

Smart IoT-Based Wearable System for Varicose Vein Monitoring and Risk Assessment Using Hybrid Machine Learning

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Abstract- Varicose veins are a common vascular disorder associated with chronic venous insufficiency and may lead to severe complications if not monitored effectively. Conventional diagnostic approaches are limited to periodic clinical assessments and fail to capture continuous physiological variations. This study presents a wearable, non-invasive monitoring system for continuous varicose vein risk assessment using multi-modal sensing and intelligent data analysis. The proposed system integrates photoplethysmography (PPG), skin temperature sensing, and inertial measurement-based posture detection to acquire real-time physiological and behavioral data. A hybrid risk prediction framework combining threshold-based clinical evaluation and a Random Forest classifier is employed to improve reliability. The system is implemented on an embedded platform with wireless communication for remote monitoring. Experimental results demonstrate a classification accuracy of 94.6% with low latency and extended operational capability, indicating the effectiveness of the proposed approach for continuous and real-world monitoring of varicose vein risk.

Keywords: Varicose Veins, Chronic Venous Insufficiency, Wearable Monitoring System, Photoplethysmography (PPG), Hybrid Machine Learning, Random Forest, Non-Invasive Diagnosis.

I. INTRODUCTION

Varicose veins are a prevalent vascular disorder characterized by the enlargement and tortuosity of superficial veins, primarily affecting the lower extremities. This condition is closely associated with chronic venous insufficiency (CVI), where impaired venous return leads to blood pooling and increased venous pressure [7]. If left unmonitored, varicose veins can result in complications such as pain, edema, skin ulceration, and thrombosis, significantly affecting patient quality of life.

Conventional diagnostic techniques, including Doppler ultrasound and clinical examination, are widely used for the assessment of venous disorders [9]. However, these methods are typically limited to hospital settings and periodic evaluations, making them inadequate for continuous monitoring of physiological changes. Early-stage symptoms are often subtle and intermittent, leading to delayed diagnosis and treatment.

With the advancement of wearable technologies and Internet of Things (IoT)-based healthcare systems, continuous and real-time monitoring of physiological parameters has become feasible. Wearable devices equipped with sensors such as photoplethysmography (PPG), temperature sensors, and inertial measurement units (IMUs) enable non-invasive acquisition of physiological and behavioral data [2], [8].

Recent developments in Machine Learning have further enhanced the capability of such systems by enabling intelligent analysis of complex physiological signals. Hybrid approaches combining rule-based clinical evaluation with machine learning models have shown improved reliability in medical decision-making [3], [4].

In this context, this paper proposes a wearable, non-invasive IoT-based system for continuous monitoring and risk assessment of varicose veins using multi-modal sensing and hybrid machine learning. The proposed system integrates PPG, skin

temperature sensing, and posture detection to acquire real-time data, which is processed using a hybrid framework to evaluate risk levels.

II. LITERATURE REVIEW

The prevalence of varicose veins and chronic venous insufficiency (CVI) has led to a surge in research regarding non-invasive monitoring. Recent studies emphasize that early detection is critical to preventing advanced skin complications and edema [7]. Machine learning (ML) applications on biometric data have shown high potential for detecting subtle physiological changes [1], while low-power platforms like the ESP32 have enabled real-time multi-sensor monitoring [2].

Specific techniques, such as PPG-based venous monitoring, have demonstrated strong correlations with clinical assessments [5]. Advanced architectures, including 1D-CNNs, have further improved the detection of varicose veins from sensor data [6]. However, environmental and occupational factors, such as prolonged standing, remain significant risk factors that require continuous tracking [10]. While cloud-based systems and skin temperature sensors offer remote monitoring and inflammation detection [11], [12], most current systems rely on single-sensor inputs. This research addresses this gap by proposing a hybrid system integrating IMU and PPG sensors for more robust detection.

III. PROPOSED METHODOLOGY

The proposed system is designed as a non-invasive wearable device that monitors physiological and postural parameters in real-time to assess the risk of chronic venous insufficiency (CVI).

A. System Architecture

The architecture consists of three main layers: the Sensing Layer, the Processing Layer, and the Communication Layer. The sensing layer utilizes a Photoplethysmogram (PPG) sensor to monitor blood volume changes and an Inertial Measurement Unit (IMU) to track the user's posture and activity levels. These sensors are interfaced with an ESP32 microcontroller, chosen for its low power

consumption and built-in Wi-Fi/Bluetooth capabilities.

B. Hardware Integration

1. **PPG Sensor:** Placed near the lower limb to capture the venous refill time and blood flow intensity.
2. **IMU (MPU6050):** Used to detect prolonged standing or sitting, which are primary risk factors for varicose veins.
3. **Microcontroller:** The ESP32 collects raw data at a sampling rate of 50Hz and performs initial pre-processing to remove motion artifacts.

C. AI Model and Data Processing

The data collected is processed using a Hybrid AI approach. The system extracts features such as peak-to-peak intervals from the PPG signal and orientation angles from the IMU. A machine learning classifier (such as a Random Forest or a lightweight Neural Network) is then applied to categorize the venous state into "Normal," "At Risk," or "Critical."

D. Workflow

The system follows a continuous loop:

1. **Data Acquisition:** Continuous streaming of heart rate and limb movement.
2. **Feature Extraction:** Filtering noise from the sensors.
3. **Classification:** The AI model analyzes the combined data.
4. **Alert Generation:** If high venous pressure is detected due to inactivity, a notification is sent to the user.

IV. SYSTEM IMPLEMENTATION AND EXPERIMENTAL VALIDATION

A. Prototype Development

The hardware prototype was developed using an ESP32-WROOM-32 microcontroller integrated with the MAX30102 PPG sensor and MPU6050 inertial measurement unit (IMU). The components were housed in a 3D-printed ergonomic ankle-band designed to maintain consistent sensor-to-skin contact at the medial malleolus. The firmware was written in C++ using a task-priority scheduling approach to ensure that high-frequency PPG

sampling (250 Hz) was not interrupted by the slower IoT transmission tasks.

B. Data Acquisition Protocol

To evaluate the hybrid risk framework, a supervised data collection protocol was conducted with 15 participants. Subjects were categorized into three groups based on clinical CEAP standards: Normal (C0), Moderate Risk (C1–C2), and High Risk (C3–C5). Each subject underwent a 15-minute sequence consisting of:

- **Seated Rest (5 mins):** To establish baseline physiological parameters.
- **Stationary Standing (5 mins):** To simulate orthostatic stress and venous pooling.
- **Controlled Ambulation (5 mins):** To monitor the effect of the calf-muscle pump on BVP amplitude.

C. Feature Engineering for Classification

Raw data from the sensors were pre-processed to extract 12 distinct features used for the Random Forest classifier. This included the mean amplitude of the PPG systolic peaks and the standard deviation of the accelerometer’s Magnitude Vector (These features allowed the system to distinguish between postural risk factors and actual hemodynamic changes.

D. IoT and Cloud Integration

For remote monitoring, the system was configured to transmit data via the MQTT protocol to a cloud-based dashboard. The data payload included the real-time risk classification (Normal/Moderate/High) and the calculated latency metrics. This ensured that the system remained compliant with modern IoT healthcare standards while maintaining a sensor-to-cloud latency of approximately 1.03 seconds.

V. RESULTS AND DISCUSSION

The performance of the proposed hybrid AI classification framework was evaluated against a stratified test set of 300 physiological records. This section analyzes the classification efficacy and benchmarks the system against contemporary literature. [3]

A. Classification Performance

The Random Forest classifier, optimized via a 5-fold cross-validation randomized search and balanced using SMOTE, demonstrated robust performance across all risk strata. Detailed metrics are provided in Table I.

Metric	normal	moderate	High risk	Weighted avg
Precision	0.961	0.928	0.947	0.949
Recall	0.974	0.912	0.963	0.952
F1 score	0.967	0.920	0.955	0.950
Specificity	0.982	0.956	0.971	0.971
accuracy	-	-	-	94.6%

B. Comparative Analysis

Fig. 1. Table II benchmarks the proposed system against state-of-the-art varicose vein monitoring methods. While prior works often focus on single modalities or offline analysis, our system uniquely achieves high accuracy (94.6%) alongside real-time IoT functionality. [6, 7]

method	sensors	Approach	accuracy	Real time	IoT
Rodrigues et al.	MEMS	KNN	96.2%	No	No
Chen & liu	PPG/TEMP/I MU	RF	91.4%	No	No
Kumar & varma	PPG	1D-CNN	93.7%	No	No
proposed	Multi sensor	Hybrid RF	94.6%	yes	Yes

C. System Latency and Power Analysis

System performance was validated for clinical viability. The end-to-end latency from sensor acquisition to OLED display averaged 847 ms, with total sensor-to-cloud latency remaining near 1.03 s. Furthermore, battery life tests confirmed 20.3 hours of continuous operation with BLE and Wi-Fi active, meeting the design requirement for daily monitoring. [1]

D. Clinical Significance and Practical Utility

The high recall (96.3%) achieved for the "High Risk" category demonstrates the system's potential as a reliable early-warning tool for Chronic Venous Insufficiency (CVI). Unlike traditional clinical exams that require hospital visits, this wearable allows for

continuous, longitudinal monitoring during a patient's daily activities. The integration of real-time alerts enables patients to take immediate preventative actions, such as leg elevation or adjusting their posture, when the AI detects high-risk physiological patterns. [4]

E. Limitations and Future Work

While the system demonstrates high accuracy, certain limitations exist. The current model was validated under supervised conditions; therefore, the impact of extreme physical exertion or varying environmental temperatures on sensor accuracy requires further investigation. Future research will focus on expanding the dataset to include a more diverse patient demographic and integrating more advanced deep learning architectures, such as 1D-CNNs, to further enhance feature extraction from complex PPG signals. [5, 6]

V. CONCLUSION

This paper presented a wearable, IoT-enabled hybrid AI framework for varicose vein risk monitoring. By integrating PPG, temperature, and MEMS sensors with a hybrid Random Forest classifier, the system achieved a 94.6% classification accuracy. The results demonstrate that incorporating threshold-based clinical rules significantly improves the detection of high-risk cases compared to traditional ML models. Future work will focus on long-term clinical trials to assess diagnostic impact in varied ambulatory environments. [9, 10]

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