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Flexible multilayered skin health sensing platform for eyewear applications

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Abstract
Skin diseases are among the most prevalent health issues worldwide, and the prevalence of these diseases is increasing, driven by factors such as aging populations and urbanization-related infrastructure imbalance. As skin diseases become more widespread, the need for their early detection and proper management is gaining prominence, underscoring the importance of developing advanced real-time skin health monitoring technologies. In this study, we propose a flexible, multi-layered skin health monitoring platform capable of the real-time measurement of key indicators such as humidity, sweat secretion, and pH levels. The platform collects sweat from direct skin contact, providing real-time, noninvasive data on humidity, sweat secretion, and pH levels, which are transmitted to a smartphone for continuous monitoring. Sensors for this platform were fabricated using inkjet printing, which enables low-cost and straightforward manufacturing, and were integrated into a vertically stacked configuration designed to fit wearable forms, such as eyewear. In addition, each sensor was constructed using a flexible substrate, making the platform adaptable to various applications beyond skin health monitoring. This platform holds potential for broader use across diverse areas of healthcare and medical science, laying the groundwork for technologies that enable continuous physiological monitoring to advance fundamental research and facilitate practical solutions.

Keywords Skin health analysis, Flexible multi-layered platform, Skin humidity, Sweat rate, Sweat pH level, Continuous monitoring

Introduction

The human skin is the organs most directly exposed to the external environment; as such, it serves as the first line of defense, protecting the body from external mechanical and chemical factors. Specifically, it plays a vital role in blocking ultraviolet rays, preventing excessive moisture loss, and safeguarding against harmful chemicals, while also acting as a barrier to pathogens attempting to infiltrate the body [1–3]. According to the 2010 World Health Organization (WHO) Global Burden of Disease (GBD) report, skin diseases are among the most prevalent health issues globally, ranking fourth among all disease types, and affecting approximately 30% of the population [4]. The prevalence of skin diseases is steadily increasing, particularly because of the increasing number of elderly individuals susceptible to such conditions as a result of global aging, and the growing population in region where access to treatment is limited by the infrastructural imbalances triggered by rapid urbanization [5–7]. Skin diseases not only impose psychological burdens on patients but, when left untreated, can progress to severe conditions such as skin cancers, including basal cell carcinoma, squamous cell carcinoma, and melanoma, the latter of which carries significant mortality risks [8–10]. Consequently, the importance of early intervention and proper management of skin diseases is

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increasingly being emphasized, driving the need for technologies capable of real-time skin condition monitoring. As such, interest in skin healthcare technologies continues to grow alongside the expanding market for related solutions [11–15]. Currently, skin analyzers that assess skin conditions using indicators such as pH and humidity are generally limited to measuring a single parameter, or while being portable, tend to be large and expensive. Additionally, they are designed for short-term usage rather than long-term monitoring, providing only temporary insights. However, these methods have clear limitations in capturing the dynamic nature of certain skin conditions or simultaneously detecting multiple indicators. These skin conditions are generally influenced by factors such as physical health, diet, and emotional state, and can change continuously [16–20].

Therefore, the present study proposes a platform capable of simultaneous real-time monitoring of humidity, sweat secretion, and sweat pH, which are the key indicators of skin conditions. These three metrics provide essential information that enables a comprehensive evaluation of skin health. First, Skin humidity is a crucial indicator of skin health and is used to assess moisture levels. Maintaining a relative humidity of at least 40% is essential for healthy skin. If humidity drops below 40%, skin aging begins, and levels below 10% can lead to fine lines, dryness, and other skin conditions. However, prolonged exposure to humidity above 60% increases the risk of heat-related illnesses, dermatitis, and eczema. Therefore, maintaining an optimal humidity environment is vital for preserving skin elasticity, smoothness, and protection against external irritants [21–23]. Sweat secretion plays a vital role in thermoregulation and directly reflects an individual's physical activity and physiological conditions. Proper sweat production is essential for maintaining overall health, and offers crucial insights into factors such as stress, fatigue, and dehydration, making it an indispensable parameter for understanding body functions [24–29]. Finally, pH levels can indicate the natural protective barrier function and immune conditions of the skin. Healthy skin typically maintains a slightly acidic pH range of 4.5–5.5. Deviations from this range can compromise the skin's barrier, thereby reducing its ability to prevent bacterial growth, and increasing its vulnerability to conditions such as atopic dermatitis and acne [30, 31].

Building on our previous work [32–34], we have developed specialized sensors for humidity, sweat secretion, and sweat pH, each integrated into a vertically laminated structure within an eyewear platform. This platform is designed to enable users to assess their skin condition easily, without relying on bulky conventional equipment or specialized medical expertise. Further, it offers convenience and effectiveness and is not restricted by time or location. Additionally, each sensor is manufactured on a flexible substrate, polyimide (PI), so that it can be easily applied to curved surfaces, thereby allowing expansion into various types of platforms. The platform proposed in this paper operates in a non-invasive manner compared to previously developed and researched devices and can be applied to flexible substrates or plastics through a printing process. Furthermore, while it currently measures only skin moisture, pH, and sweat rate, it can be expanded into a platform capable of acquiring a wider range of skin-related information by integrating additional biosensors. Consequently, the proposed platform not only functions as a personal skin diagnostic device, but also delivers tailored solutions based on individual user needs. In particular, its real-time monitoring capability and flexible design hold significant potential for application across diverse industries, including beauty, sports, military operations, and environmental hazard detection. These features are expected to expand the usefulness of this platform, allowing its establishment as an innovative tool that surpasses the limitations of conventional diagnostic methods.

Results and discussion

The multi-layered flexible sensor for skin health monitoring

The skin health monitoring platform sensor proposed in this study was designed as a multi-layered structure arranged sequentially from the surface in contact with the skin. The layers included a humidity sensor, a channel for sweat flow, a sweat rate sensor, and a pH sensor. The humidity sensor in layer 1 directly contacts the skin to measure the relative humidity of the skin surface. The channel in layer 2 collects sweat produced by the skin, guides it through an inlet, and releases it via an outlet. Layer 3 contains a sweat rate sensor that detects the amount and flow rate of sweat exiting the outlet. Layer 4, the final layer, contains a pH sensor to measure the pH of the sweat using the collected sweat (Fig. 1a). The sensors were fabricated by inkjet printing using a V-ONE printer (Voltera) and silver ink (Conductor3 Ink, Voltera). Polyimide (PI) and Polyethylene Terephthalate (PET) were selected as substrates due to their flexibility, which enables the sensors to adhere seamlessly to curved surfaces, such as the skin. This flexible form enhances the adaptability and usability of the device (Fig. 1b).

Flexible humidity sensor

The humidity sensor operates based on a capacitive mechanism, in which the detection of sweat on the sensor induces changes in permittivity, leading to variations in capacitance, which is expressed as the relative humidity (RH). The sensor was fabricated on a PI substrate

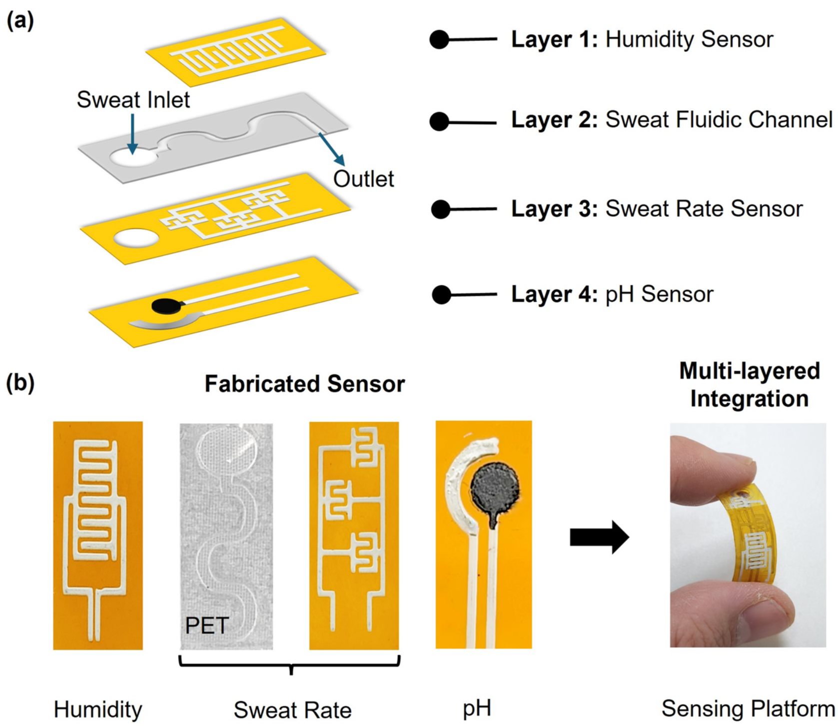

Fig. 1 Overview of the flexible multi-layered sensing platform (**a**) A deconstructed view of the multi-layer sensing platform (**b**) Images of the fabricated humidity, sweat rate, and pH sensors, as well as the integrated multi-layer sensor

using an interdigitated patterned structure via inkjet-printing (Fig. 2a). The device categorizes skin humidity levels as dry (< 40%), optimal (40–60%), or humid (> 60%). Accordingly, the performance of the humidity sensor was evaluated within an RH range of 30–80%. The measured skin humidity was derived from capacitance changes corresponding to the relative humidity caused by sweat on the skin surface. The sensitivity of the sensor was calculated as approximately 0.0765 pF/%RH in the RH range of 30–80% (Fig. 2b). Further, to assess the performance of the sensor under varying moisture levels, an experiment was conducted by attaching the sensor to the skin and comparing bare skin with skin treated with a moisturizer. The capacitance of the untreated skin was measured at a baseline RH of 30%, which revealed that the $\Delta C/C_0$ value increased by approximately 1 when the moisturizer was applied compared to bare skin (Fig. 2c).

Flexible sweat rate sensor

The sweat rate sensor consists of a sensing layer that detects sweat flow and a channel layer that directs sweat toward the sensing layer. The sensing layer was designed using three interdigitated capacitors connected in parallel, whereas the channel layer was fabricated from PET material cut using a cutting machine (Cameo4, Silhouette), and attached above the sensing layer. The operating principle of the sensor begins when sweat enters the inlet of the PET channel and flows along the channel from high to low pressure. At this point, as sweat passes through the parallel capacitors, its dielectric constant ($\varepsilon = 80$) significantly surpasses that of the air ($\varepsilon = 1$), resulting in a change in capacitance. Based on this principle, a sweat rate sensor was designed to estimate the sweat volume. As the sweat progressed through the channel and crossed each curved section, the capacitance measured by each parallel capacitor increased sequentially, allowing the amount of sweat to be quantified (Fig. 3a). The sensor's performance was evaluated by introducing 20 μL of a blue solution into the channel, and observing its progression through the three curved sections under pressure differences, while measuring the capacitance at each point. The results revealed capacitance increases of 0.51 pF, 0.52 pF, and 0.62 pF at the first, second, and third capacitor sections, respectively (Fig. 3b). The slope of the capacitance change relative to the flow rate was calculated using the measured data. This enabled the estimation of the sweat volume flowing through the channel per unit time, allowing the sweat rate of the user to be determined (Fig. 3c).

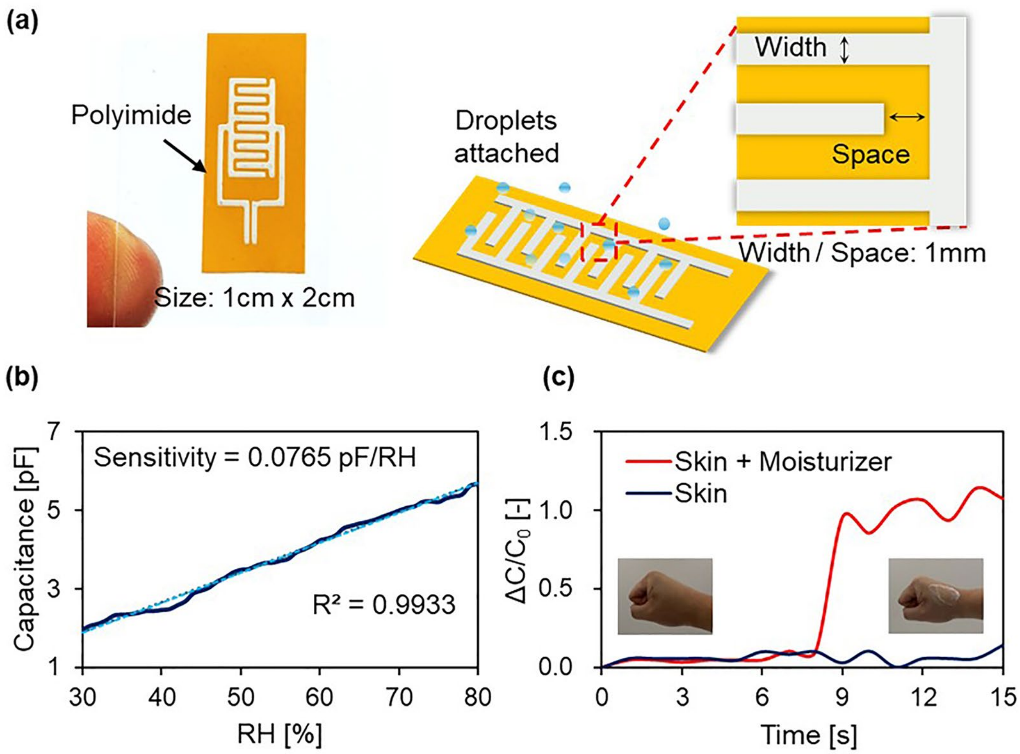

Fig. 2 Overview of the humidity sensor (**a**) Structure of the humidity sensor (**b**) Capacitive measurements of the humidity sensor according to the relative humidity (**c**) Sensitivity of the humidity sensor and comparison of capacitance differences resulting from the presence of a skin moisturizer

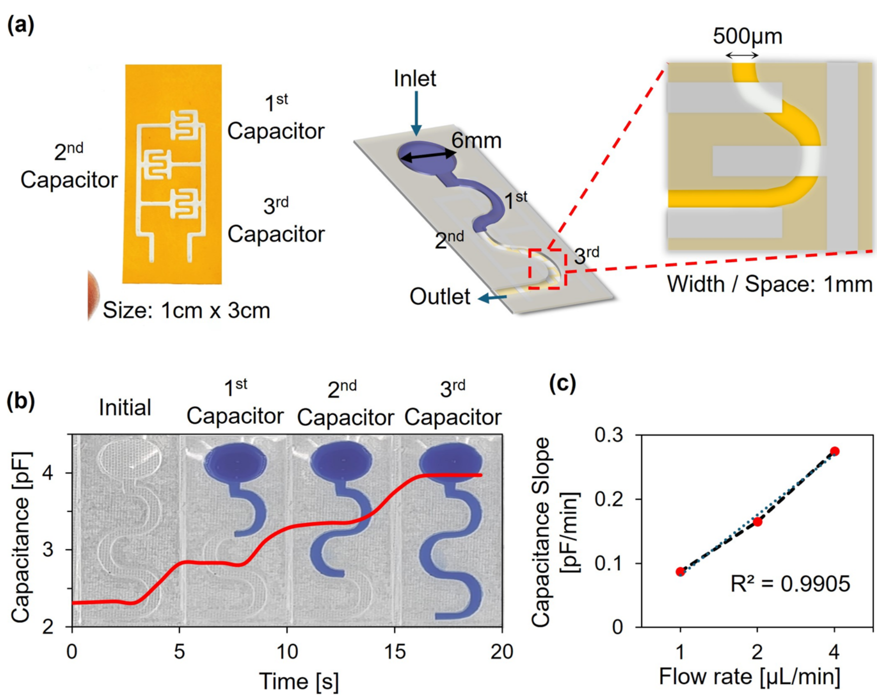

Fig. 3 Overview of the sweat rate sensor (**a**) Structure of the sweat rate sensor (**b**) Capacity measurement of the sweat rate sensor as blue liquid passes through each capacitor (**c**) Relationship between the flow rate and capacitance slope

Flexible pH sensor

Skin pH and sweat pH exhibit a strong correlation [31, 35, 36]. The pH sensor in this platform is designed to measure pH by detecting the hydrogen ion concentration in sweat. This sensor measures the pH of sweat that comes into contact with it through the inlet of the channel layer of the Sweat Rate Sensor. Additionally, based on the Nernst equation, it calculates the pH by detecting the potential difference between two electrodes, corresponding to the hydrogen ion concentration in sweat. The sensor was fabricated on a polyimide (PI) substrate comprising a working electrode and a reference electrode (Fig. 4a). The working electrode was patterned with flexible Ag ink using inkjet printing, followed by deposition of graphene and polyaniline (PANi) layers. Graphene was screen printed into a circular structure, and dried at room temperature for 30 min. PANi solution was prepared by dissolving N-Methyl-2-pyrrolidone (NMP) at a concentration of 10 mg/mL; 8 μL of this PANi solution was then drop-cast onto the graphene. The electrode was cured at 80 °C for 2 h to complete its fabrication. The reference electrode was hook-shaped, fabricated by screen-printing Ag/AgCl over Ag ink, and cured at 80 °C for 10 min (Fig. 4b). The performance of the pH sensor was evaluated using a source meter (2400 Standard, Keithley) to measure the potential differences. The sensor was initially stabilized by bathing it in deionized (DI) water, and then sequentially exposing it to buffer solutions (Samchun Chemicals) with pH values ranging from 4 to 9. The stabilization interval was set to 15 s. The evaluation revealed a sensitivity of − 55.6 mV/pH within the pH range of 4–9, thus demonstrating the sensor's suitability for rapidly detecting pH changes in sweat on the skin (Fig. 4c).

Integrated platform test

To monitor skin conditions in real-time, the humidity, sweat rate, and pH sensors were vertically integrated into an eyewear-type platform. This integrated sensor system was then connected to a microcontroller unit (MCU) and a Bluetooth module, enabling the real-time transmission of skin condition data to a smartphone to allow continuous monitoring (Fig. 5a). The experiment was conducted in an environment conducive to sweat collection with the participants engaging in physical exercise to facilitate data acquisition. During the experiment, real-time

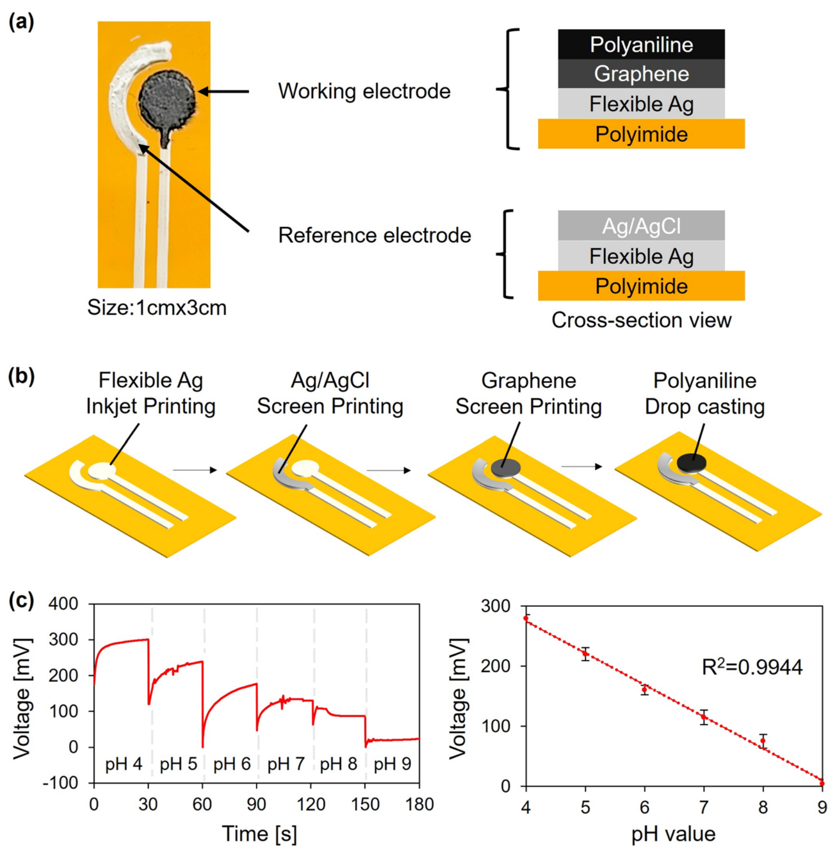

Fig. 4 Overview of the pH sensor (**a**) Structure of the pH sensor (**b**) Fabrication process of pH sensor (**c**) Performance evaluation of the pH sensor's open circuit voltage with a pH range of 4–9 and the resulting linear calibration curve

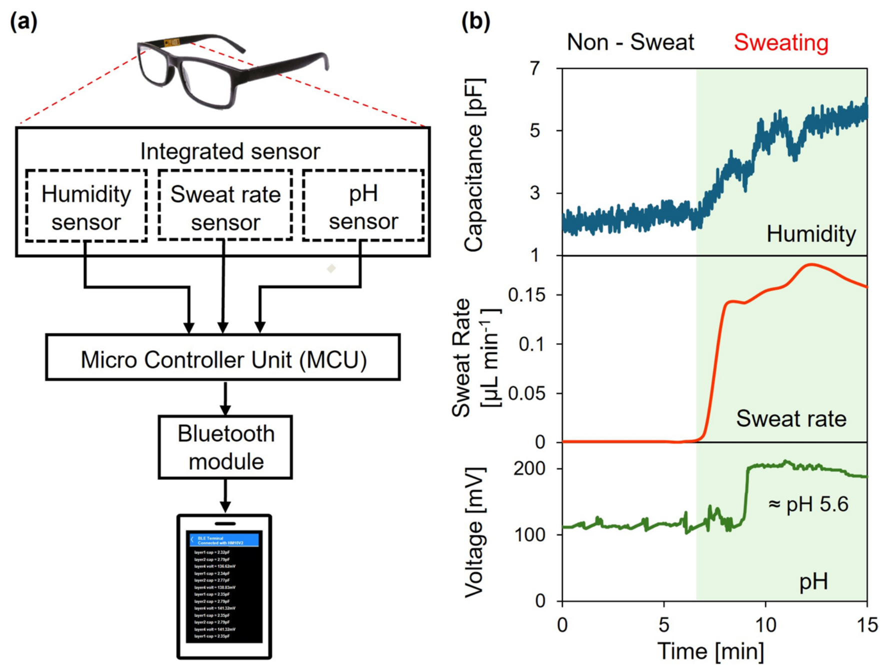

Fig. 5 Overview of the integrated platform test (**a**) Diagram showing the system configuration of the flexible multi-layer sensing platform (**b**) An example of the real-time on-body monitoring of the subject skin's humidity, sweat rate, and sweat pH levels

monitoring of the data collected from the participants' skin was performed. For the initial 6 min, the participant remained inactive, during which the humidity, sweat rate, and pH sensors maintained relatively stable readings, owing to the absence of sweat secretion. After six minutes, sweat secretion commenced as the participants began exercising, resulting in a rapid increase in skin humidity and sweat rate. Before exercise, the capacitance readings representing humidity remained in the range of 1.9–2.7 pF, whereas the post-exercise sweat secretion caused the readings to exceed 3 pF. The sweat rate was ultimately calculated to peak at 0.18 μL/min during the maximum sweat secretion. Regarding pH, the values showed a sharp increase approximately 7 min after sufficient sweat collection was initiated following exercise and subsequently stabilized at approximately pH 5.6 (Fig. 5b).

Conclusion

Overall, this paper proposes a flexible multi-layer eyewear platform for real-time skin condition monitoring. The proposed platform collects real-time data on humidity, sweat rate, and sweat pH, and transmits it to a smartphone via a Bluetooth module, thereby enabling users to monitor their skin condition without any constraints on time or location. The findings of this study indicate that this platform can overcome the limitations of conventional large-scale equipment and measurement devices that provide only temporary information by demonstrating the feasibility of a sensor system capable of performing continuous skin condition monitoring. Notably, the proposed sensor system successfully detected and quantitatively evaluated the physiological changes in the skin with high sensitivity and stability. This study primarily focused on testing the platform in a specific scenario, transitioning from a non-sweating state to a sweating state. While the results validate the functionality of the platform in this scenario, future research should expand the scope of the application of this platform by exploring its performance under various environmental conditions, situational scenarios, and long-term monitoring. Additionally, incorporating stretchable substrates or further physical and chemical sensing functionalities could enhance its potential. Such advancements could be expected to facilitate the development of personalized health management solutions in the healthcare and medical fields, as well as its applications in sports, military, and industrial settings. Moreover, the platform's lightweight and adaptive design suggests its potential as a key tool for providing tailored medical services to specific groups (e.g., the elderly, athletes, and soldiers). This not only anticipates a paradigm shift in healthcare technology but also establishes a comprehensive platform that sets a new standard for skin condition monitoring technology.

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Author contributions
BP, SL, YS fabricated the devices, conducted experiments, and analyzed the data. BP and SL drafted the figures and manuscript. PY and MK supervised the experiments and revised the manuscript. All the authors have read and approved the manuscript.

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Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
The authors declare that they have no competing interests.

Consent for publication
The authors consent the Springer Open license agreement to publish the article.

Competing interests
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