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Smart Sensor-Based Microvascular Health Tracking In Diabetic Patients

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Abstract: This invention presents a smart, non-invasive wearable device for continuous monitoring and early detection of diabetes-related vascular complications. The system integrates a photoplethysmography sensor to measure perfusion index, blood oxygen saturation (SpO_2), and heart rate, combined with an accelerometer–gyroscope module to correct motion artifacts and ensure accurate real-world measurements. Local data processing and disease classification are performed on an embedded ESP32 microcontroller, preserving user privacy by eliminating external data transmission. Multi-mode diagnostic functionality enables early detection of Peripheral Artery Disease, Hypoglycemia, and Diabetic Neuropathy, while an OLED display provides real-time numerical values and threshold-based alerts. Compact and user-friendly, the device supports affordable continuous monitoring in home and clinical settings, delivering actionable health insights for timely intervention and personalized preventive care.

Keywords: Diabetes, Microvascular health, Perfusion index (PI), Blood oxygen saturation (SpO_2), Heart rate monitoring, Photoplethysmography (PPG), Motion artifact correction, multi-mode diagnostics, Peripheral Artery Disease, Hypoglycemia, Diabetic neuropathy

I. Introduction

Diabetes mellitus is a complex long-term metabolic disease characterized by elevated blood glucose levels caused by insufficient insulin production or impaired insulin activity. It is one of the fastest-growing chronic illnesses worldwide, with the International Diabetes Federation (IDF) predicting that its prevalence will exceed 640 million cases by 2030. This continuing rise contributes significantly to the global healthcare and economic burden due to the disease's chronic nature and multiple associated complications. Vascular disorders, particularly those involving the microvasculature, are major factors leading to disability, reduced life expectancy, and poor quality of life in diabetic populations. The earliest and most common outcomes of prolonged diabetes is due to microvascular damage. The microvascular network is essential for maintaining adequate tissue oxygenation and nutrient delivery. Continuous exposure to hypoglycemia leads to reduced warning symptoms, impaired hormonal response, and increased risk of severe hypoglycemia. Over time, this dysfunction leads to hypoxia, inflammation, and progressive structural damage to the microvasculature. Consequently, diabetic patients are highly susceptible to several complications, most commonly Peripheral Artery Disease (PAD), Hypoglycemia-related perfusion alterations, and Diabetic neuropathy, all of which progressively worsen functional health and increase clinical costs. Peripheral Artery Disease involves narrowing of peripheral arteries, limiting blood flow to extremities and increasing the risk of ischemia, ulceration, and amputation. Hypoglycemia, often linked to insulin therapy or certain medications, disrupts vascular homeostasis and tissue oxygen balance, particularly in the brain and peripheral regions. Repeated hypoglycemic episodes still worsen neural and vascular deterioration, further increasing existing complications. Additionally, diabetic neuropathy, a major consequence of chronic ischemic injury to peripheral nerves, leads to sensory deficits, muscular weakness, and slow wound healing. Early identification and accurate monitoring of these vascular impairments are therefore crucial for timely intervention and prevention of irreversible tissue damage. Traditional assessment methods for evaluating vascular function such as Doppler ultrasonography, angiographic imaging, and nerve conduction testing are valuable clinical tools but possess inherent limitations. They are often invasive, expensive, and restricted to clinical environments, providing only periodic data instead of continuous physiological insight. As a result, real-time tracking and early detection of microvascular changes in diabetic individuals remain difficult. To overcome these challenges, continuous non-invasive monitoring technologies have gained attention for their ability to bridge clinical precision with everyday usability.

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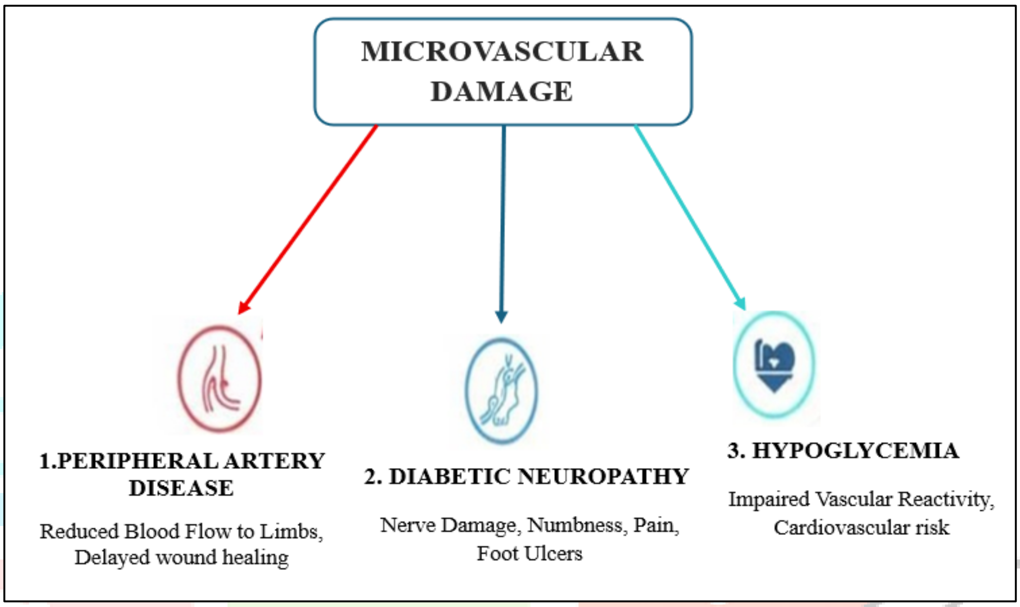

Fig. 1: Some Microvascular Complications

These systems incorporate miniature sensors and microelectronic components into compact, user-friendly designs that can capture essential physiological data seamlessly and without causing discomfort. Among various biomedical sensing technologies, photoplethysmography (PPG) is a well-established optical technique used for non-invasive vascular assessment. Using this principle, PPG enables continuous monitoring of key physiological parameters such as heart rate, blood oxygen saturation (SpO_2), and perfusion index (PI). The perfusion index, derived from the ratio of pulsatile to static blood components in the PPG waveform, serves as a sensitive indicator of peripheral blood flow and microvascular integrity. Regular measurement of SpO_2 and PI enables identification of subtle changes in vascular performance, tissue oxygen supply, and circulatory regulation. In diabetic patients, these indicators often reveal early manifestations of PAD, vascular constriction, or neuropathic perfusion decline before symptoms become clinically evident. PPG based monitoring can also help recognize hypoglycemia, where rapid shifts in blood oxygenation and cardiac rhythm precede neurological or autonomic responses. Real-time observation of such parameters thus enhances understanding of disease dynamics and enables personalized therapeutic decisions.

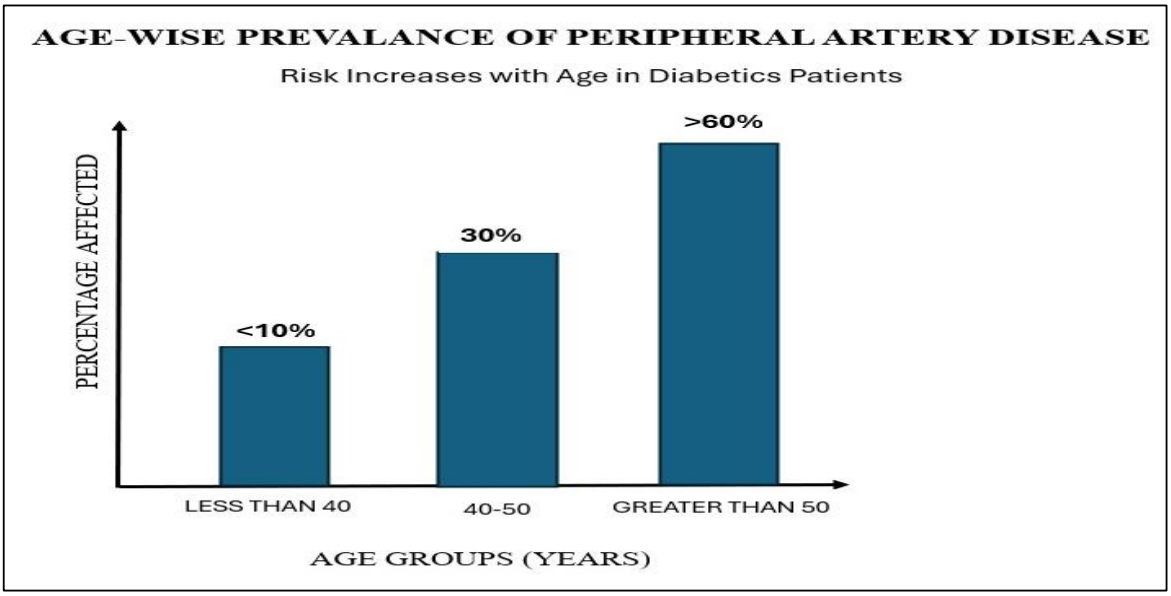

Fig. 2: Real-time analysis of PAD risk across age groups

Moreover, the integration of PPG sensing into wearable devices has greatly advanced the practicality of diabetes monitoring. Modern systems combine PPG with embedded signal processing and motion-compensation algorithms to minimize noise caused by physical movement or ambient light. This ensures that the recorded data remains accurate and clinically valid in everyday conditions. With the incorporation of efficient microcontrollers, these devices can process data locally, filter disturbances, detect abnormalities, and produce direct visual feedback through integrated displays—all while maintaining user privacy by reducing reliance on cloud-based data transfer. Recent evolution in diabetic care emphasizes three primary objectives: early diagnosis, continuous observation, and predictive analysis. Early detection helps clinicians identify impending vascular deterioration before major complications arise. Continuous tracking facilitates more frequent assessment, improving disease supervision outside clinical settings. Predictive analytics, driven by machine learning and data modeling, allows forecasting of possible complications, enabling proactive prevention. Together, these advancements redefine chronic disease management through the lens of personalized medicine.

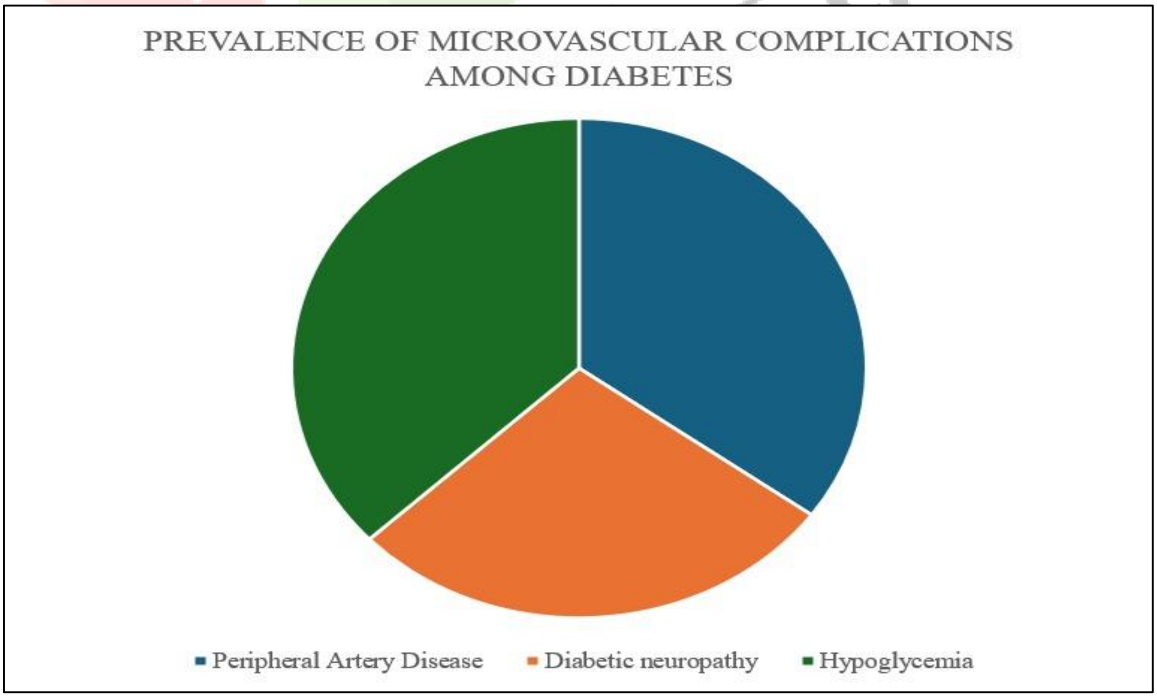

Fig. 3: Distribution of major microvascular complications in diabetes

The advancement of sensor-assisted microvascular health monitoring reflects the growing synergy between biomedical science and engineering innovation. Integrating physiological insights with precision sensing technologies, such as photoplethysmography (PPG), enables continuous and non-invasive assessment of vascular health in diabetic patients. This interdisciplinary approach not only enhances diagnostic accuracy but also promotes preventive healthcare strategies aimed at reducing long-term complications. Ultimately, sensor-based real-time monitoring frameworks have the potential to transform diabetes management from reactive treatment toward predictive and preventive care models that improve life expectancy and empower patients.

II. RELATED WORK

1. Noninvasive On-Skin Biosensors for Monitoring Diabetes

This research focuses on the development of wearable, skin-interfaced biosensors for noninvasive monitoring of diabetes. These devices detect biomarkers in sweat and other skin biofluids, along with physiological signals, to track blood glucose levels and related metabolic changes. Flexible and stretchable sensor patches, combined with microfluidics and electronic integration, enable real-time monitoring and personalized health management. The study highlights challenges such as low biomarker concentrations, calibration, and user variability. Overall, it presents a promising approach toward comfortable, continuous, and accurate diabetes monitoring without the need for invasive methods. (Sedighi et al., 2025)

2. Photoplethysmography for Cardiovascular Monitoring

This study investigates how wearable photoplethysmography (PPG) devices can be used for continuous cardiovascular monitoring in every setting, exploring their potential for detecting cardiovascular disease. It reviews sensor technologies, signal-processing challenges (like motion artefact and skin tone variation), and the integration of PPG with mobile/wearable platforms for long-term monitoring. The authors highlight the promise of wearables for accessible health tracking, while noting limitations such as calibration, validation in diverse populations, and translating data into clinical decision-making. (Charlton et al., 2022)

3. Mobile and Wearable Technology for the Monitoring of Diabetes-Related Parameters

This is a systematic review of studies from 2010 to mid-2020 that used mobile phones and wearable devices to track parameters related to diabetes. The review included 26 papers and found that wearables (especially accelerometers) were most commonly used, followed by glucose and heart-rate sensors. Many studies applied data processing techniques like statistical analyses or machine learning to recognize activity, correlate health outcomes, or predict diabetic conditions. However, the review highlighted several gaps: few studies focused on type 2 diabetes, clinical trials were limited, and issues like privacy, security, and ethics were rarely addressed. The authors conclude that while the use of mobile and wearable technology for monitoring diabetes shows promise, the field is still nascent and requires more rigorous clinical validation. (Rodríguez-León et al., 2021)

4. Wearable Sensors for Blood Perfusion Monitoring in Patients with Diabetes Mellitus

This chapter discusses the development of wearable electronic devices that use laser Doppler flowmetry (LDF) to continuously monitor microvascular blood flow (perfusion) in patients with type 2 diabetes. By analyzing capillary blood flow rhythms in both time and frequency domains, these sensors provide detailed diagnostic insights into microvascular complications associated with diabetes. The authors emphasize the potential for round-the-clock, non-invasive vascular monitoring, which could advance precision medicine in diabetic care. (Zherebtsov et al., 2025)

5. Advances in Biosensors for Continuous Glucose Monitoring Towards Wearables

This review explores the latest developments in wearable biosensors for continuous glucose monitoring (CGM), focusing on non-invasive and minimally invasive techniques using sweat, tears, saliva, and interstitial fluid. It evaluates different sensing approaches, including enzymatic, non-enzymatic, and microneedle-based sensors, emphasizing sensitivity, stability, and detection range. Innovative form factors like skin patches, mouthguards, and contact lenses are discussed. Key challenges such as biofouling, sensor lifetime, calibration, and cost are highlighted. The study emphasizes the need for robust, accurate, and affordable CGMs for widespread adoption. (Johnston et al., 2021)

6. Glycemic Variability in Diabetic Vascular Complications

This review highlights how fluctuations in blood glucose, known as glycemic variability (GV), contribute to both macrovascular (heart, arteries) and microvascular (eyes, kidneys, nerves) complications in diabetes. It explains key GV metrics, mechanisms of vascular damage like oxidative stress and inflammation, and the role of continuous glucose monitoring (CGM) and lifestyle or drug interventions to reduce GV. Targeting GV, beyond average glucose levels, may improve prevention and management of diabetic complications. (Sun et al., 2021)

7. A Review of Skin-Wearable Sensors for Non-Invasive Health Monitoring Applications

This review explores flexible and stretchable skin-wearable sensors that non-invasively monitor health by detecting signals from the skin. It categorizes these sensors based on the types of input energy they use: thermoelectrical (temperature), neural electrical (ECG, EEG, EMG), photoelectrical (PPG), electrochemical (sweat biomarkers), and mechanical pressure. The authors discuss how these devices conform to skin, maintain comfort, and reliably capture physiological data over time. They also highlight challenges like limited device lifetime, power supply, and the need for self-learning signal processing. Finally, they present future directions: wireless communication, on-device AI, actuator integration, and improved biocompatibility. (Mao, Li & Yu, 2023)

8. Noninvasive Monitoring of Glycemia Level in Diabetic Patients by Wearable Advanced Biosensors

This research demonstrates the feasibility of using sweat to noninvasively predict blood glucose levels in diabetic patients, thanks to a stable, subject-specific correlation between sweat glucose and blood glucose. The authors used a highly sensitive biosensor based on glucose oxidase and a Prussian Blue transducer to detect very low concentrations of glucose in sweat (which is 30–50× lower than in blood). They found that the blood-to-sweat glucose ratio remains stable over weeks, reducing the need for frequent finger-prick calibration. Their method also addresses issues of selectivity and sensor degradation: the Prussian Blue-based sensor shows better stability and fewer false positives than platinum-based sensors. (Daboss et al., 2024)

III. RESEARCH METHODOLOGY

Materials Used

- MAX30102 Sensor measures heart rate, oxygen saturation level and perfusion index using photoplethysmography.
- MPU6050 Sensor detects motion, orientation and body activity to support accurate monitoring.
- ESP32 acts as microcontroller unit which controls sensors, processes data, manages modes and displays results on the OLED screen.
- SSD1306 OLED Display shows live sensor readings and system status in real-time.
- Push button enables the user to switch between Peripheral Artery Disease, Hypoglycemia and Diabetic Neuropathy modes.
- Battery, Regulator and Charger module together provides stable power to the ESP32 and sensors while safely charging the battery.

Methodology

This structured methodology ensures accurate data acquisition, reliable signal processing, and effective assessment of diabetic microvascular complications.

1. **System powering:** The prototype is powered by a rechargeable battery regulated to 3.3V using a charging module to ensure safe and stable operation of all components.
2. **Microcontroller Initialization:** The ESP32 microcontroller initializes the sensors (MAX30102 and MPU6050) and OLED display during startup, ensuring synchronization and readiness for data acquisition.
3. **Mode Selection:** A push button is used to select between different monitoring modes: Normal, Peripheral Artery Disease (PAD), Hypoglycemia, and Diabetic Neuropathy-each mode triggering specific data processing logic.
4. **Signal Acquisition:** The MAX30102 sensor measures heart rate, oxygen saturation (SpO_2), and perfusion index (PI) based on the photoplethysmography (PPG) principle, while the MPU6050 captures motion and orientation data to minimize motion artifacts.
5. **Data Processing:** The ESP32 processes raw sensor signals, filters noise, and converts them into meaningful physiological parameters through embedded algorithms.
6. **Microvascular Analysis:** Based on processed parameters, the system evaluates microvascular health to detect abnormalities linked to PAD, hypoglycemia-induced dysfunction, and neuropathic conditions.
7. **Display of Results:** The OLED display shows real-time values of heart rate, SpO_2, and perfusion index, along with the active mode and detected condition status.
8. **Continuous Monitoring:** The system performs live, continuous measurement to enable early identification of microvascular impairments in diabetic patients.
9. **Prototype Validation:** The developed model is tested under simulated diabetic conditions to validate accuracy, responsiveness, and reliability of real-time monitoring.

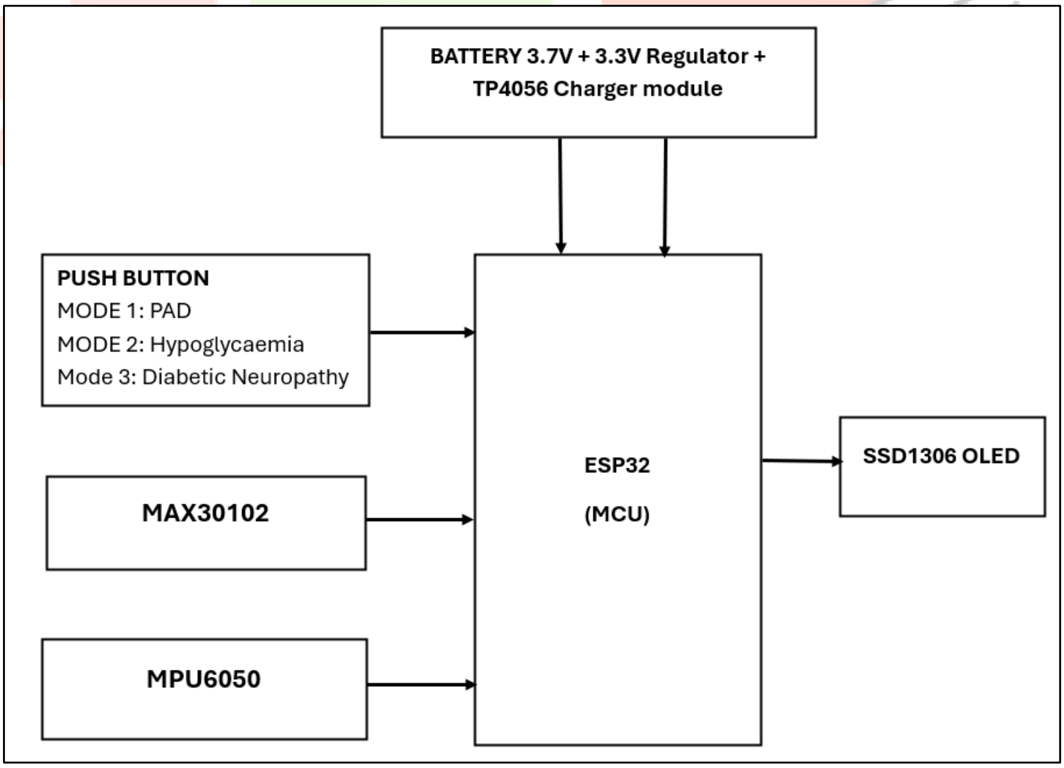

Fig. 4: Block Diagram

IV. RESULT AND DISCUSSION

The Smart Microvascular Health Monitoring System was successfully developed using photoplethysmography sensor (MAX30102), ESP32 microcontroller, MPU6050 for motion artifact detection along with a battery power supply and a charging module. The system continuously monitors SpO2, Heart rate and Perfusion index for detecting the condition like Peripheral Artery Disease (PAD), Hypoglycemia and Diabetic neuropathy. These conditions are detected by the variations observed in SpO2, Heart rate and Perfusion index as shown in Fig 5.

- PAD is detected by a significant decrease in perfusion index and irregular variations in SpO_2.
- Hypoglycemia is detected when SpO2 is low and heart rate is higher than the normal value.
- Diabetic Neuropathy is detected by variations in perfusion index along with abnormal heart rate variability.

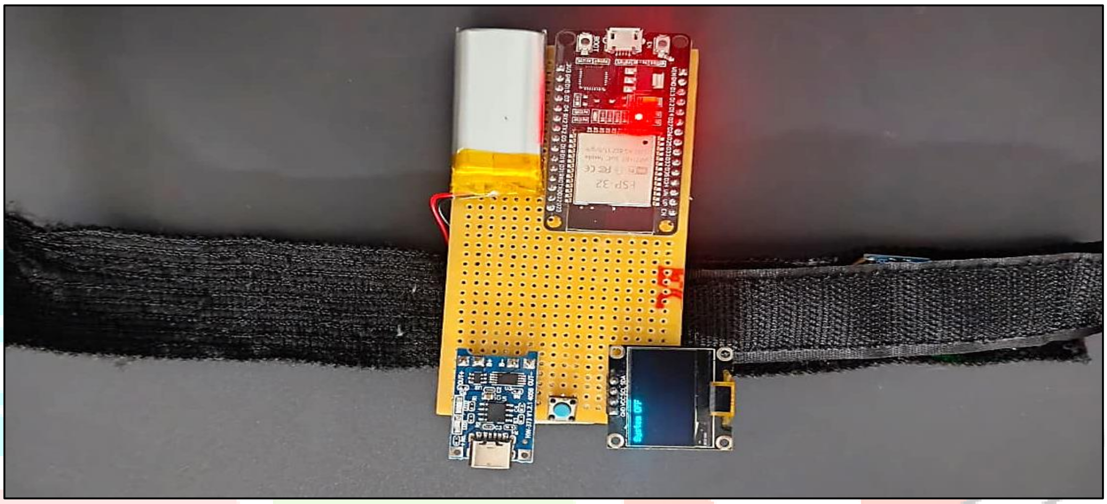

Fig. 5 Health Monitoring Prototype

A survey was conducted for 150 people of different age groups to monitor SpO2, Heart rate (HR) and Perfusion index (PI) for detecting the microvascular complications. The different age groups include 18-24, 30-40 and 45 and above. The results indicated that people with age group between 18–24 had stable SpO_2 and PI values, with minimal variations in heart rate. In the age group between 30–40, mild variations in perfusion index and heart rate were observed in individuals with underlying conditions such as early-stage diabetes. Also, some individuals were observed to have low SpO_2 and elevated heart rate showing signs of hypoglycemia. Among people aged 45 and above, significant variations in PI and HR were recorded, with multiple instances of PAD and diabetic neuropathy, as well as increased occurrence of hypoglycemia. Overall, the system demonstrated effective continuous monitoring capabilities and could reliably detect early microvascular complications, including hypoglycemia, across different age groups, highlighting its potential for preventive health tracking in at-risk populations.

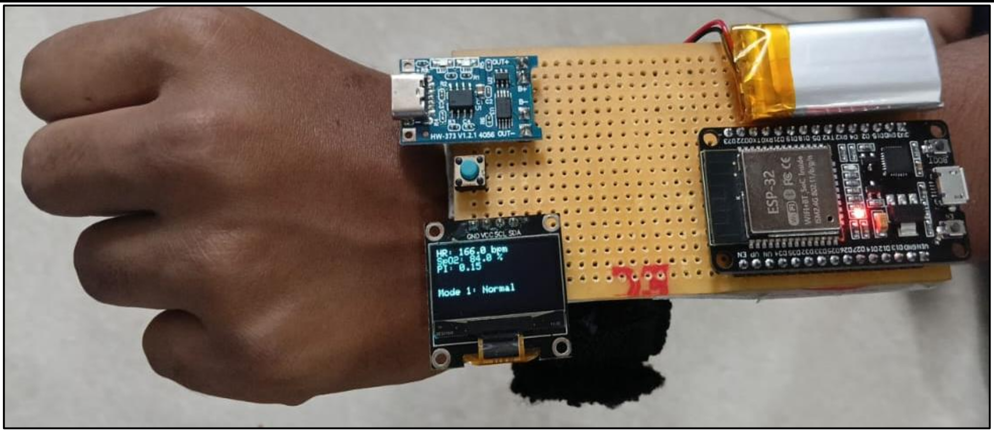

Fig. 6: Measured Output

PARAMETERS	AGE 18-24	AGE 30-40	AGE 45+ AND ABOVE
SpO2	Stable values	Some individuals with low SpO_2	Increased occurrence of low SpO_2
Heart Rate (HR)	Minimal variations	Mild variations, elevated HR in hypoglycemia cases	Significant variations; elevated HR common
Perfusion Index (PI)	Stable values	Mild variations in early-stage diabetes	Significant variations recorded
Observation	No significant complications	Early-stage diabetes, hypoglycemia	PAD, diabetic neuropathy, hypoglycemia

Table 1: Analysis using detected output

The survey results from 150 participants show that the Smart Microvascular Health Monitoring System can clearly identify age-related changes in SpO_2, heart rate, and perfusion index. Younger individuals (18–24) showed stable readings with no noticeable abnormalities, confirming that the system accurately captures normal baseline conditions. However, in the 30–40 age group, mild variations in PI and HR were observed, especially among individuals with early diabetic indicators. The system also detected low SpO_2 with elevated heart rate in some cases, suggesting early hypoglycemic episodes. These observations highlight the system's ability to detect changes that may indicate the initial stages of microvascular dysfunction.

In adults aged 45 and above, the system recorded significant variations in PI and HR, along with more frequent cases of low SpO_2. These changes correlate with conditions such as Peripheral Artery Disease (PAD), diabetic neuropathy, and increased hypoglycemia risk, which are common in this age group. Overall, the findings demonstrate that the developed system provides reliable continuous monitoring and effectively identifies abnormalities across different age groups. This proves its potential as a practical tool for early detection and preventive tracking of diabetes-related vascular complications.

V. CONCLUSION

The developed smart sensor-based prototype provides a simple, non-invasive, and continuous method to monitor microvascular health in diabetic patients. By applying the photoplethysmography (PPG) principle through the MAX30102 sensor, the system accurately measures heart rate, oxygen saturation, and perfusion index, displaying real-time readings on an OLED screen. The findings showed that variations in these parameters effectively indicate complications such as peripheral artery disease, hypoglycemia, and diabetic neuropathy. Among them, the perfusion index proved to be a sensitive marker for reduced peripheral circulation, while heart rate changes reflected autonomic responses during hypoglycemic episodes. Together, these metrics enable early identification of vascular and neural impairments, supporting preventive and patient-centered care. This study highlights the potential of integrating smart sensors with embedded systems to create affordable and wearable solutions for continuous diabetic monitoring. With further improvements—such as advanced signal processing, AI-based data analysis, and mobile connectivity—the system could become a reliable tool for proactive and personalized diabetes management, enhancing both clinical outcomes and patient quality of life.

Future Scope

1. The wristband can be further enhanced with IoT and cloud connectivity, enabling continuous remote monitoring and doctor–patient data sharing.
2. Integration of additional biosensors such as skin temperature and electrodermal activity can improve detection accuracy for diabetic neuropathy and hypoglycemia.
3. Battery optimization and energy-efficient circuit design can extend device runtime, making it more suitable for long-term daily use.
4. Clinical validation on diverse diabetic populations can help establish standardized diagnostic thresholds and enhance medical reliability.
5. Advanced data analytics and mobile app synchronization can provide personalized health insights, trend analysis, and early alerts for vascular complications.

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