Analyzing the Viability of a Real-Time Sweat Analysis System Utilizing Electrospun Textiles

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I. INTRODUCTION

Health and wellness have become significant trends of the 21st century, with people embracing lifestyles that prioritize physical and mental wellbeing. Continuous monitoring of vital body functions is vital for a holistic approach to wellbeing. As a result, the research and business arena of wellness devices that seamlessly integrate into modern consumers' daily lives is rapidly growing, showing promising potential. Wearable technology, incorporating micro-controllers and electronic devices on the skin or within clothing, serves as signal receptors, analytical tools, and signal transmitters for monitoring human body vitals. This study aims to develop a smart textile-based wearable platform to enable continuous monitoring of vital signs [1].

Non-invasive sampling and analysis of body fluids have achieved continuous vital sign monitoring in recent times[2]. Techniques involving tears, saliva, urine, and sweat without penetrating the skin have gained traction over conventional invasive methods like blood draws, which can cause discomfort, infections, and sample contamination [3], [7]. Sweat, in particular, emerges as a promising non-invasive sampling medium due to its lower chances of tampering, longer detection windows, and easier sample preparation. Sweat analysis offers various advantages, such as the detection of certain drugs, making it a potential biomarker for specific diseases [4], [8].

The composition of chemical compounds in human sweat, including water, amino acids, urea, metabolites, glucose, xenobiotic molecules, and ions, varies depending on the condition of the body's biological systems [4]. Consequently, these compounds can serve as biomarkers for specific diseases. Additionally, sweat analysis can be used to detect substances such as heroin and 6-acetylmorphine, as parent drugs are often excreted in higher concentrations than their metabolites [4], [8], [10]. This offers an opportunity to identify substance abuse and doping through sweat testing.

However, using sweat as a clinical sample comes with challenges like obtaining sufficient sweat volume, preventing sample evaporation, and ensuring accurate analysis. To address these limitations, this research focuses on creating a smart textile-based wearable platform that optimizes moisture management and measures the variation in chemical components' concentration through surface conductivity assessment.

II. LITERATURE & BACKGROUND OF THE STUDY

In both continuous and non-continuous health monitoring, the aggregation, analysis, and disposal of samples play a critical role [5]. Wearable health monitoring devices commonly employ invasive and non-invasive sampling methods to collect and analyze biofluids from the human body. Invasive methods involve drawing fluids such as blood and cerebrospinal fluid, while non-invasive methods rely on naturally excreted biofluids like sweat, tears, saliva, and skin interstitial fluid [6]. However, invasive sampling has limitations, including infection risks due to frequent sampling, susceptibility to contamination, limited sample storage, and challenges in continuous monitoring [7], [11].

Furthermore, the invasive nature of these sensors hinders data acquisition for biomedical applications, particularly in patients such as neonates, the elderly, and those with blood-related phobias [8-10]. In this context, textile-based structures offer an opportunity to create microfluidic platforms within the substrate [11-14] Incorporating microfluidics enhances the sampling process of biofluids and improves the temporal resolution of wearable sensors by continuously supplying freshly secreted biofluids to the sensor [15]. Accordingly, this research aims to achieve these advancements by implementing a textile substrate. For the platform to function effectively as a wellness device, it must efficiently absorb aggregated sweat and facilitate its evaporation after analysis. Therefore, appropriate modeling of fluid flow kinetics through the medium is essential to enhance the sensitivity and accuracy of the wearable platform.

Several techniques have been employed as present in previous research for the analysis of bio samples. Colorimetric analysis employs color reagents to determine compound concentrations in sweat [5],[7],[12]. While being simple and cost-effective, this technique suffers from the lack of real-time data due to delays in analysis. Cross-contamination during sample handling and analysis also poses challenges for accuracy and reliability [13].

Additionally, Enzymatic and electrochemical analysis techniques have been widely investigated for sweat monitoring [9],[11],[14]. However, certain issues, such as rapid fluctuations in sweat generation rates and unpredictable analyte dilution, have been reported, demanding further improvements for prolonged and precise monitoring [11]. The analysis of sweat pH, a well-established technique, has been explored as an indicator and analysis parameter for various skin conditions [9]. While offering consistency and reliability, pH-based analysis may have limitations in detecting neutral components or those with minimal pH variations [11]. Moreover, Conductivity-based analysis has shown promise for real-time sweat monitoring. Utilizing alternating current conductivity, this technique effectively collects and detects sweat, considering the temperature-dependent nature of conductivity. However, further research is needed to evaluate its broader application for different sweat constituents [7], [15-16].

After critically examining the various techniques available, this research has selected conductivity-based analysis as the optimal approach for sweat monitoring, offering real-time, accurate, and continuous assessment of sweat constituents within the context of wearable health devices.

III. Materials and Methods

A wearable sweat monitoring platform was fabricated using a sandwich structure consisting of three layers: the Skin Layer, in contact with the skin and possessing moisture-wicking properties; the electrically conductive and flexible electrospun fabric (Active Layer); and the External Layer, responsible for sweat excretion. The functions of each layer in the sandwich structure were as follows: the Skin Layer effectively transported sweat from the body to the Active Layer, without retention, while protecting the Active Layer from abrasion; the Active Layer absorbed and retained transferred sweat for analysis, accumulating it in a localized area before transferring it to the External Layer; and the External Layer provided protection to the Active Layer from humidity and other external factors and transferred the sweat to the atmosphere after analysis.

A. Fabrication of the layers of the sandwich structure

To create a wearable wristband, the fabric construction needed to achieve successful moisture transportation and inbuilt stretchability to conform to the wearer's hand. A knitted structure with an open-knitted design was chosen for its high moisture permeability, large surface area, and ability to conform to desired shapes, increasing contact with the skin and facilitating sweat transference through the layers. The fabric composition for each layer was carefully selected based on their expected properties and functionalities. The Skin Layer was constructed using hydrophobic fibers, 100% Polyester fabric, to facilitate functionality and provide protection. The Active Layer used a blend of 65% cotton and 35% polyester to ensure effective moisture retention and transportation. The External Layer consisted of 80% polyester and 20% cotton to facilitate sweat transfer to the atmosphere with a high drying rate.

The Active Layer was crucial for conductivity analysis and sweat retention. Electrospinning techniques were used to incorporate conductivity into this layer. Reduced Graphene Oxide (RGO) was chosen as the most suitable graphene-based agent, imparting conductivity to the textile. Polycaprolactone (PCL) was selected as the polymeric material for its biocompatibility and ease of processing. The electrospinning process involved creating two samples: one with direct electrospinning of RGO/PCL and the other with electrospinning of PCL followed by RGO dip coating, as presented in Fig 1. The latter process was found to provide better RGO distribution and continuous conductive paths, making it the recommended methodology for fabricating the conductive layer.

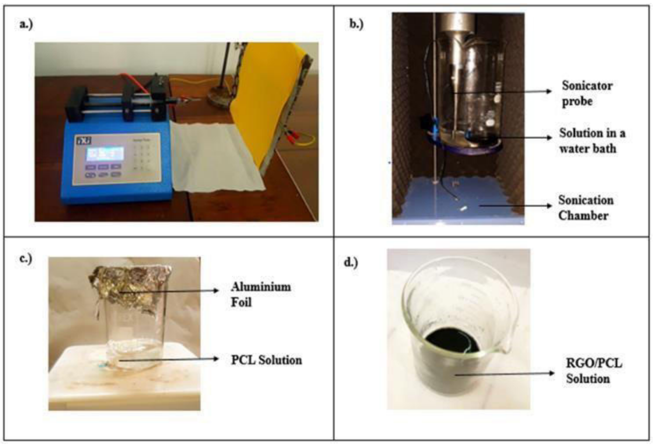

Fig. 1. (a) Electro spinning the Active Layer, (b) Sonication of the RGO/PCL solution, (c) Heat stirring process of the PCL solution (d) RGO/PCL dip coating solution

The three layers were assembled to create the wearable sweat monitoring platform, effectively combining sweat sample collection, analysis, and excretion capabilities. While segregating electrolytes from the sweat pool using an ion-selective electrode was a common method, this research assumed that electrolytes were already segregated into different ionic groups before analysis.

B. Fabrication of The Conductivity Assessment and Real-time Analysis System

The conductivity assessment system utilized the voltage divider principle, measuring the surface resistivity of the Active Layer to assess sweat conductivity, as demonstrated in Fig 2. A microcontroller interfaced with an IoT platform, "Thingspeak," facilitated real-time monitoring and data upload remotely, as illustrated in Fig 3. The conceptual design of the wearable platform was based on maintaining a thickness of 1mm for each layer and using 150-300 GSM fabric to achieve the necessary porosity. An area of 0.5cm x 0.5cm was left uncovered during electrospinning for localized sweat accumulation.

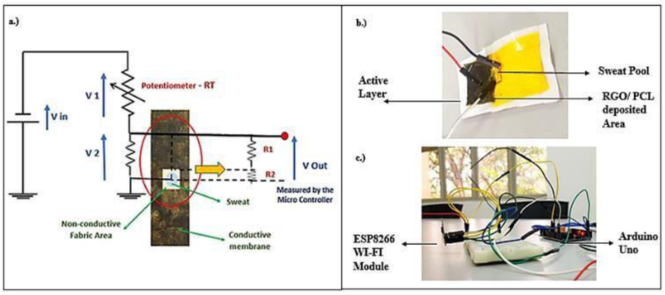

Fig. 2. The conductivity assessment system (a) Voltage Divider Principle Employed in this Assessment, (b) Fabricated Active Layer, (c) Fabrication of the Conductivity Assessment System

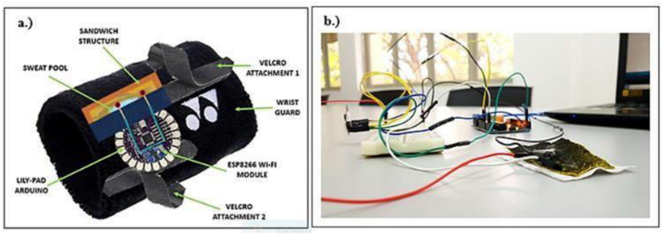

Fig. 3. (a) The Conceptual Design of the Wearable Platform (b) The Fabricated Platform for Analysis

IV. Results and discussion

A. Conductivity Assessment

The results of the conductivity assessment of the Active Layer showed that the microcontroller-based platform coupled with the fabricated layer successfully detected variations in sweat concentrations relative to the base concentration values of a healthy individual, particularly for Na+ ions. The artificial sweat solutions, representing NaCl concentrations ranging from 7-44 mM, were dropwise added to the platform to analyze voltage fluctuations resulting from platform saturation or evaporation. The obtained results depicted similar mean voltage values for each concentration level with slight variations over time. Notably, the upper boundary of the standard concentration range exhibited significantly higher voltage fluctuations, attributed to a higher number of mobile ions remaining in the solution while the rate of wicking did not match the rate of ions entering the Active Layer. However, these fluctuations did not compromise the accuracy of the measurement for voltage increments within the lower and upper concentration ranges. Concentrations exceeding 0.44 M (the cutoff top boundary value of Na+ for a healthy individual) showed a significant rise of 10 v/mol in the voltage value, indicating an excess number of mobile ions and increased voltage response. Conversely, concentrations below the 0.07 M range demonstrated a significant drop of 10 v/mol in the voltage value, indicating limited mobile ions and reduced charge carrier density. The observed consistency of concentration levels regardless of varying sweat volumes due to external environmental conditions validated the platform's reliability. Even with differing rates and volumes of sweating among individuals, the platform remained unaffected, ensuring accurate and reliable sweat analysis.

B. Morphology Analysis

The characterization of the Active Layer's morphology through Scanning Electron Microscopy (SEM) analysis further supported the effectiveness of the fabrication process. Process B, involving PCL electrospinning followed by RGO dip coating, exhibited significantly improved coverage and distribution of RGO flakes on the surface compared to Process A. The enhanced distribution of RGO flakes on the PCL mat in Process B ensured a continuous conductive path, resulting in higher conductivity and reduced surface resistance. This is demonstrated in Fig 4 and Fig 5. The results confirmed that Process B offers advantages in terms of improved coverage and distribution of RGO flakes, contributing to the material's characteristics and its potential for future applications in electronics, sensors, and energy devices, where high conductivity and low surface resistance are crucial.

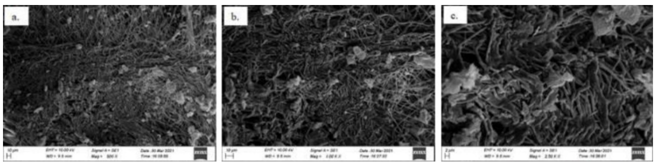

Fig. 4. PCL electrospun RGO dip coated membrane (a) 250x magnification level, (b) 500x magnification level, (c) 1000x magnification level.

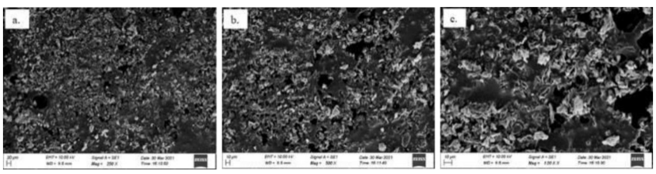

Fig. 5. PCL/RGO directly electrospun membrane (a) 500x magnification level, (b) 1000x magnification level, (c) 2500x magnification level

C. Moisture management properties

In the evaluation of moisture management properties, the study conducted tests on fabric samples from the Skin layer and the Atmospheric layer using the SDL-ATLAS Moisture Management Tester and the AATCC Test Method 195 under standard conditions. The 100% Polyester fabric used for the Skin layer demonstrated the highest one-way transport index, indicating its superior liquid management capability and efficient sweat transfer to the Active layer. In contrast, the Active layer fabric exhibited lower spreading rate and wetted radius, which promoted localized sweat accumulation for analysis. The 65% Cotton 35% Polyester fabric in the Active layer showed slow drying rate and limited one-way transfer ability, making it suitable for retaining sweat volume during analysis without transferring it to the Atmospheric layer.

These results support the choice of 100% Polyester fabric for the Skin layer, enabling effective sweat wicking from the skin and subsequent transport to the Active layer for analysis. Similarly, the 65% Cotton/35% Polyester fabric is considered ideal for the Active layer due to its ability to absorb sweat molecules during analysis and facilitate quick wicking to the Atmospheric layer for evaporation.

V. Conclusion

In conclusion, this research successfully explored the development of a smart textile-based wearable platform for continuous monitoring, with a focus on sweat as the analyzed body fluid. The conceptual design featured a sandwich structure, enabling efficient sweat aggregation, analysis, and excretion. The selection of fabric composition and construction, including 100% Polyester for the Skin Layer and 65% Cotton 35% Polyester for the Active Layer, facilitated optimal sweat transport across the layers. The PCL electrospun/RGO dip coating technique for the Active Layer was validated through SEM analysis. Real-time analysis using artificial sweat solutions demonstrated the platform's ability to detect concentration fluctuations within the desired ranges, with higher concentrations resulting in increased voltage readings and vice versa. Overall, this study highlights the promising potential of the developed wearable platform for continuous monitoring, offering valuable insights into various applications in sports science, healthcare, and wearable technology.

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