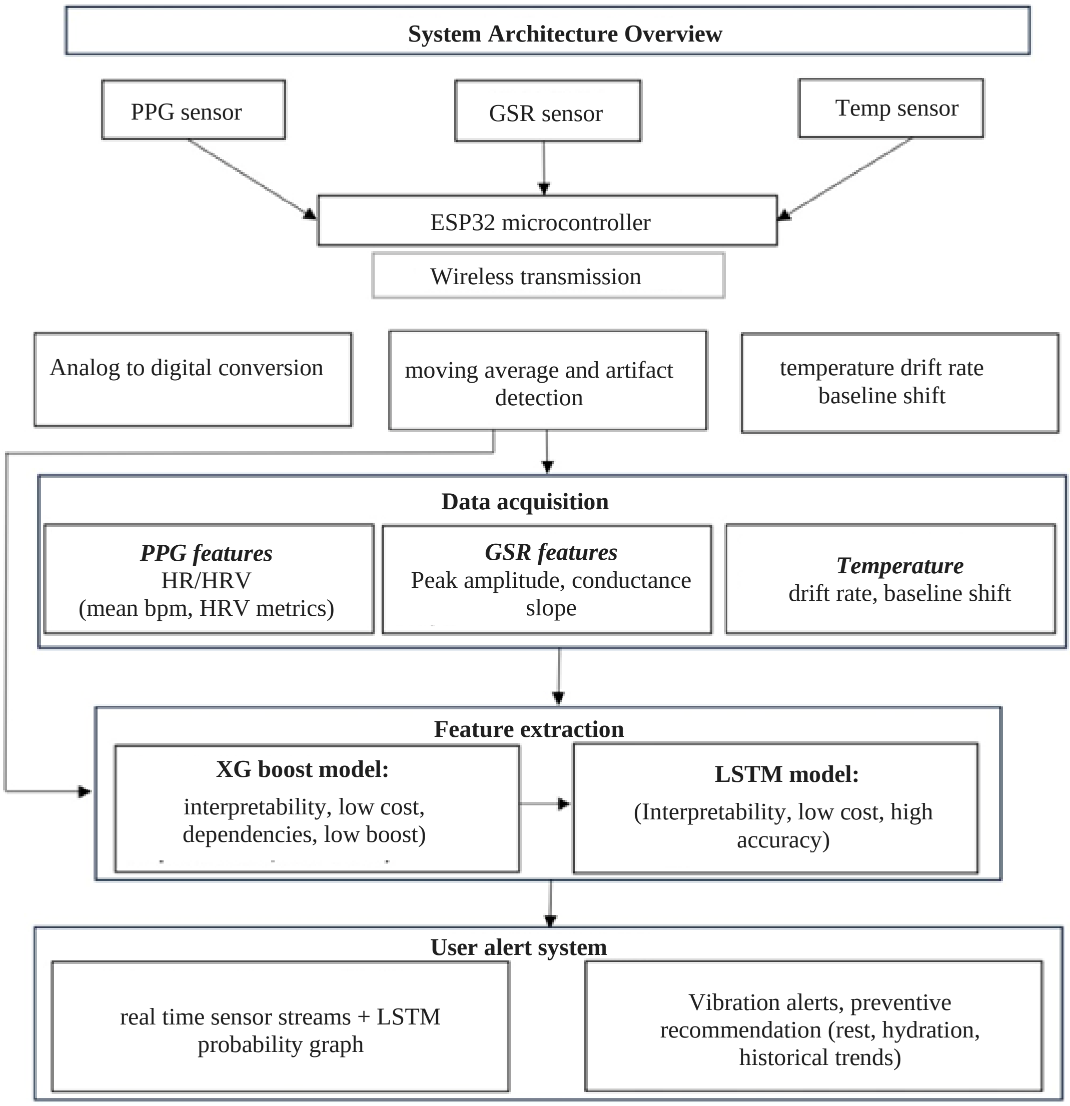

Figure 2. System architecture overview.

The ESP32 module serves as a processing and communications center with an in-built Wi-Fi and Bluetooth low energy solution for communications, processing power sufficient for edge-level processing, and power efficiency suitable for wearable devices. The sensors will be hosted on a polymer composite material with a flexible trait suitable for good skin fit, reducing artifacts caused by motion and offering wear comfort while interacting with the device [18, 19]. The system architecture allows for real-time data acquisition and processing.

Rationale for Polymer-Based Biosignal Sensing

Polymer-based materials were selected over conventional metallic or inorganic sensors due to biomechanical compatibility, signal stability, and long-term wearability.

Mechanical Compatibility with Skin

Human skin exhibits:

- Elastic modulus: 0.42–0.85 MPa
- Continuous micro-motions during daily activity

Conventional metallic electrodes:

- Are rigid or semi-flexible

- Cause motion artifacts
- Lead to poor conformal contact
- Induce skin irritation during prolonged wear

In contrast, polymer composites:

- Exhibit stretchability >50%
- Provide conformal skin adhesion
- Maintain stable electrode–skin impedance
- Reduce motion-induced noise

Electrical Performance Advantages

Conductive polymers (PEDOT:PSS, PANI):

- Provide low interfacial impedance
- Improve signal-to-noise ratio
- Enable dry-electrode operation
- Eliminate need for conductive gels

This improves practicality for daily wearable migraine monitoring.

Biocompatibility and Long-Term Wear

Polymeric materials:

- Are lightweight
- Are breathable
- Reduce allergic reactions
- Improve user compliance

For predictive systems requiring continuous pre-ictal monitoring, long-term comfort is critical. Metallic electrodes are less suitable for such extended use.

Integration with Flexible Electronics

Polymers enable:

- Stretchable interconnects
- Embedded sensors within soft bands
- Integration of energy harvesting layers
- Thin-film fabrication

Thus, polymer-based sensing is not only a material choice but a system-level design strategy for scalable wearable healthcare.

Data Acquisition

Signals from the PPG, GSR sensor, and temperature sensor are continuously sampled with a predetermined time interval for optimized fidelity power consumption. The PPG sensor records the wave signals for heart rate and heart rate variability analysis, while the GSR sensor measures the skin conductance level change that reflects the activity of the sympathetic nervous system. Skin temperature is measured for detecting the gradual change in temperature associated with the prodrome of the migraine episode.The ESP32 has a built-in analog to digital converter that converts the analog signals to digital signals from the sensor. In order to have accurate results from the sensor, it does some processing on the raw signals received from the sensor, which includes filtering, smoothing, and removing artifacts. Motion artifacts as well as other temporary disturbances in the signals are removed using digital filtering methods such as moving averages and adaptive thresholding techniques.

Feature Extraction

The relevant physiological parameters are derived from preprocessed sensor measurements that describe the pre-ictal features related to migraine attacks. For PPG signals, heart rate and heart rate variability parameters are derived, which include time domain parameters such as average interbeat interval and standard deviation of NN intervals (SDNN). Such parameters describe autonomic function and cardiac homeostasis.

Machine Learning Workflow

The predictive model first uses two machine learning algorithms to evaluate system performance and interpretability: Extreme Gradient Boosting and Long Short-Term Memory networks. The former is due to its nonlinear relationship handling ability and the importance of the features that make it interpretable. In this approach, one will be able to evaluate what biological features are most influential on migraine prediction.

In this paper, the authors propose a deep learning model incorporating the LSTM algorithm that can capture the temporal relationships embedded in the time series nature of physiological data. It is established that the LSTM model proves to be particularly useful when handling patterns and relationships embedded in a series of multimodal data streams.

The models will be trained and tested on labeled datasets incorporating periods leading up to and including the ictal phases of seizures. The model performances will then be compared based on metrics such as accuracy, precision, recall, and the F1 score. A comparison underlines the fact that the LSTM model is more accurate in the pre-ictal phase compared to the rest.

The improvement is attributed to:

- Reduced false positives
- Better pre-ictal transition detection
- Enhanced sensitivity to subtle autonomic changes
- Improved recall (89.2%)

Fusion Strategy

The proposed system will utilize feature level multimodal fusion as follows:

1. Independent preprocessing of PPG, GSR, and temperature signals
2. Feature Extraction from each Modality
3. Concatenation into a unified multimodal feature vector
4. Temporal modeling using
5. Nonlinear classification refinement using XG

This enables the model to learn:

- Cross-modal interactions
- Temporal dependencies
- Progressive physiological changes before migraine onset

MULTIMODAL DATA FUSION FRAMEWORK

Multimodal Data Fusion Framework for Migraine Prediction

Yes, multimodal data fusion is implemented in the proposed system.

Migraine prodrome is characterized by simultaneous alterations in:

- Cardiovascular regulation (HR, HRV)
- Sympathetic nervous activity (GSR)
- Thermoregulation (Skin temperature)

Single-signal systems fail to capture the full physiological complexity.

Improvement in Detection Accuracy

Table 1. Performance comparison:

Model Type	Accuracy
Single-signal baseline (PPG only)	~75–78%
Multimodal + RF	78.1%
Multimodal + XGBoost	82.5%
Multimodal + LSTM	88.9%

Why Multimodal Fusion Works for Migraine?

Migraine is not a single-parameter disorder. It involves:

- Hypothalamic activation
- Autonomic imbalance
- Neurovascular dysregulation

Thus, fusing multimodal physiological streams improves physiological realism and prediction.

User Alert and Interface

For the purpose of ensuring timely user interaction, the system makes use of a real-time alert system, which sends notifications every time the probability of an attack surpasses a certain threshold. These notifications are in the form of vibrations emanating from the wearable component, as well as notifications transmitted wirelessly into a user interface. The online dashboard developed by applying Polymer.js is able to provide a real-time graph of data coming from sensors, features, and predictive probabilities of migraine attacks. The online dashboard is significant in that it enables users of HealthRider to monitor their physiological trends with an early warning system that is easily comprehensible. The online dashboard promotes active health monitoring.

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SENSOR DEPLOYMENT AND DATA ACQUISITION SIGNALS

These physiological patterns were measured through the use of wearable sensors that were positioned on the human body, for example, on the wrist or upper arm, with the aim of monitoring in a continuous, unobtrusive manner. The wearable device is made up of a set of sensors that include photoplethysmography (PPG) sensors intended for the analysis of heart rate/heart rate variability, galvanic skin response (GSR) sensors in charge of the physiological functions of the autonomic nervous system, and skin temperature sensors intended for analyzing the thermoregulatory functions of the human body. These physiological patterns are analyzed while carrying out normal day-to-day activities that define the pre-ictal stage before the occurrence of migraines.

The sensor signals were digitalized through the incorporation of low noise ADCs. These signals were then transmitted through the use of wireless communication interfaces such as BLE and Wi-Fi to the processing units. The rate at which the signals were sampled varied depending on the signal. The signals that were sampled at 1-10Hz were GSR and skin temperature, and the rest were sampled at 100-250Hz. Continuous data and redundancy were utilized to ensure reliability and elimination of motion artifacts.

Data Preprocessing and Feature Extraction

The preprocessing part ensured that high-quality and credible input was fed to the AI model through the following ways:

1. *Noise Reduction:* Low-pass filters removed motion artifacts, while adaptive filters removed ambient noise. Smoothing filters reduced high-frequency noise in the GSR and temperature signals.
2. *Normalization:* Min-Max scaling helped to normalize the physiology signals across distinct individuals and sensor channels. This ensured that training the models uniformly became easy.
3. Outlier removal using thresholding and validation of Z-scores eliminated outliers introduced by movement of sensors, rapid motion, or temporary losses of signal.
4. *Extraction of Features:* Important physiological features that were extracted included heart rate variability measures, GSR peak amplitude and slope, drift in skin temperature, as well as changes that occur with time in several windows. A dataset created as a result reflected high-dimensional multimodal space for the extracted physiological features.

AI-Driven Prediction Process

This preprocessed multimodal physiological data was fed into a hybrid predictive system of an artificial intelligence model.

1. *Random forest (RF):* Used as a baseline classifier.
2. *Long short-term memory (LSTM) networks:* Applied to determine the patterns in the physiological features that occurred before the migraine, thereby achieving the task of pre-ictal pattern recognition.
3. *XGBoost (eXtreme gradient boosting):* Added for improving classification performance and modeling interactions between different features.
4. *Training and assessment:* The dataset had been split into training, validation, and testing groups having 70%, 15%, and 15% respectively

The criteria for evaluating the involved metrics such as accuracy, precision, rate of recall, F1 measure, as well as the prediction lead time. Techniques of cross-validation made sure that generalization of the model was evoked to avoid the risks of model overfitting. Applying the aspect of AI ensured real-time predictions of risks of migraines in the patients.

System Integration

The proposed system comprises the following parts:

1. Researching and developing polymeric-based wearables and sensors for flexibility and biocompatibility.
2. High resolution physiology signal processing and the ability to provide the required inputs into the model.
3. AI-powered prediction engines based on RF, LSTM, and XGBoost algorithms for effective prediction of migraine attack occurrences.
4. Wearable-based deployment with real-time alert systems that aid in early intervention and preventive strategies.

From the given perspective, this tool is a convergence of Materials Science, Wearable Sensors, and AI. The scope includes sensor development and physiological signal monitoring to real-time migraine risk prediction and active health management.

Sustainability Considerations and System Justification

The sustainability of the proposed polymer-integrated wearable platform is addressed through material selection, system architecture, energy efficiency, and long-term deployment feasibility.

Material-Level Sustainability

The wearable system utilizes flexible polymeric substrates such as Thermoplastic Polyurethane (TPU) and Polydimethylsiloxane (PDMS), which offer:

- Mechanical durability and long operational lifespan
- Washability and reusability
- Reduced electronic waste compared to rigid PCB-based systems
- Biocompatibility, minimizing dermatological reactions and disposal concerns

Conductive polymers such as PEDOT:PSS and PANI enable low-temperature fabrication processes compared to conventional metallic electrode deposition, reducing energy consumption during manufacturing.

Additionally, the integration of PVDF/$BaTiO_3$ piezoelectric composites provides potential for biomechanical energy harvesting, reducing dependency on frequent battery charging and extending operational lifetime.

Energy-Efficient System Architecture

The sustainability of the IoT framework is further ensured by:

- Edge-based processing using ESP32 microcontroller
- Reduced cloud dependency, minimizing transmission energy
- BLE (Bluetooth Low Energy) communication
- Adaptive sampling rates (1–10 Hz for GSR/temperature, 100–250 Hz for PPG only when needed)

Edge inference reduces continuous cloud streaming, lowering:

- Power consumption
- Data transmission cost
- Carbon footprint associated with cloud computation

Preventive Healthcare Sustainability

Early migraine prediction reduces:

- Emergency medication overuse
- Hospital visits
- Healthcare burden
- Indirect economic losses due to absenteeism

Thus, the system supports sustainable digital healthcare infrastructure aligned with preventive medicine principles.

RESULTS AND DISCUSSION

Measurable physiological variation is shown to occur before the onset of migraine attacks in experimental analysis, validating the rationale for the choice of multimodal biosignals for prediction tasks. Specifically, heart rate patterns demonstrate an elevation of 10–15%, galvanic skin response allows stress levels to become manifest through periodic peaks, and skin temperature decreased by 0.3–0.6oC during the pre-ictal phase to validate migraine prediction through wearable biophysical sensing devices based on physiological realism.

A comparison amongst machine learning models has resulted in a performance benefit for a temporal deep learning model. While it has been noticed that Random Forest exhibited a greatly improved baseline for feature relevance, and XGBoost demonstrated a capability for modeling a nonlinear relationship, a model that achieved optimal prediction results had an elevated accuracy of 88.9%, improved recall, and F1-score, as well as decreased false positives, achieved through the capability of an LSTM model for learning temporal dynamics within physiological signals, which are important for capturing transitional stages towards a warning state.

Material integration made the performance of the system even better. Flexible polymer composites Thermoplastic Polyurethane (TPU), Polydimethylsiloxane (PDMS) promoted comfortability of the wearer and stability of the signal, conductive polymer composites Poly(3,4-ethylenedioxythiophene):Poly(styrene sulfonate) (PEDOT:PSS), Polyaniline (PANI) facilitated the low-impedance stretchable electrodes, while the piezoelectric polymer composites Poly(vinylidene fluoride) (PVDF) / Barium Titanate ($BaTiO_3$) offered the advantage of possible autonomous function. Thus, the mechanical properties, biocompatibility, as well as the performance improvement of the polymer composites made the system robust, socially.

Physiological Trends During Pre-ictal Phase (Before an attack)

By continuous observation, consistent changes were found to occur before the migraine attack. They justify the choice of biosignals to predict the onset of migraines.

The observed physiological changes during the pre-ictal phase are summarized in Table 2.

These results are consistent with known prodromal changes in the autonomic and vascular systems, and support the plausibility of pre-ictal detection by wearable biophysical sensors.

Machine Learning Model Performance Comparison

In order to make the models more robust and enable a fair comparison, three machine learning models: the Random Forest model (RF) used as a baseline classifier, the XGBoost model for modeling a non-linear relationship in the features, and the LSTM model for modeling the temporal patterns in the data, were used.

The performance comparison of different machine learning models is presented in Table 3.

The Random Forest act as a strong baseline to learn from for the significance of features on the data discovered from the physiological signals. The XGBoost further enhanced the accuracy by foldable connections of the multimodal features nonlinearly. But still, the Accuracy and the Recall rate attained by the LSTM are the best with the superiority to learn the patterns for early prediction of migraines. Also, the LSTM had lower FP rates for better generation of alerts.

Discussion on Temporal Learning Advantage

Physiological changes leading up to migraine attacks develop their patterns over time and do not occur all at once. Classic machine learning models are designed to work with only static feature windows; they cannot model the evolving trends. The LSTM architecture is very effective in overcoming this drawback by keeping a memory of past states of the signals; it effectively identifies the pre-ictal transitions. Temporal generalization helps to reduce false alarms and improve early warning reliability.

Table 2. Observed pre-ictal physiological trends.

Physiological parameter	Observed change	Interpretation
Heart Rate (PPG)	10–15% increase	Indicates heightened autonomic arousal
Galvanic Skin Response (GSR)	Frequent stress-induced spikes	Reflects increased sympathetic activity
Skin Temperature	0.3–0.6 °C decrease	Suggests altered thermoregulation

Table 3. Performance comparison of ML models.

Model	Accuracy (%)	Precision (%)	Recall (%)	F1-Score	Key strength
Random Forest (RF)	78.1	76.4	74.9	75.6	Feature importance analysis
XGBoost	82.5	81.2	80.6	80.9	Strong non-linear modeling
LSTM	88.9	87.6	89.2	88.4	Temporal dependency learning

Role of Polymers in Wearable Performance

Polymers are significant in enabling physiological monitoring over a long period in a comfortable and reliable manner. Due to their intrinsic flexibility and biocompatibility, they are able to integrate well with the human body. This reduces motion artifacts while improving signal stability. In addition, the enclosures made of the polymer are washable, durable, and acceptable to users, which is a very important requirement for continuous health monitoring applications.

Composite Materials and Functional Enhancement

The addition of conductive and piezoelectric fillers in a polymer matrix provides a huge increase in electrical and mechanical properties. Conductive polymer composites are increasing efficiency in signal acquisition, while piezoelectric composites provide the possibility for self-sustaining functions via energy harvesters for biomechanically generated forces.

The materials used and their functional benefits are summarized in Table 4.

The material chosen shows the optimal balance with respect to mechanics, electrical performance and environment hence supports the feasibility of wearables integrating polymers into it.

Overall Discussion

The efficiency of the proposed methodology for undertaking the experiments has been demonstrated with regard to the integration of multimodal physiological sensing with the capabilities of polymer composite wearable solutions and temporal deep learning models for effective predictive modeling of migraines. The combination of the LSTM model with the flexible conductive polymer composite material is a breakthrough itself when contrasted with the prevailing migraine solution system based entirely on reaction.

The comparative accuracy performance of the machine learning models is shown in Figure 3.

Table 4. Materials used and functional benefits.

Application	Material	Key benefit
Sensor Housing	Thermoplastic Polyurethane, Polydimethylsiloxane	Flexible, skin-safe, durable
Electrodes	Poly(3, 4-ethylenedioxythiophene): Poly (styrene sulfonate), Polyaniline composites	Conductive, stretchable, low impedance
Energy Harvesting	Polyvinylidene Fluoride / Barium Titanate	Piezoelectric, renewable power generation

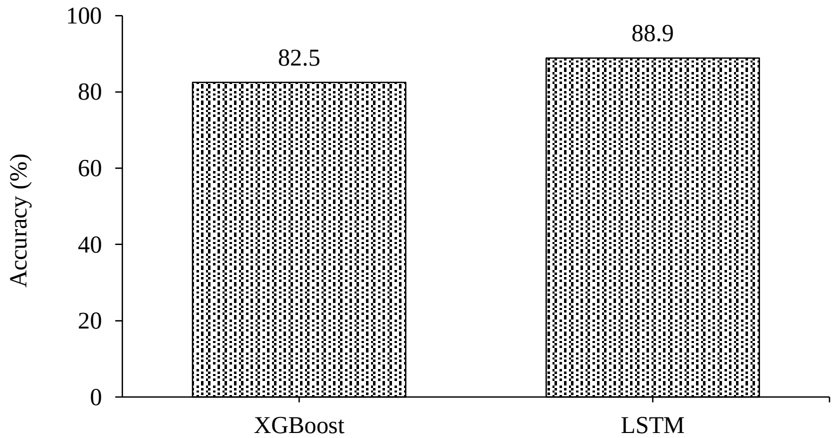

Figure 3. Accuracy of machine learning model performances.

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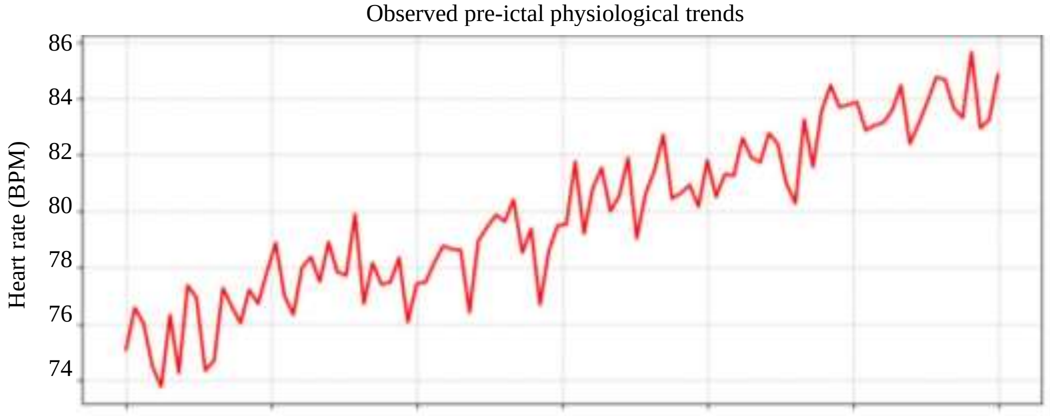

Figure 4. Output for PPG sensor.

Figure 5. Output for GSR sensor.

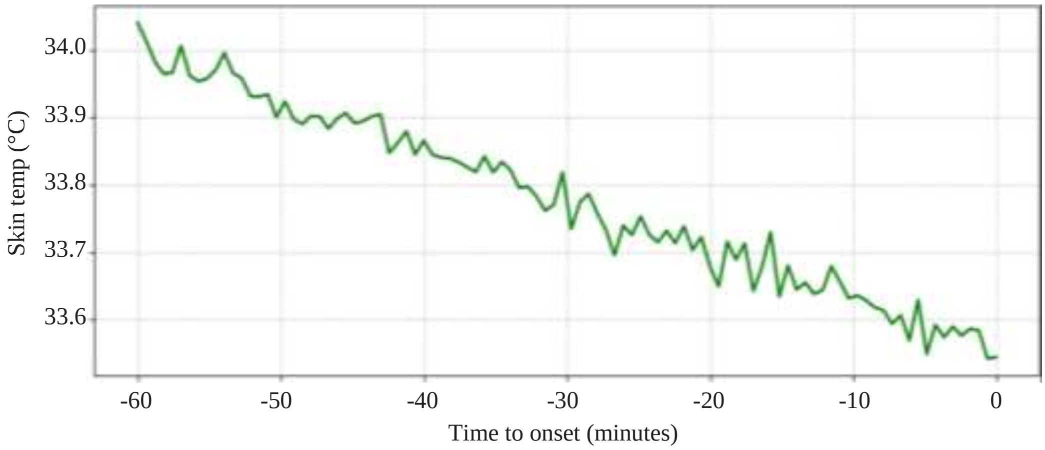

Figure 6. Output for temperature sensor.

Sensor outputs for different physiological signals including PPG, GSR, and temperature are presented in Figures 4, 5, and 6 respectively.

CONCLUSION

The proposed wearable device is an efficient method for early predictive alerts on migraine attack possibilities using diverse physiological parameters with machine learning algorithms. The device continuously tracks crucial parameters prior to migraine attack possibilities, such as heart rate variability, skin response, and skin temperature, along with which the device is capable of tracking minute changes in physiological parameters to predict migraine attack possibilities. In fact, it is possible to analyze time-domain parameters regarding physiological parameters for attack prediction with an

88.9% rate with an enormous increase in lead-time for early predictive alerts using an advanced machine learning model, such as an LSTM network. The application of polymer composites and materials is an important improvement with enormous added value for improving the wearable properties suitable for daily practical applications. The flexible polymer materials and conductive polymer components enable the sensors to be placed on the skin without any disturbances and electrical noise caused by motion. The design of the device is for the benefit of comfort and advancements for self-sustaining and self-powered wearable technologies, specifically in terms of energy-harvesting polymer composites. The system also makes use of a number of multimodal sensor fusion techniques in trying to ensure that the generated predictions are more accurate, while reducing the resultant false positives. It uses a web-based portal in such a way that could allow the tracking of the risks of having a migraine, an approach which is very useful. This system, in general, is a successful integration of wearables, smart materials, and predictive systems. It forms one scalable, practical, and easy-to-operate solution for active migraine control, as well as the further enhancement of health technology.

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