SweatSkin: Rapidly Prototyping Sweat-Sensing On-Skin Interface Based on Microfluidics

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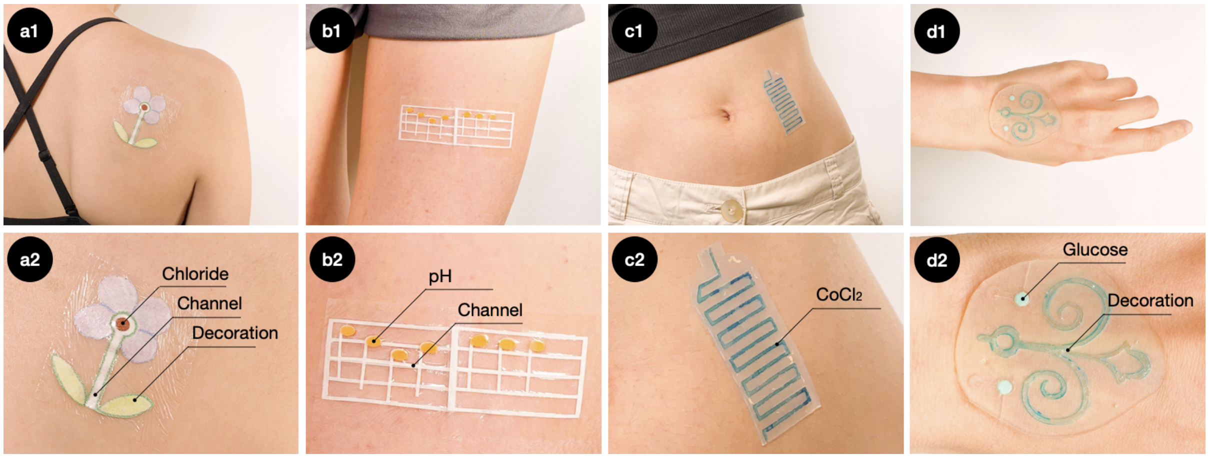

Fig. 1. SweatSkin is a versatile platform for fabricating on-skin sweat-sensing interfaces using microfluidics and colorimetric analysis. Four different fabrication methods are proposed: (a) The microfluidic channel (the stem) can be drawn using crayons, and the chloride test paper (the flower center) can be used to measure electrolyte levels. (b) The microfluidic channel (the staff) can be made using cut paper, and the pH test paper (the notes) can be used to measure the hydration state. (c) The device can be made using molded silicone rubber, with CoCl2 hydrogel in the channel, to measure sweat loss. (d) The device can be made using molded UV resin with decorative channels (the ornaments) that do not serve any functional purpose but add to the aesthetic value. The glucose test paper (the dots) can measure blood sugar levels.

Sweat sensing affords monitoring essential bio-signals tailored for various well-being inspections. We present SweatSkin, the fabrication approach for customizable sweat-sensing on-skin interfaces. SweatSkin is unique in exploiting on-skin microfluidic channels to access bio-fluid secretes within the skin for personalized health monitoring. To lower the barrier to creating skin-conformable microfluidics capable of collecting and analyzing sweat, four fabrication methods utilizing accessible materials are proposed. Technical characterizations of paper- and polymer-based devices indicate that colorimetric analysis

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can effectively visualize sweat loss, chloride, glucose, and pH values. To support general to extreme sweating scenarios, we consulted five athletic experts on the SweatSkin devices' customization guidelines, application potential, and envisioned usages. The two-session fabrication workshop study with ten participants verified that the four fabrication methods are easy to learn and easy to make. Overall, SweatSkin is an extensible and user-friendly platform for designing and creating customizable on-skin sweat-sensing interfaces for UbiComp and HCI, affording ubiquitous personalized health sensing.

CCS Concepts: • **Human-centered computing** → *Ubiquitous and mobile computing systems and tools.*

Additional Key Words and Phrases: On-skin interface, wearable computing, sweat sensing, microfluidics, rapid prototyping, do it yourself, maker movement

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1 INTRODUCTION

Wearable devices, or more specifically, on-skin interfaces, are a popular method for realizing personalized healthcare since they can continuously collect data from our bodies and provide relative information [28]. Compared with other health-monitoring devices, on-skin interfaces conform to the skin and thus support the more accurate collection of human physiological signals. However, current research in on-skin interfaces in UbiComp and human-computer interaction (HCI) focuses on the placement of sensors or actuators *on* the skin surface, with limited engagement with the secretion of bio-fluids from *within* the skin [36, 41, 42, 45, 81, 82]. Specifically, bio-fluids from sweat can encompass a wealth of essential biomarkers, including electrolytes, small molecules, and proteins [5, 22]. These biomarkers potentially provide valuable information about a person's well-being at the molecular level, including hydration status, electrolyte balance, vitamin level, and metabolism [4, 19, 20, 40, 69, 70, 85]. Moreover, the sweat collection allows non-invasive and non-destructive collection, which is ideal for realizing UbiComp's visions of pervasive and personalized healthcare in an everyday setting.

While sweat analysis has been used in the medical field for decades, current sweat-sensing methods typically collect the sweat from the skin, which is then analyzed in the laboratory with expensive in-lab equipment. This means real-time in-situ monitoring is impossible, presenting a gap in personalized healthcare. Additionally, this high barrier makes it difficult for the general population to benefit from sweat analysis. While sweat analysis is used in some professional scenarios, the measurement is inconvenient. For example, athletic teams still depend on measuring athletes' weight before and after training to calculate the sweat loss and rate [23]. Also, because of the laboratory equipment required to fabricate these interfaces, the accessibility for broader populations is limited, resulting in the lack of customization. Given the significant diversity in sweating, there is a need to develop personalized devices based on individual sweat profiles [3]. The lack of customization means the functionality cannot be personalized according to the users' needs. For example, blood sugar level is critical information for marathon runners, hydration state is more important to ice hockey players, while properly taking in the required electrolytes is critical after a regular workout. Furthermore, the aesthetic design of an on-skin device is also central to one's style and desire to wear a device [35].

We present SweatSkin, the first Do-It-Yourself (DIY) platform for customized sweat-sensing interfaces that can be fabricated in a typical UbiComp lab without needing advanced material science facilities or hard-to-obtain materials. The thin and soft on-skin interface uses lab-on-a-chip, or microfluidic techniques [49], to harvest sweat from the skin's surface and route it through channels to chambers for real-time in-situ analysis while maintaining a small form factor. To lower the barrier to creating customized interfaces, we propose four prototyping methods that can be realized in a DIY fashion, and the materials can be easily obtained from familiar sources such as home improvement stores and pharmacies. The SweatSkin fabrication platform supports users in designing and fabricating a personalized sweat-sensing interface that meets their needs regarding placement, shape, size, and aesthetic design. These customizations can further improve wearability, minimize movement restrictions, and stay stylish.

The technical characterization results indicate that the devices fabricated with the SweatSkin platform effectively visualize sweat loss, chloride, glucose, and pH values. These biomarkers have the potential to be interpreted as sweat rate [4], electrolyte level [4], blood sugar level [94], and hydration state [40], respectively, as demonstrated by the prior work. Athletic experts were invited to provide insights into the customization guidelines, potential applications, and envisioned usage of SweatSkin in situations involving intense sweating and vigorous body movement, i.e., athletics. The professional advice garnered from these experts holds relevance not only for athletes but also for individuals engaging in regular exercise routines. Furthermore, by understanding the devices' effectiveness in such extreme scenarios, their applicability can extend to a broader range of everyday use cases. With a ten-participant, two-session fabrication study, the four prototyping methods were validated as easy to learn and execute.

By enabling a user-friendly approach to realize customized sweat-sensing interfaces, SweatSkin introduces bio-fluids as a new detection mechanism for UbiComp health monitoring systems. This paper presents the following contributions:

- We introduce a five-dimensional design space of customized sweat-sensing on-skin interfaces based on microfluidics to support personal healthcare in an everyday setting.
- We present SweatSkin, a rapid prototyping platform that enables the user-friendly fabrication of customized sweat-sensing on-skin interfaces.
- We explore the potential of customized on-skin sweat-sensing interfaces based on athletic expert interviews and evaluate the user-friendliness of SweatSkin through a fabrication workshop study with ten participants.
- We propose three proof-of-concept applications to showcase the application scenarios and customization potential of the SweatSkin platform.

2 RELATED WORK

2.1 Sweat Sensing

Sweat contains rich biomarkers and thus can derive a variety of biological information [31], including stress [61] and blood sugar levels [94]. Conventional sweat-sensing approaches depend on absorbent patches to collect sweat and further analyze the sweat with benchtop equipment in the laboratory [6, 24, 52, 53, 71]. These methods prevent individuals from real-time in-situ health monitoring without professional health providers, even though sweat is accessible to everyone and can be collected non-invasively. Fluid-driven methods were proposed by researchers in many fields to support real-time in-situ sweat analysis [20, 22, 88]. Researchers have explored wearable electric devices for portable healthcare [19, 59, 80]. However, the solid electronic components limit the comfort of wearing and further affect movement. Soft epidermal devices based on microfluidics and colorimetric techniques were presented to address these issues. Microfluidics made with polydimethylsiloxane (PDMS) can precisely collect and direct sweat to a specific position for reliable analysis [4, 40, 68]. While PDMS is transparent and thus can efficiently show the colorimetric results, the fabrication of these devices relies on expensive equipment, often limited to proprietary laboratories and the realms of material science. Thread-based [13, 64, 85, 90] and paper-based [54, 62] approaches can cut down the cost. However, these papers primarily focused on exploring how the particular material can be used for sweat analysis. Overall, how users interact with microfluidics and how these devices can be easily fabricated beyond proprietary laboratory settings remain underexplored. In this paper, we propose a low-cost and easy-to-access fabrication platform to introduce the field of UbiComp and HCI to user-friendly sweat-sensing interfaces to support personalized healthcare.

2.2 Microfluidic Devices

Microfluidic devices have found diverse applications across numerous fields, including but not limited to robotics [73], chemistry [77], and nutrition science [7, 39]. Quick and easy fabrication methods were proposed to support education and rapid prototyping. Esfahani et al. developed children-friendly approaches using scratch art cards, chocolate chips, and crayons for fabricating microfluidics [16]. Chakrabarti et al. explored the characteristics of microfluidics made with crayons [10]. Silicone Devices [57] proposed a DIY fabrication workflow for prototyping stretchable silicone devices. They utilized microfluidics with liquid metal to embed electronic components into the devices. SweatSkin takes inspiration from these accessible fabrication methods and exploits the potential of customizing skin-conformable microfluidic interfaces.

HCI researchers have also explored applications of microfluidics. Haptic feedback can be generated on users' skin by rendering vibration [27] or using chemicals [46]. Soft circuit boards can be made based on the microfluidic concept [57, 78]. Depending on the dynamic change of the channel filling, reconfigurable interfaces were realized [47, 76]. The dynamic change can further support responsive interfaces that react to user input [55, 75]. However, sweat sensing remains underexplored in microfluidics research in HCI. In this paper, we aimed to explore how microfluidics prototyping approaches could facilitate personalized sweat-based health monitoring.

2.3 On-Skin Interfaces

On-skin interfaces are distinguished by their thin and flexible design, employing materials that prioritize comfort even during prolonged usage [38, 43, 86]. Many of these devices were developed to provide real-time feedback [26, 84], sense physical characteristics, including gestures [30, 44], touch [34, 37, 81], and strain [45], or enable both input and output capabilities [82, 87]. Notably, the potential of on-skin interfaces extends beyond these applications and holds promise for supporting healthcare. Various studies have investigated the use of on-skin interfaces to measure biomarker variations in UV exposure levels [2], harmful environmental factors [33], and muscle strain and tension [95]. Considering recreational running, a prototype was explored to monitor foot-strike-related information [67]. The Dermal Abyss [79] presented a biosensor for reacting to the biomarker in the interstitial fluid under the skin. This method is invasive and thus encounters challenges in achieving widespread acceptance. As for the prototyping methods of on-skin health interfaces, Lotio [72] is a noteworthy DIY-friendly skin-worn display inspired by the application of lotion, a common element of healthy skincare routines. Nonetheless, a noticeable gap remains in capturing and analyzing biofluids from within the skin, *i.e.*, sweat, to inform valuable healthcare insights. Thus, this paper proposes SweatSkin, the fabrication of customizable sweat-sensing microfluidics, to complement existing health-monitoring on-skin interfaces, and highlights the user-friendly fabrication methods for personal applications.

In terms of on-skin interface fabrication, various rapid prototyping methods have been proposed with a focus on customization. To address the challenges associated with designing and fabricating on curved body surfaces, researchers have proposed design [17] or fabrication [11, 18, 25, 63] methods directly on the body. While these customization methods addressed on-body design issues, SweatSkin focuses on customization for usage scenarios, especially for personal healthcare. Other researchers have explored alternative fabrication methods for on-skin interfaces. DuoSkin [37] employed gold leaf to enable touch sensing, output display, wireless communication, and aesthetic customization. SkinWire [36] leveraged embroidery and PCB design to support self-contained on-skin interfaces. ElectroDermis [50] introduced a novel fabrication method for creating highly stretchable on-skin circuit boards that emulate the properties of bandages. Skintillates [45] and PhysioSkin [58] allowed users to print on-skin sensors using inkjet printers. WovenSkin [74] explored the possibilities of weaving on-skin circuitry. Similarly, using weaving structures, SkinPaper explores the possibilities of using paper to fabricate on-skin interfaces [92]. To enhance the accessibility of on-skin interfaces, SkinKit [42] provided a modularized toolkit. While prior research focused on placing sensors and actuators, this paper aims to advance the UbiComp and wearable computing field by focusing on the facilitation of biosensor fabrication based on microfluidics and colorimetric. Specifically, our research delves into the potential applications of on-skin biosensors and explores novel approaches to fabricating these devices. Through this investigation, we aim to contribute to the ongoing exploration of personalized healthcare within UbiComp and wearable computing.

3 DESIGN SPACE FOR MICROFLUIDIC SWEAT-SENSING DEVICES

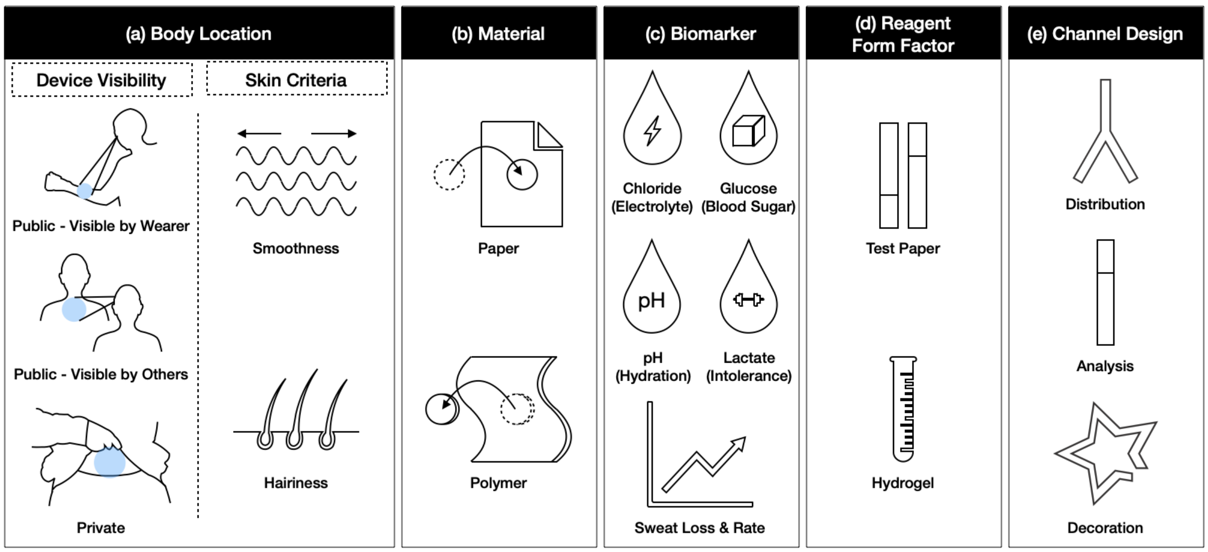

Fig. 2. The five-dimensional design space of SweatSkin.

The intention behind studying SweatSkin is not to assess the technology as a finished product but rather to present a fabrication platform that allows end-users to generate a range of applications. Customized sweat-sensing devices open up considerably more possibilities for personalized healthcare for UbiComp and HCI. Below, we present a five-dimensional design space for prototyping customized sweat-sensing on-skin interfaces.

3.1 Body Location: Where to Place (Fig. 2 (a))

Eccrine sweat glands are distributed across the majority of the body and open directly onto the surface of the skin [12], which means that sweat can be collected almost everywhere on the body. While our approach depends on colorimetric analysis, in which the results can be directly read from the device in real-time, how and when the device is visible are the main considerations for the placement of the device. When the wearer would like to track up-to-the-minute information in real-time, the device needs to be put at the body location that is visible and easy to access for the wearer. For example, the forearm is accessible when running, and the thigh is accessible when biking. When the wearer concentrates on what they are doing without distraction and relies on others to track the information, the device must be visible to the bystanders. For example, although the shoulder and back are not accessible to the wearer, others can tell the results from these places. An example would be an athletic trainer monitoring the health status of an athlete wearing the device on their back or neck. When the wearer wants the device to be private and will check the information afterward instead of monitoring it in real time, the device can be placed somewhere invisible. For example, devices placed at body locations covered by clothes can be removed and show the overall results afterward.

On the other hand, when considering different skin types, it is advisable to position the device on a smoother and less hairy skin area. Given that sweat is collected and directed to the device, the presence of wrinkles and hair could impede the device's ability to adhere effectively, potentially leading to gaps and unintended channels between the device and the skin. The sweat might not be adequately collected, resulting in possible leakage.

3.2 Material: How to Make (Fig. 2 (b))

Microfluidic devices may be made with various materials that vary in thickness, stretchability, and opacity. We propose four methods for fabricating the microfluidic sweat-sensing interface to support more user-friendly prototyping. Two methods are based on paper, a popular material for rapid prototyping in HCI [65, 66, 91]. Paper, a commonly utilized material in our daily lives, stands out due to its affordability and accessibility. Its lightweight form factor has been demonstrated to be skin-conformable to wear [92]. However, considering that paper lacks stretchability, it's advisable to wear paper-based devices in areas where there is less skin movement, such as the back or thigh (Fig. 1(a), (b)). The other two methods are based on polymers, including silicone rubber and UV resin. These materials are commonly used for handcrafting, e.g., keychains, fake food, and special effects makeup. In addition, these polymers are soft and stretchable, which minimizes the effect on movement while wearing while also retaining their lightweight nature. While polymer-based devices are thicker than paper-based devices, they offer greater stretchability. Consequently, polymer-based devices are well-suited for areas of the skin that exhibit more movement, such as the waist and hands (Fig. 1(c), (d)).

The manufacture of the device channels can be divided into two categories, i.e., additive (Fig. 2(b) Paper) and subtractive (Fig. 2(b) Polymer) manufacturing, based on the used materials. Additive manufacturing builds objects by adding material, while subtractive manufacturing depends on material removal. The paper-based methods we propose create channels by *adding* hydrophilic materials, which are paper. In contrast, the polymer-based methods depend on the *subtractive* removal of hydrophobic materials, which are polymer, or more specifically, silicone rubber and UV resin. Additive channels rely on capillary action to manipulate the fluid, while subtractive channels utilize a combination of capillarity action and pressure from sweat secretion.

3.3 Biomarker: What to Analyze (Fig. 2(c))

The colorimetric assay enables the analysis and visualization of various biomarkers on the sweat-sensing interface. Upon contact with sweat, the reagent in the microfluidic channels or chambers reacts to specific ingredients and changes color, yielding biological information. Using common off-the-shelf colorimetric reagents, diverse analyses are possible. The color change enables the quantitative assessment of the pH value and concentration of chloride, glucose, and lactate in sweat, providing information about hydration state, electrolyte levels, blood sugar levels, and exercise intolerance, respectively [40]. This paper focuses on chloride, pH value, and glucose, the most commonly studied biomarkers in the literature [20]. Additionally, analyzing the sweat travel distance in the channels based on the color change area enables the calculation of sweat loss volume and rate.

3.4 Reagent Form Factor: How to Analyze (Fig. 2 (d))

Colorimetric reagents possess the advantageous ability to change color under specific conditions, making them highly desirable for visualizing assay results. However, the form factor of the colorimetric indicator can vary, necessitating careful consideration for its application in microfluidic devices to support diverse functionalities. In this context, two types of indicators can be adopted. The first type is test paper, which involves impregnating paper with the relevant reagent and is commonly utilized in experimental settings. Test paper is readily available for purchase at pharmacies or home improvement retailers and can be seamlessly integrated with the paper-based methods proposed in this paper. The second type of indicator is a hydrogel. A thin film of indicator material is required to accommodate the diverse shapes of the polymer-based microfluidic channels while ensuring stretchability. Incorporating the reagent into a hydrogel makes it possible to maintain the desired stretchability properties while enabling the integration of the colorimetric indicator into the device.

3.5 Channel Design: What Type of Function (Fig. 2 (e))

The channels in microfluidic devices can support various functionality. In the most straightforward case, the channels can convey and distribute the fluids. In another instance, the analysis can happen in the channels as well. By filling the channels with reagents, the channels can become analysis channels, which means the chemical reaction will occur along the channels. Thanks to the channels' diverse shapes and lengths, we can easily decipher the liquid's traveling condition and further analyze the amount and moving rate. With these two methods, the proposed device can support a variety of analyses. In addition, dummy channels without functions can be added for decorative purposes.

4 SWEATSKIN

Paper-Based Device		Polymer-Based Device	
Material: Wax (Crayon)	**Cut Paper**	**Silicone Rubber**	**UV Resin**
Weight: 0.6g	**0.4g**	**4.0g**	**3.4g**
Thickness: 300μm	300μm	650μm	650μm
Cost: $0.57	**$0.57**	**$0.73**	**$0.88**

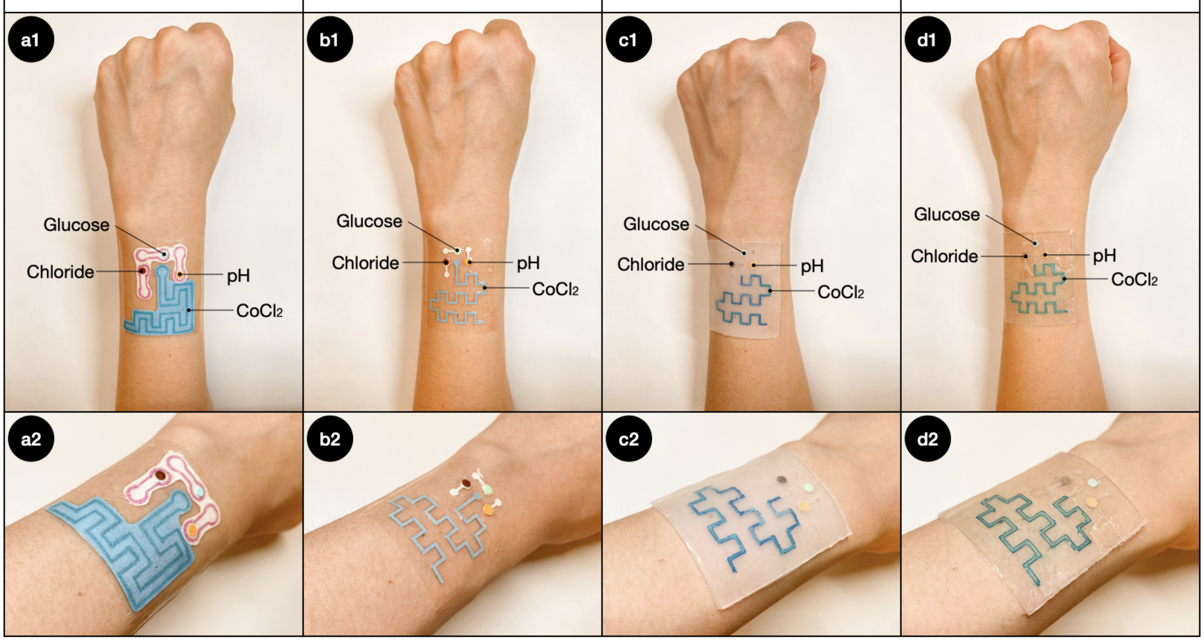

Fig. 3. We propose two form factors and, in total, four fabrication methods using different easily-accessible materials: (a) a paper-based device with wax (crayon) as a hydrophobic barrier, (b) a paper-based device with cut paper as a hydrophobic barrier, (c) a polymer-based device made with silicone rubber, and (d) a polymer-based device made with UV resin. The weight, thickness, and cost of each proposed device are listed.

4.1 Theory of Operation

SweatSkin is a platform that supports the customization and fabrication of a microfluidic-based sweat-sensing on-skin interface. Microfluidics is the technique of manipulating fluids at a very small scale [55]. The basic components of microfluidic devices are *channels* and *chambers*. *Channels* serve as fluidic paths; the fluids will travel along the channels. With the channels, the flow of the fluids can be controlled. *Chambers* in microfluidic devices are small reservoirs that can hold the fluids. With reagents in the chambers, the fluids can be measured and analyzed.

The measurement method we exploit in this paper is the colorimetric technique [2]. When the sweat comes into contact with the colorimetric assay, the color of the assay will change according to the existence or concentration of specific ingredients in the sweat. For interpreting the results, users have two options. Firstly, they can directly match the resulting color with the color chart derived from our technical characterization (Fig. 8 and Fig. 11). This approach mirrors regular test strips, offering an intuitive and effortless method. Alternatively, users can employ a smartphone application to scan the color, providing a more precise interpretation. However, this method demands taking out the smartphone and performing the scan. All the colorimetric assays we select are easy to obtain from common sources such as supermarkets or pharmacies. More specifically, we leverage the test strips commonly used for urine tests, pool water, drinking water, or popular science projects. Because of the simplicity and rapidity, the resulting device can support real-time analysis while maintaining accessibility.

4.2 Device Fabrication Overview

We propose four colorimetric measurements for sweat analysis in this paper. Different biological information can be derived with the color change and further support diagnostic applications [14]. First, the chloride test paper (FUNSWTM Drinking Water Test Strips) will change its color from deep brown to light brown when the concentration of chloride ions is higher, and the electrolyte level can be derived [6]. Second, the pH test paper (Hydrion pH Strips pH Range 2.0-10.0) is used to measure the pH value of sweat. When the sweat is more acidic, the test paper will be redder, while when the sweat is more alkaline, the test paper will be greener. With the pH value, the hydration state can be predicted [40]. Third, according to the glucose concentration, the glucose test paper (Diastix Reagent Strips) will change its color from light blue to deep brown. The blood sugar level can be extracted from the concentration of glucose [56]. Fourth, the cobalt chloride test paper (Bartovation Cobalt Chloride Test Paper), which is generally used for moisture and humidity detection, will perceive the existence of sweat. The paper will be blue when dehydrated and turn pink when hydrated. We use this test paper to create the *analysis channels* (Section 3.5). Based on the range of the pink area, we can tell the amount of sweat absorbed by the test paper and thus derive the sweat loss and sweat rate.

On the other hand, filling the channels with indicators to create analysis channels is a similar idea to the additive channel manufacturing approach. For the paper-based methods, we simply replace the paper used for the channels with the test paper. However, for the polymer-based methods, or the subtractive manufacturing approach, the channels should be empty before the fluids come in. Also, the polymers are more stretchable than the test paper. Hence, putting the test paper in the channels of polymer-based devices is not advisable. To address these issues, we propose mixing the reagent dissolved from the test paper, cobalt chloride ($CoCl_2$), with gelatin-based hydrogel and applying it to the channel to form a thin indicator film on the channels (Section 3.4).

Overall, the proposed device consists of three layers (Fig. 4 (a)). From the closest proximity to the skin, the first layer, known as the *harvesting layer*, serves as the adhesive layer that attaches the interface to the user's skin. This layer is waterproof primarily to protect the channels and chambers. Still, it has a small harvesting area that is open to the skin to collect sweat from pores on the skin's surface and direct it into the channels in the next layer.

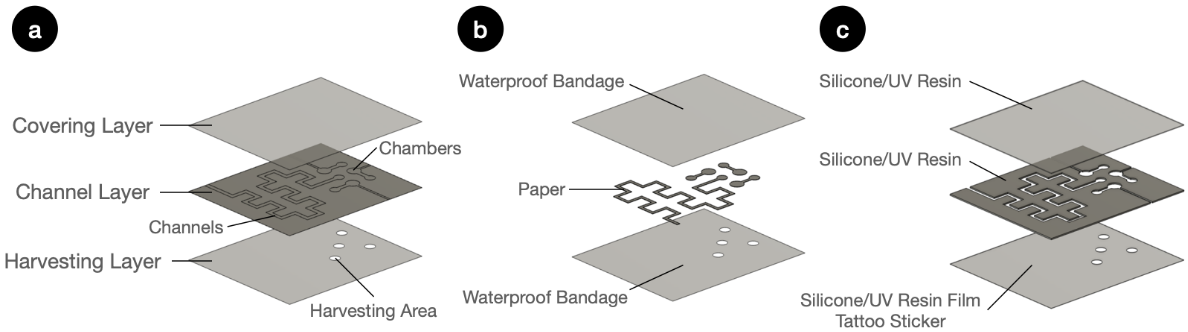

Fig. 4. SweatSkin device structure: (a) general design, (b) paper-based device, and (c) polymer-based device.

The second layer is the *channel layer*, which contains microfluidic channels that route the collected sweat to different chambers for analysis. Choosing the appropriate channel size involves careful consideration of several factors. Opting for thicker, wider, and/or longer channels corresponds to an increase in the overall capacity to accommodate sweat, thereby raising the activation threshold of the device. Additionally, the overall dimensions of the device itself will impose constraints on the size of the channels. On the other hand, the design of the channels is various (Section 3.5). The shape can be designed to make the measurement easier or achieve aesthetic customization. For example, when considering the analysis channel for sweat loss, the absorbed volume can be calculated by utilizing the known cross-sectional area of the channel in conjunction with the travel distance. We present the curved analysis channel. Each segment of the curved channel has the same length, which means the amount of absorbed sweat will be the same. This design can help the wearer to approximately measure the total sweat loss more easily. This design facilitates a simplified estimation of total sweat loss for the wearer. By simply counting the number of channel segments the sweat has traversed and multiplying it by the amount of sweat each segment can absorb, the wearer can attain an approximate measurement of total sweat loss with a glance.

The chambers at the end of the channels contain test papers that allow for other analyte measurements (Section 3.3). Analytes are the substances whose chemical constituents are identified and measured. The dimensions of the chambers primarily influence the visibility of the resulting color change, thus inherently shaping the user-friendliness of data interpretation. Both channel and chamber sizes can be customized to meet diverse application needs. Generally, smaller channels necessitate less sweat volume to activate sensors, while larger channels can accommodate more sweat. Similarly, smaller chambers lead to reduced color change visibility, while larger chambers enhance it. The dimensions of the device (Fig. 13 (a1), (b1)) we used for demonstration and user study in this paper were determined from optimal recommendations from prior research [4, 40].

The third layer is the *covering layer*, which is waterproof and protects the channels and chambers. With this three-layer microfluidic structure, the device enables the wearer to monitor the health condition.

4.3 Supporting Software Design Tool

We developed a supporting software design tool to facilitate the user-friendly design of customized sweat-sensing interfaces. Based on the wearer's body size and the body location with where the device is worn, the preferred device size can vary [89]. Thus the design tools support device size customization. Also, the channels' size and segment length can vary to tackle the individual differences in sweat profiles. With the tool, it is possible to customize the monitoring analytes as required to get personalized health information. Furthermore, the design tool can simulate the resulting device to make it easier to envision its appearance.

The workflow of SweatSkin involves four key steps:

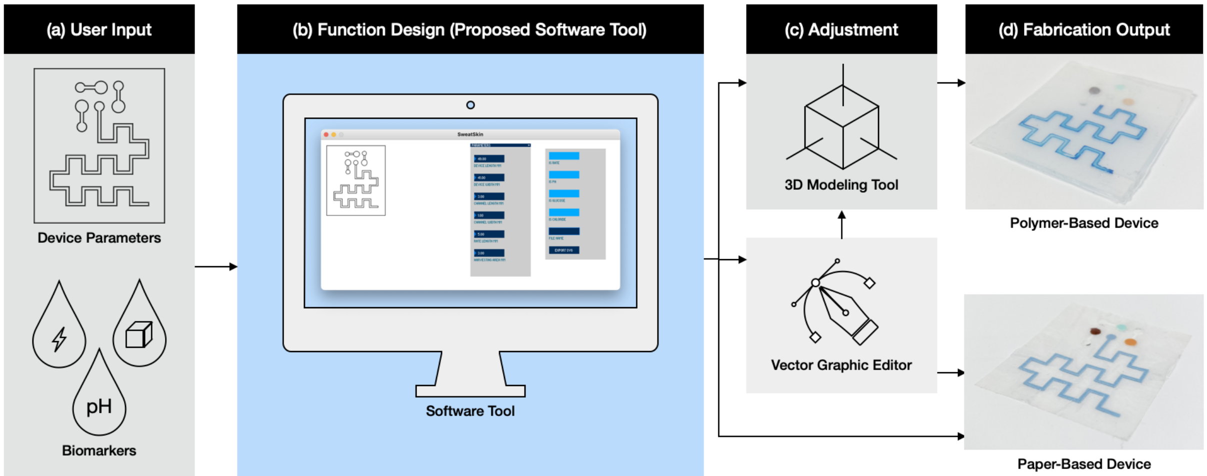

Fig. 5. The workflow of SweatSkin: First, (a) the user determines the parameters of the device and the biomarkers they are interested in measuring. Second, (b) with the input from the previous step, the user can generate the basic design of the device and export an SVG file with the support software tool we developed. Third, (c) the SVG file can be imported into a 3D modeling tool to generate the molds for making polymer-based devices or a vector graphic editor to make some further designs. Last, (d) with the molds or the vector designs, polymer- or paper-based devices can be fabricated, respectively.

(1) User input. (Fig. 5 (a)) The user begins by determining the parameters of the device and identifying the specific biomarkers they wish to measure. The user has the flexibility to determine the quantity and specific biomarkers (Section 3.3) they wish to measure using the device. For example, in the device designed for the user study (Fig. 13), four biomarkers, including chloride, glucose, pH value, and sweat loss, could be measured. Furthermore, customization options include the dimension of the channels, influencing the required sweat volume for activation, and the dimension of the chambers, affecting the visibility of colorimetric outcomes. Additionally, the length of the analysis channel, utilized for sweat loss measurement, can be tailored to accommodate diverse sweating scenarios. This step allows users to customize the functionality and scope of their device, tailoring it to their individual needs.

(2) Function design with the proposed software tool. (Fig. 5 (b)) With the input from the previous step, the user can generate the basic design of the device using the software tool we developed. This tool is implemented with Processing and offers a user-friendly interface for designing the device. The software tool not only supports customization but also facilitates parameter configuration. Once the design is complete, the user can export the design as an SVG (Scalable Vector Graphics) file. The SVG file serves as the blueprint for the device fabrication process. It contains all the necessary information for creating the device, including the dimensions, shapes, and placement of various components. The SVG file can be shared, stored, and used for future reference. It provides a clear and comprehensive representation of the device design, ensuring consistency and accuracy.

(3) Adjustment. (Fig. 5 (c)) For polymer-based devices, the SVG file can be imported into a 3D modeling tool to generate molds that will be used in the fabrication process. For paper-based devices, the SVG file can be imported into a vector graphic editor to make further designs and adjustments, enhancing the aesthetic appeal of the device. In some cases, the adjusted design from the vector graphic editor may also be imported into the 3D modeling tool for mold generation.

(4) Fabrication output. (Fig. 5 (d)) The user proceeds to fabricate the device based on the generated molds or vector designs. For polymer-based devices (Section 5), the molds are used to cast silicone or UV resin, resulting in the final device. On the other hand, paper-based devices (Section 6) are constructed using crayons or cut paper, following the design outlined in the SVG file.

5 FORM FACTOR 1: PAPER-BASED DEVICES

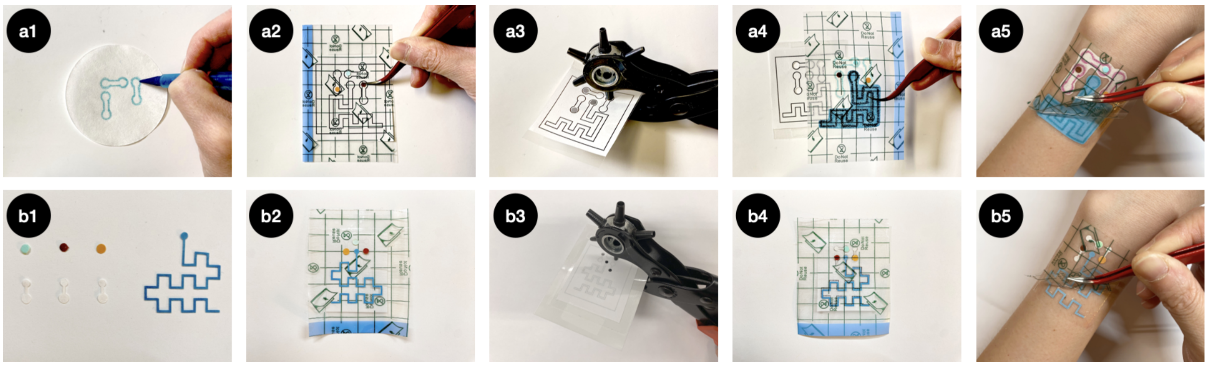

Fig. 6. The workflow of fabricating paper-based devices using (a) wax and (b) cut paper as hydrophobic barriers. Step 1 (a1, b1): Create the channels. Step 2 (a2, b2): Position the test paper and channels. Step 3 (a3, b3): Punch the harvesting area. Step 4 (a4, b4): Seal the device. Step 5 (a5, b5): Apply the device onto the skin using the same method as applying a sticker.

Paper-based microfluidic devices are commonly used for bioassay and medical and forensic diagnostics, e.g., pregnancy and rapid COVID-19 tests [51]. In addition, being cheap and handy, paper is a popular prototyping tool [66, 91, 92]. To address accessibility, paper-based devices are proposed. In this form factor, the capillary action of the paper is used to draw sweat from the skin's surface to the channels and chambers created on the paper. Two methods are presented to create the hydrophobic barrier to form the channels and chambers.

5.1 Fabrication Implementation Workflow

5.1.1 Wax as A Hydrophobic Barrier. For the harvesting layer (Fig. 4 (b)), a waterproof bandage is used to prevent the sweat from directly contacting the channels and chambers and serve as the adhesive to the skin. Round harvesting areas ($7.07mm^2$ and $3mm$ diameter) can be cut with hands, a puncher, or a vinyl cutter.

In the channel layer (Fig. 4 (b)), channels and champers are made by applying hydrophobic wax to the filter paper along the outline of the channels and chambers, which creates a barrier to form channels and guides the sweat to the chambers. To apply the wax, various techniques have been proposed, including wax printing [9] and screen printing [15]. Considering the accessibility of the tools, we selected the method of hand drawing with wax crayons (Crayola Crayons). The design from the software tool is printed out as a tracing template. A laser-cut or vinyl-cut template can also be used to facilitate the drawing. After applying the wax, the filter paper needs to be baked in the oven at a temperature over 65°C, the melting point of the crayons. The melted wax can then be absorbed by the filter paper and create the barrier.

Another piece of waterproof bandage is used for the covering layer (Fig. 4 (b)). The adhesive on the bandage can help with binding the three layers. The channel layer can be first pasted on the covering layer and then sandwiched with the harvesting layer. The overall thickness is around $300\mu m$.

5.1.2 Cut Paper as A Hydrophobic Barrier. The fabrication of the harvesting layer and the covering layer is the same as the previous method. To create the channel layer, filter papers are directly cut into the shape of the channels and chambers. The cutting can be done by hand or using a vinyl cutter. The SVG file generated by the software tool can be fed to the vinyl cutter. Since the harvesting layer and covering layer are hydrophilic, sweat can only travel in the cut paper channels and thus be directed to the relative chambers. The channel layer is sandwiched by the harvesting layer and the covering layer to complete the device. Note that once all the layers have been stacked, it is advisable to apply pressure and gently slide across the surface of the device. This action ensures that all the layers are firmly adhered together. Failing to achieve proper adhesion could result in gaps forming between the layers, inadvertently creating new unintended channels. These unintended channels have the potential to lead to sweat leakage, undermining the functionality of the device. The overall thickness is around 300μm.

5.2 Technical Characterization

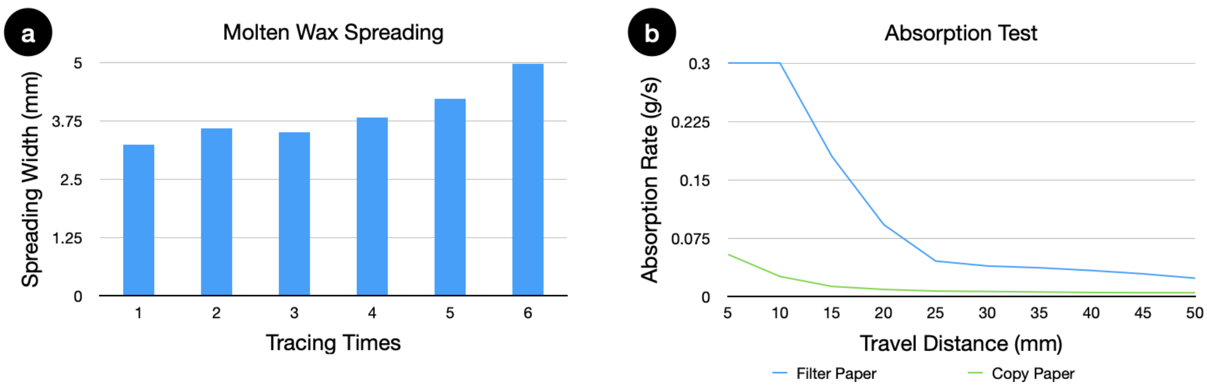

Fig. 7. (a) The results of the molten wax spreading test. (b) The results of the absorption test.

5.2.1 Molten Wax Spreading Test. Since the crayon strokes always contain cracks, tracing multiple times can prevent the cracks and, thus, the leakage. However, from more repetitive traces, there will be more applied wax. Due to capillary action, the molten wax will spread on the paper and may block the channels or chambers. To understand the appropriate number of tracing times, we conduct the molten wax spreading test [9]. To control the drawing force, we used a vinyl cutter with a pen holder to draw the traces. The drawing force is set to 210gF, and six tracing times (1-6) are drawn. The drawings were then baked in an oven at 70°C for 30 minutes. We repeated this test three times for each sample. We stopped at six tracing times, as our pilot study showed that a 3-mm wide channel was the thinnest channel that was easy to draw with crayons by humans. Drawing four times already resulted in traces thicker than the channel, and we did not want to draw thicker traces. The spreading of the wax is then measured and recorded (Fig. 7). Based on our results, we landed on four repetitive traces as the ideal number of tracing times according to the channel width. This number provides a good balance between reducing gaps and avoiding channel blockage caused by the spreading of wax.

5.2.2 Absorption Test. We conducted an absorption test to evaluate the absorbency and absorption rate of different types of paper. Two paper types were examined: copy paper and filter paper (AeroPress Microfilters). Copy paper was selected as the baseline due to its widespread usage in daily life. Filter paper is commonly employed in paper-based microfluidic devices [9, 16]. For the experiment, the papers were cut into strips measuring $7mm * 50mm$ and submerged in water for ten minutes to ensure complete water absorption. This process was repeated five times for each paper type. The average change in weight resulting from water absorption was measured and recorded as the amount of water absorbed by the paper.

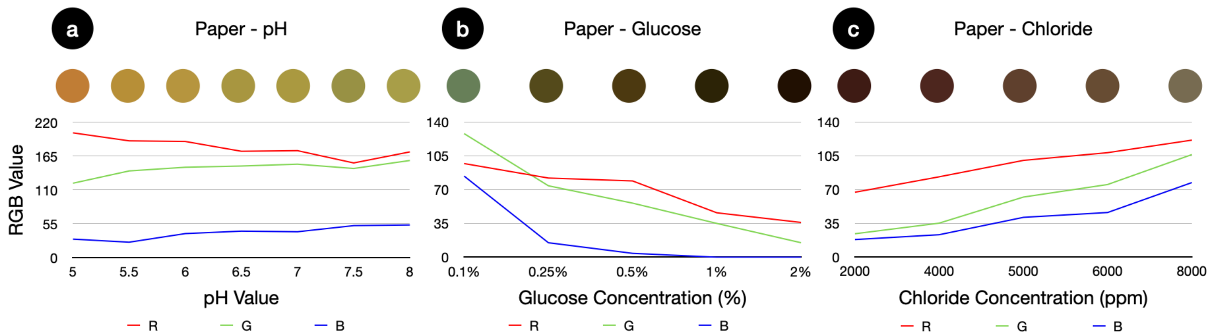

Fig. 8. Artificial sweat test results: The captured RGB color change of the test paper when the device successfully collected artificial sweat with different (a) pH values and (b) concentrations of glucose and (c) chloride.

To measure the absorbing rate, the two types of paper strips were dipped into the water at one end, and the traveling distance and the relative time were recorded. The following formula can then calculate the absorbing rate: $Rate = ((AbsorbingWater \div 50) \times Distance) \div Time$. Based on the results, the filter paper has a higher absorption rate. In addition, filter paper is easy to get from supermarkets. As a result, filter paper is suggested to be used as an easily accessible material to fabricate paper-based microfluidic devices.

5.2.3 Artificial Sweat Test. An artificial sweat (ISO standard ISO 3160-2) test was conducted to evaluate the device's functionality. To simulate human eccrine sweat glands, we developed an artificial sweat pore system based on previous work [29, 40]. The system consists of a perforated PI membrane mounted in a fixture with a fluid reservoir connected to a syringe pump. The sample devices, featuring a 3-mm circular harvesting area, a $1mm * 3mm$ microfluidic channel, and a 4-mm circular chamber with test paper inside, were attached to the membrane so that the artificial sweat could be pumped into them. Artificial sweat with different pH values and concentrations of glucose and chloride was used for testing. The artificial sweat was absorbed from the harvesting area, guided by the channel, and absorbed by the test paper in the chamber. The color change of the test paper was captured and recorded using a smartphone application. The process is repeated three times for each sample. The results (Fig. 8) demonstrate a strong correlation between the captured RGB values of the color change in the detection chamber and the corresponding pH values or concentrations. All samples successfully absorbed and conveyed the artificial sweat to the chambers with test paper, resulting in clear color changes that varied with different artificial sweat samples. The distinct color changes observed indicate that wearers can easily interpret the colorimetric results obtained from our proposed devices. These color changes can be translated into relevant pH values or concentrations, providing insights into the hydration state, blood sugar level, or electrolyte level. Overall, the artificial sweat test validates the feasibility and functionality of the device.

6 FORM FACTOR 2: POLYMER-BASED DEVICES

The device is mainly made of polymer for this form factor. Different polymers have been proposed to fabricate soft microfluidic devices in HCI [57, 78]. In this paper, we propose devices made with two common handcrafting polymers, platinum-catalyzed silicone rubber (Ecoflex 00-30) and soft UV resin (Miraclekoo UV Resin Soft Type), which are commonly seen in craft stores. These devices take advantage of the combination of capillary action and pressure change to direct the flow of sweat through the tube-like channels and into the chambers.

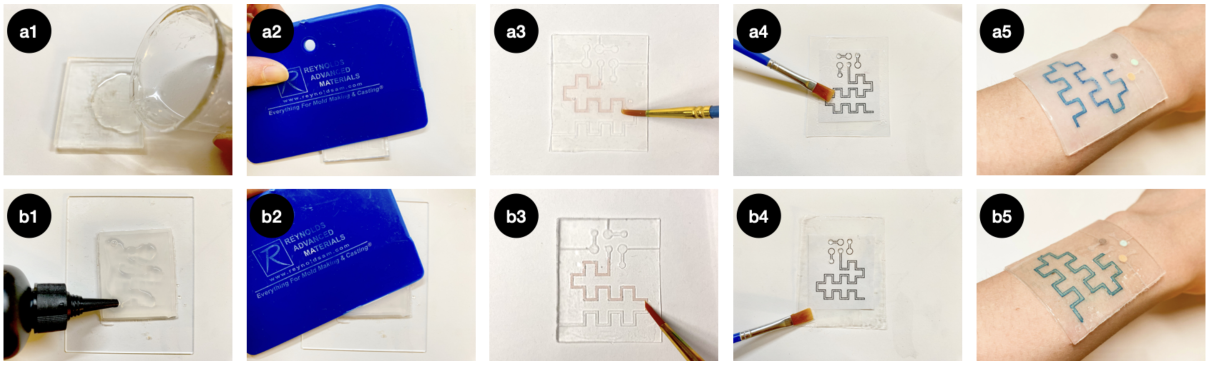

Fig. 9. The workflow of fabricating polymer-based devices using (a) silicone rubber and (b) UV resin. Step 1 (a1, b1): Cast the polymer in the mold. Step 2 (a2, b2): Scrap the exceeded polymer. Step 3 (a3, b3): Apply the hydrogel and test paper. Step 4 (a4, b4): Glue and seal the device. Step 5 (a5, b5): Apply the device onto the skin using the same method as applying a sticker.

6.1 Fabrication Implementation Workflow

Since silicone rubber and UV resin are hard to stick to other materials after curing, we directly cast a thin-film layer of the polymers on the tattoo sticker to create the harvesting layer (Fig. 4 (c)). Mixing part A and part B in a 1:1 ratio by weight or volume means the silicone rubber will cure at room temperature without significant shrinkage. The UV resin cures under a UV LED lamp for 2-4 minutes. The harvesting area can then be cut off with hands, a puncher, or a vinyl cutter.

The fabrication of the channel layer and the covering layer depends on the manufacturing process of molding (Fig. 4 (c)). 3D-printed (FormLabs Form 3) molds are used to shape the polymers. The mold is a negative version of the device's final shape. By pouring the polymers into the mold, they will be shaped after curing. After curing, the indicators can be applied to the chambers or analysis channels. Then, the channel and harvesting layers can be combined with silicone (3rd Degree Silicone) or UV resin. It should be recognized that the silicone and the UV resin function as the *glue* to bind the layers together in this step. It is important to ensure that the glue is spread evenly across the entire surface to guarantee proper device adherence and prevent any leakage. The overall thickness is around $650\mu m$.

6.2 Technical Characterization

6.2.1 Capacity Test. To understand the amount of sweat the devices can contain, we made 6 $100mm \times 10mm \times 650\mu m$ samples, with a $100mm \times 1mm \times 300\mu m$ channel. Three of the samples were applied with the hydrogel reagent, while the other three remained empty to explore whether the reagent would affect the capacity. According to the volume of the channel, it can contain $30.0\mu l$. The results indicate that the empty channel can contain $27.0\mu l$ on average, while the channel with hydrogel can contain $24.3\mu l$. To sum up, the hydrogel does not affect the function of the channels.

6.2.2 Stretchability Test. To understand the stretchability of the devices, we made 3 $10mm * 50mm * 650\mu m$ samples (without channels, with a $300\mu m$ thick $1mm$ wide horizontal channel, and with a $300\mu m$ thick $1mm$ wide vertical channel) and tested the tensile strength using Instron Universal Testing System (Instron 5566). Based on the results (Fig. 10), the silicone-based samples can all be stretched to more than three times their original length. Once cured, the silicone rubber is soft, strong, and highly stretchy, making it an ideal material for use as an on-skin interface. Its flexibility and durability make it well-suited for use in a device that will be worn on the skin for an extended period of time. On the other hand, the UV resin samples can all be stretched to more than

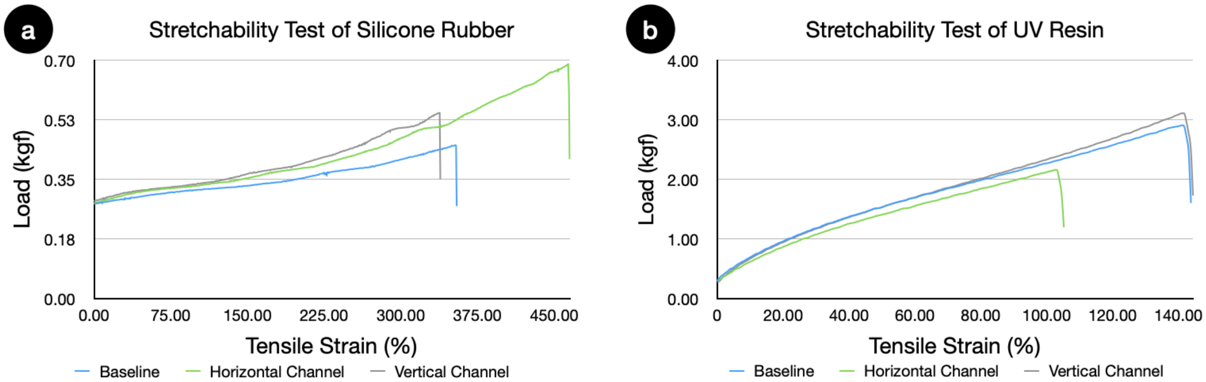

Fig. 10. The results of the stretchability test: (a) silicone rubber and (b) UV resin.

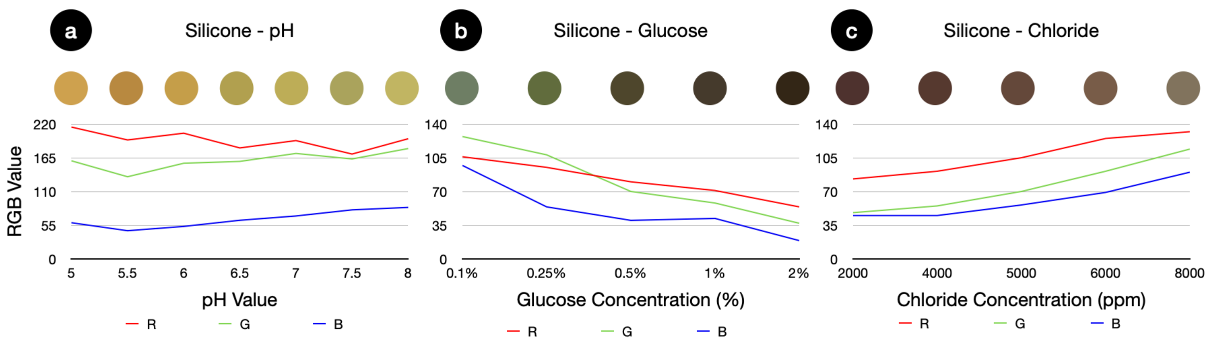

Fig. 11. Artificial sweat test results: The captured RGB color change of the test paper when the device successfully collected artificial sweat with different (a) pH values and (b) concentrations of glucose and (c) chloride.

1.4 times their original length. While UV resin is not as stretchable as silicone rubber, its high opacity allows the wearer to clearly decipher the colorimetric results.

6.2.3 Artificial Sweat Test. The same experimental setup as described in Section 5.2.3 was employed. Sample devices with a 3-mm circular harvesting area, a $1mm * 3mm * 0.3mm$ microfluidic channel, and a 4-mm circular chamber with test paper inside were utilized for the tests. The RGB values of the color change of the test paper, induced by the absorbed sweat, were captured and recorded using a smartphone application. Each sample was tested three times to ensure reliable results. The obtained results (Fig. 11) demonstrated the successful collection and direction of artificial sweat to the chambers with test paper in the sample devices. The observed color changes were visually distinguishable, suggesting their potential to be easily translated into relevant pH values or concentrations. It has been observed that the colors obtained are not consistent with the ones of the paper-based devices. This difference is caused by varying levels of transparency in the covering layer. This experiment serves as a validation of the device's capability for real-time sweat analysis in on-skin applications.

7 EVALUATION

We conducted two user studies to evaluate the feasibility and user-friendliness of the SweatSkin platform. In the first study, we invited domain experts to explore the potential applications of on-skin sweat-sensing devices.

This study aimed to gain insights into sweat-sensing devices' various potential uses and requirements. In our second study, we invited general users to fabricate on-skin sweat-sensing devices using our SweatSkin platform to evaluate the user-friendliness of our platform.

7.1 Study 1: Understanding Envisioned Usage of On-Skin Sweat-Sensing Devices

This study aims to explore the potential usage scenarios of on-skin sweat-sensing devices and identify the customization considerations. Specifically, we used the devices developed with the SweatSkin platform as a material probe [32] to draw insight into the emergent materialities and envisioned applications and customization perspectives towards the device. While almost everyone participates in exercise and sports on some level, we particularly engaged athletic experts with extensive experience with the body under sweating scenarios, including student-athletes, athletic coaches, and athletic trainers, for their deeper understanding of the demands and physiological responses of the body under sweat. The insights provided by these professionals carry significance not only for athletes but also for individuals following regular exercise routines. Moreover, by understanding how to improve the devices' efficacy in such demanding situations, i.e., the athletic scenarios with intense sweating and vigorous body movement, their utility can be extended to various everyday contexts.

7.1.1 Participants & Study Protocol. To gain insights into SweatSkin devices under sweat-generating activities, we recruited five athletic domain experts (Table 1). The participants were recruited with snowball sampling at a local university. The participants comprised three males and two females, aged 19-52 (M = 33.8, STD = 13.83). One participant was an athletic coach, two were athletic trainers, and the remaining two were student-athletes. All participants in the study had over ten years of experience in athletics.

Table 1. The demographic information of the participants in Study 1.

Pseudonym	Gender	Age	Role	Expertise	Athletic Experience
Avery	M	52	Coach (College Level)	Physical Education	20 Years of Coaching (Football)
Bobby	F	44	Athletic Trainer (College Level)	Athletic Training / Exercise Science	19 Years of Athletic Training (Gymnastics, Swimming and Diving, Volleyball, Women's Lacrosse)
Camille	F	19	Athlete (National Level)	Ice Hockey	National Level Athlete (Ice Hockey)
Drew	M	24	Athlete (National Level)	Tennis	National Level Athlete (Tennis)
Erin	M	30	Athletic Trainer (College Level)	Athletic Training / Kinesiology	10 Years of Athletic Training (Football, Tennis, Heavyweight Rowing)

The study consisted of three sections, with a total of 60 minutes to complete:
(1) SweatSkin introduction (10 mins). The study commenced with an introductory section where we provided a concise overview of the functions and capabilities of the on-skin sweat-sensing devices we proposed. The participants were informed that the devices crafted using the SweatSkin platform could visualize sweat loss, chloride, glucose, and pH values. Furthermore, these measurements could potentially provide insights into sweat rate, electrolyte levels, blood sugar levels, and hydration states, respectively. We also discussed the advantages and disadvantages associated with the different form factors. This introduction aimed to familiarize the participants with the key aspects and considerations of on-skin sweat-sensing technology.

(2) SweatSkin device tryout (10 mins). To provide the participants with firsthand experience of wearing our devices, we facilitated a wearability trial section where they had the opportunity to try out our devices in two form factors: a paper-based device with cut paper as a hydrophobic barrier (Fig. 3 (a1, a2)) and a polymer-based device with silicone rubber as a substrate (Fig. 3 (c1, c2)). The participants were encouraged to engage in various activities and move around freely while wearing the devices. This allowed them to gain insights into the comfort, flexibility, and overall user experience of our proposed on-skin sweat-sensing devices in different form factors.
(3) Semi-structured interview (40 mins). Following the trial section, we conducted a semi-structured interview with the participants to gather insights into the potential applications of personalized on-skin sweat-sensing interfaces and their efficacy in various sweating scenarios, particularly during physical activities such as sports. The interview focused on understanding the participants' perspectives on the practicality, benefits, and challenges of using these devices in real-life situations. The discussion concerned how the devices could enhance performance monitoring, hydration management, and overall well-being during physical exertion and other sweating-related activities.

7.1.2 Analysis. Audio recordings of the semi-structured interviews were manually transcribed to identify salient themes, outlined in the Observations section (Section 7.1.3) below. All qualitative data underwent iterative coding conducted independently by two researchers. Then, all of the authors discussed the meaning of the text to identify common themes. In both stages, we used codes with a reasonable degree of agreement among the coders to identify salient themes based on thematic analysis [8].

7.1.3 Observations. Our analysis of the feedback received from the participants yielded the following themes:
Envisioned Usage Scenarios. We observe the following usage scenarios for a sweat-sensing device:

- For Training and Practice. During repetitive and outdoor activities, it is common to have an increased sweat rate without realizing it. Therefore, it is crucial to receive alerts and reminders so that *"you would visually see it and know when it's getting into a dangerous area and know to replenish"* (Bobby). Avery and Erin also emphasized the importance of timely replenishment and hydration. This concept can be extended to the wider user base, emphasizing the significance of maintaining awareness about one's personal health conditions.
- For Use During Sports Game. In a sports game, players are usually entirely focused on the game and may ignore their hydration status and electrolyte levels. Avery and Bobby believed that a sweat-sensing device could provide just-in-time notifications to remind them to replenish fluids and electrolytes. On the other hand, in endurance races such as marathons and triathlons, glucose intake is critical for sustaining performance. Real-time glucose monitoring can help athletes determine the optimal timing for replenishment and avoid energy depletion. This holds potential for general users as timely health monitoring and alerts are critical during intensive and extended activities, like field days or regular jogging.
- For Use Post Game. As Camille mentioned, *"in the game, I'm obviously going to be hydrating, but in the recovery process after the game, I'll see that I could have done this, this, and this better."* Athletes often neglect their nutrition intake during recovery sessions, so monitoring the electrolyte level can help maintain performance. Furthermore, when returning from an injury, the training load could be adjusted based on the change in sweat rate. Sweat-sensing devices can be particularly useful in such situations. This also holds relevance for general users, particularly when transitioning to new environments, where customized health monitoring becomes particularly prominent.
- For Everyday Use. Bobby appreciated the non-invasive nature of the device, suggesting that *"you could use it on the elderly population in hospitals where instead of having to do blood draws, they could slap one of these on the skin."* While Camille envisioned to *"use it with people with certain health issues with their blood sugar."* These highlighted the applicability beyond athletes or regular exercisers.

Customization Considerations. Erin highlighted the significance of customized designs that align with body sizes to ensure result in consistency across users. He pointed out, *"There's so many different size athletes and students and things along those lines, which changes what we need to do based on that."* Moreover, the placement of the device and its size should be customized according to the specific application. For example, in American football, where there is a lot of body contact and the bodies are fully covered, the device should be placed somewhere less likely to be contacted, such as the back of a calf (Avery). However, for sports like running, placing the device on the upper forearm is recommended for easy checking by the wearer (Bobby). Athletes may also have their own nutrition intake strategy (Drew). With the device tracking the nutrition they are not willing to have before or during the game, they can be notified when it comes to a danger zone and replenishment is required. Overall, users are encouraged to customize the device according to their specific needs. This involves considering device dimensions that suit their body size, ensuring result consistency, selecting a device placement that minimizes its impact on activities, and determining the necessary monitoring data.
Comparison with Other Wearable Devices and Objects. Compared to other commercialized health-monitoring wearable devices, such as Whoops [83] and Apple Watch [1], the device we proposed is unique in its thin, soft, and passive design without any solid electronic components. The conformable form factor can enhance comfort and reduce the risk of the device breaking during severe physical activities. In addition, other on-skin products like KT sports tape and knee braces are already commonly used by athletes. The proposed device's thin and soft form factor allows for seamless integration with these on-skin wearables. Furthermore, Avery suggested that our sweat-sensing device could be cooperatively used with *"heart rate monitors or anything that monitors workload or the person's exertion level."* This can improve the accuracy of our readings and provide more comprehensive monitoring of health conditions. By better understanding an athlete's physical state and performance, coaches and trainers can develop personalized training plans for better performance and safety. This principle is equally applicable to general users, as individual health profiles vary. Customized health plans can significantly enhance overall health improvement strategy.
Potential Challenges in Real-World Applications. While participants acknowledged the affordability and battery-free operation of the devices, some expressed concerns about the potential inadvertent fall-off, particularly in situations involving unavoidable friction (Avery, Drew, Erin). Additional adhesion reinforcement methods, like supplementary tape, could be considered. Camille raised concerns about potential issues for individuals with sensitive skin. While skin-safe materials are used for fabrication, consultation of skin concerns with healthcare providers is suggested. In addition, Bobby expressed interest in the potential of the device working underwater. While this would require an additional protective layer and subsequent experiments, it underscores our battery-free design.

While on-skin sweat-sensing interfaces are usually single-use, monitoring health should be done daily. However, off-the-shelf sweat patches can cost more than $6 each [21, 59], making them unsuitable for everyday use. In contrast, our proposed device can be made for less than $1 USD per unit. With a low-cost and customizable sweat-sensing interface, we can take a step closer to personalized healthcare [93]. Overall, there is a need for customizable and affordable sweat-sensing interfaces to make everyday sweat detection accessible to everyone.

7.2 Study 2: Evaluating the User-Friendliness of the SweatSkin Fabrication Platform

This study aims to evaluate the user-friendliness of the proposed fabrication methods by assessing the ease of learning and execution, particularly for individuals with limited experience or expertise in digital fabrication.

7.2.1 Participants. A total of ten participants comprised of two males and eight females aged 24-30 (M = 27, STD = 2.78, one preferred not to state their age) took part. Participants were recruited via the mailing list of a local university. A pre-study survey was used to collect participants' demographic data and past experiences with software design tools, digital fabrication, and handcrafting. Eight of the participants have a STEM background (e.g., Information/Computer Science), and the other two participants have a design background (e.g., Design, Architecture). Participants self-reported varying levels of proficiency in using 2D (M = 4.3, STD = 2.33 on the Likert scale; 1 = novice, 7 = expert) and 3D (M = 3.3, STD = 2 on the Likert scale; 1 = novice, 7 = expert) design tools and different frequencies of engaging in hands-on activities, ranging from once a year to nearly daily.

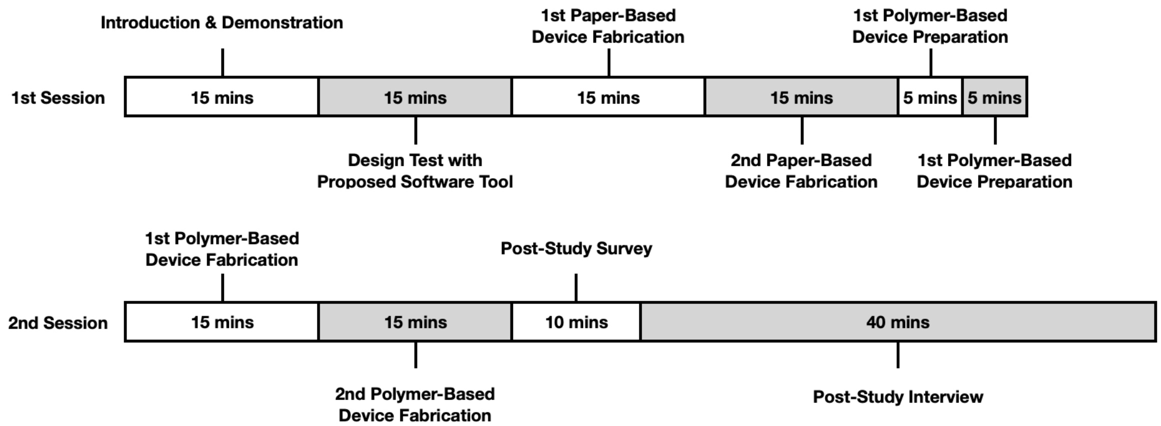

Fig. 12. Fabrication study structure.

7.2.2 Study Protocol. To evaluate the feasibility and accessibility of our SweatSkin fabrication platform, we conducted a 150-minute two-session fabrication user study (Fig. 12), following other on-skin interface prototyping work [37, 42]. The study was divided into two sessions due to the four-hour curing time of the silicone rubber used. The goal of these sessions was to gain a preliminary understanding of how easy it is to learn and execute the proposed fabrication methods for general users. The first study session lasted around 70 minutes:

(1) SweatSkin introduction (15 mins). The first session began with an introductory overview of the SweatSkin platform. We specifically focused on explaining the underlying techniques that support the platform, including microfluidics and colorimetric analysis. Furthermore, we provided an overview of the accompanying software tool (Section 4.3) and detailed information about the four different fabrication methods available within the platform. The purpose of this section was to ensure that participants were well-prepared and acquainted with the platform for the subsequent study.

(2) Design test with proposed software tool (15 mins). Participants were asked to replicate a basic design (Fig. 13 (b1)) with the developed software tool. This aimed to assess the ease of learning and proficiency in using the software tool. The participants were provided with a paper design template containing the necessary parameters to follow.

(3) First paper-based device fabrication (15 mins). To make the paper-based device with wax as a hydrophobic barrier (Fig. 13 (a1, a2)), participants were instructed to trace the design using crayons, following the provided paper template (Fig. 13 (a1)). Given the challenges of drawing intricate designs with crayons at such a small scale, we modified the design by scaling it up for easier fabrication. Furthermore, participants had the freedom to choose any color they preferred for their device design. They were encouraged to express their creativity and personalize the appearance of their devices by selecting colors that resonated with them. Once the channel layer was drawn, it was placed between a piece of covering layer adhesive and a piece of harvesting layer adhesive with pre-punched harvesting areas, forming a sandwich-like structure. Finally, we placed the device in the oven at 70°C for ten minutes while participants proceeded to fabricate the next device.

(4) Second paper-based device fabrication (15 mins). To fabricate the paper-based device with cut paper as a hydrophobic barrier (Fig. 13 (b1, b2)), participants were instructed to carefully position the pre-cut channels and test paper on the covering layer adhesive, using the given paper template for alignment assistance. A paper template was given to assist with alignment. Once the channels and test paper were correctly positioned, participants sandwiched them between the covering layer adhesive and the harvesting layer adhesive, forming a layered structure. This assembly created the paper-based device, ready for further testing and use.
(5) First polymer-based device preparation (5 mins). To fabricate the silicone-based device, participants were given a pre-printed mold and instructed to pour silicone into the mold. After pouring the silicone, participants used a scraper to ensure the device had the correct thickness by smoothing it across the mold.
(6) Second polymer-based device preparation (5 mins). To prepare for fabricating the UV resin-based device, participants were given a pre-made silicone mold and instructed to cast UV resin into the mold. The participants then scraped through the mold with a scraper to ensure the correct thickness of the device. The device was then placed under a UV lamp for curing.

The 80-min second session was conducted at least five hours apart to allow the silicone rubber to cure thoroughly:
(1) First polymer-based device fabrication (15 mins). To complete the fabrication of the silicone-based device, participants were first asked to remove the cured device from the mold carefully. Then, they were instructed to apply the CoCl2 hydrogel and test paper to the device. Finally, participants were guided to attach the device to the harvesting layer adhesive using 3rd-degree silicone as glue.
(2) Second polymer-based device fabrication (15 mins). The process of fabricating the UV resin-based device was similar to that of the silicone-based device, with the difference being the use of UV resin as the adhesive.
(3) Post-study survey (10 mins). The participants were asked to fill out a post-study survey on a 7-point Likert scale (1 = strongly disagree and 7 = strongly agree) to assess the feasibility and wearability of the devices. Prior to the survey, participants were instructed to wear the devices they had fabricated, allowing them to experience the device firsthand while freely moving and interacting during the survey and the following interview.
(4) Post-study interview and wearability experience (40 mins). We conducted a semi-structured interview to gather insights into the participants' perceptions of the fabrication process and their experience wearing the devices they had created. This approach aimed to capture their genuine reactions and feedback regarding the fabrication process and wearing comfort.

7.2.3 Analysis. For the software design test, we validated the results by comparing the design made by the participants with the proposed design. To validate the device fabricated by the participants, we pumped water inside the devices fabricated by the participants using the same method as our artificial sweat test (Section 5.2.3). For the semi-structured interview, we analyze with the same method as described in Section 7.1.2.

7.2.4 Results. All ten participants successfully completed the designated tasks, and there were no significant differences between their designs and our proposed design. All devices fabricated by the ten participants were functional per our artificial sweat test. Below, we elaborate on the participants' experiences using the software support tool, their reactions toward the four fabrication methods, and their experience of wearing the fabricated devices.
Designing with the SweatSkin Software Tool. Based on the survey results, the participants found it easy to make a design with the proposed software tool (M = 6.1, STD = 0.94 on the Likert scale; 1 = strongly disagree, 7 = strongly agree on ease of usage). They also found that the software design tool provided a lot of feedback and guidelines on making the design and gave them a better idea of what the device would look like (P1, P4, P6, P7, P9, P10). Additionally, with the real-time simulation of the device design, the participants found it useful to visualize the final outcome for facilitating the design process (P2, P4, P5, P6).

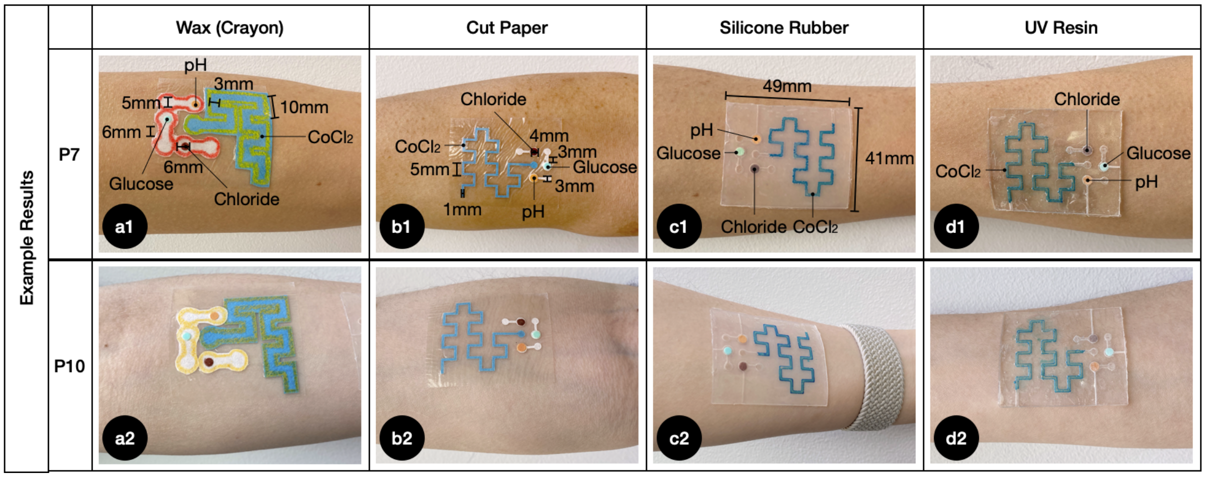

Fig. 13. Two examples of participants wearing the sweat-sensing devices they fabricated during the study. To ensure consistency, participants were asked to replicate a specific design that we provided, with the only customizable aspect being the color of the crayons used. All participants successfully fabricated the devices according to the provided design, and we present two examples of the results here.

Fabricating with SweatSkin Fabrication Methods. Overall, the participants enjoyed the hands-on experience of making the devices and found it engaging and rewarding (P1, P2, P4, P9). Participants also appreciated the flexibility of the various methods, which allowed them to choose the most suitable one based on their needs and preferences (P1, P4). The participants found that the fabrication process helped them better understand the microfluidic technology (P4, P5).

Regarding the crayon (wax) method, most participants found it to be the easiest among the four methods (M = 6.1, STD = 1.22 on the Likert scale; 1 = strongly disagree, 7 = strongly agree on ease of approach). The participants thought this method could be a good activity for children or the elderly to learn about microfluidics and sweat-sensing (P3, P4). However, the participants expressed concerns about the functionality of the channels they drew as there was no way for them to validate it before actually using it (P3, P5, P9).

Participants had mixed reactions to making the device with cut paper. Some found it interesting to follow the template to locate the components at a specific position (P1, P4, P7, P9), while others found the higher precision required to be stressful or frustrating (P3, P5, P6, P8). However, the majority of the participants still rated it as easy to make (M = 5.3, STD = 1.85 on the Likert scale; 1 = strongly disagree, 7 = strongly agree). Additionally, all participants commented that the device made through cut paper was the neatest and most aesthetically pleasing.

Most participants found the fabrication process of the two polymer-based methods (silicone rubber and UV resin) similar. While they perceived these methods to be slightly more challenging than the paper-based ones, they still found them easy to make (silicone rubber: M = 5.4, STD = 0.92; UV resin: M = 5.5, STD = 1.02 on the Likert scale; 1 = strongly disagree, 7 = strongly agree). The 3D-printed mold allowed for precise and beautiful devices to be made easily, according to several participants (P1, P5, P6). However, one main concern was that some participants were not familiar with the use of silicone rubber and UV resin, so they worried that they might choose the wrong material if they wanted to make the devices on their own in the future (P1, P2). Additionally, the long curing time of silicone rubber was not ideal, with some participants finding it time-consuming (M = 4.2, STD = 1.78 on the Likert scale; 1 = strongly disagree, 7 = strongly agree).

In this study, all participants were given the same device design to fabricate, with the only variation being the color of the crayons used. However, several participants expressed an interest in customizing their devices and exploring further aesthetic designs (P1, P3, P4, P5, P9, P10). They suggested collaborating with tattoo artists or henna designers to create more intricate and personalized designs. Some participants also expressed interest in using different materials or colors to enhance the appearance of the device. Overall, the participants were enthusiastic about the potential for artistic expression and customization in on-skin sensing devices.

Wearability of the Devices. Based on the survey results, the participants found both the paper-based devices (M = 5.8, STD = 1.17 on the Likert scale; 1 = strongly disagree, 7 = strongly agree) and polymer-based devices (M = 4.7, STD = 1.62 on the Likert scale; 1 = strongly disagree, 7 = strongly agree) comfortable to wear, with the paper-based devices receiving a higher score. The participants appreciated the thinness and tattoo-like appearance of the paper-based devices with cut paper as a hydrophobic barrier and were willing to wear them in public. They expressed an interest in more artistic designs, such as a combination with henna or collaboration with tattoo designers. As for the polymer-based devices, participants found them soft and comfortable but also noted that the background was not clear enough and could be more obvious in public. They suggested mixing them with skin-color pigment or having further aesthetic designs.

Regarding the device's positioning, we requested all participants wear the devices at the same location, arm, to maintain consistency across all the participants in this study. Nevertheless, the participants shared their preferences for alternative placement locations. For instance, P1 suggested designing channel patterns resembling symbols of specific events, enabling the device to be worn on the face, functioning as both a health monitor and an ornament. In contrast, P6 expressed concerns about privacy and preferred concealed placement, such as under sleeves. Taking their input into account, we delve into potential body locations for device placement (Section 3.1) and explore diverse applications for wearing the device on different body areas. (Fig. 1 and Fig. 14).

8 APPLICATIONS

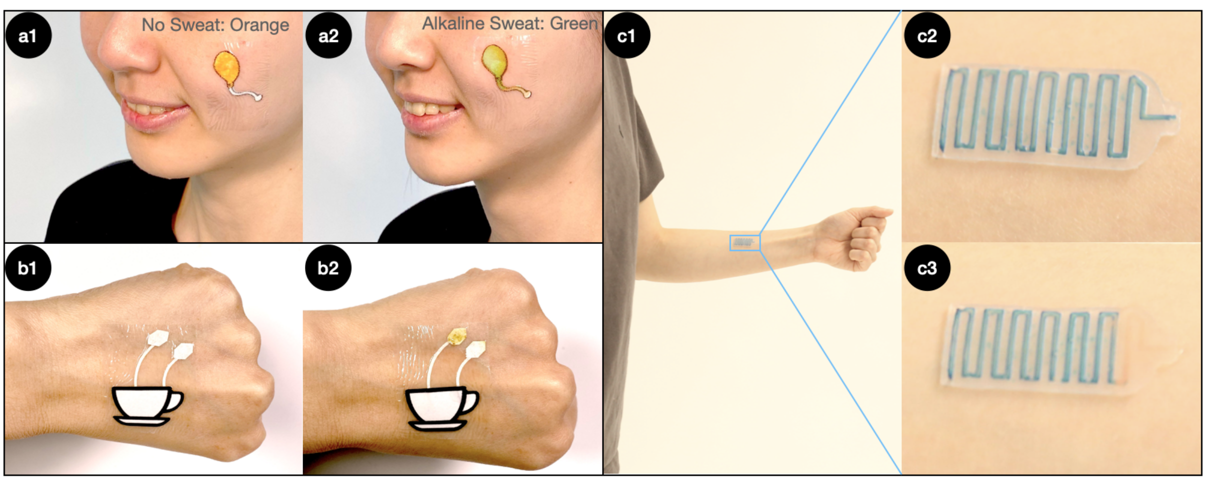

Fig. 14. We propose three applications designed and fabricated with the SweatSkin platform. The first one is a hydration state detection face painting for field day. The balloon will measure the pH value of sweat and change the color from orange (a1) to green (a2) when alkaline sweat is detected and indicates dehydration. The second one is a blood sugar monitor for diabetics. The sugar cubes above the coffee cup will change color from light blue (b1) to brown (b2) when glucose is detected in the sweat. The third one is a sweat loss measuring device for athletes (c1). The channels in the water bottle will gradually change color from blue (c2) to pink (c3). The area with color change indicates the amount of sweat loss.

8.1 Hydration State Detection Face Painting for Field Day

We propose a hydration state detection face painting sticker specifically designed for field day events. The device can be seen by others in public (Fig. 2 (a)), allowing the wearer's friends to help monitor their health during the events. This feature is based on the fact that people often get very involved in the events and may not notice changes in their health condition. The sticker incorporates channels and chambers that are hand-drawn using crayons on paper (Fig. 2 (b)), and a test paper is inserted into a chamber (Fig. 2 (d)). The test paper is intentionally shaped like a balloon, with the channel serving as the balloon string (Fig. 2 (e)), symbolizing the spirit of field day. Furthermore, the hand-drawn style complements the prevalent face painting often seen at such events. The colorimetric indicator on the test paper reacts to the pH level of the sweat (Fig. 2 (c)). If the wearer is dehydrated, resulting in a more alkaline sweat, the indicator on the test paper will undergo a color change, turning green as an indication of the hydration status.

8.2 Blood Sugar Monitoring for Diabetics

To address the need for a more natural, non-invasive, and non-destructive method of monitoring blood sugar levels in diabetics, we introduce a non-invasive blood sugar monitoring device. The device is positioned on the wearer's hand, making it easily visible and enabling self-monitoring of health status (Fig. 2 (a)). This placement is particularly advantageous because sugar intake significantly influences sugar levels. Since hands are often involved in food consumption, having the device on the hand offers convenient and accessible monitoring, serving as an effective warning mechanism. Traditional techniques rely on blood samples, necessitating invasive procedures such as finger-prick tests or subdermal implanted sensors. Our device utilizes cut paper, an everyday object, as its primary material to offer a more user-friendly solution (Fig. 2 (b)). Specifically, we incorporate glucose test paper into the device (Fig. 2 (c), (d)), shaped like sugar cubes on a coffee cup (Fig. 2 (e)). When the glucose concentration in sweat becomes excessively high, the sugar cubes on the device undergo a visible color change, turning brown. This color transformation nudges the wearer, reminding them to curtail their sugar intake. This method relies on previous research findings related to sweat glucose measurement [40, 94]. By enabling a more natural and non-invasive approach to blood sugar monitoring, we aim to enhance the overall experience and quality of life for individuals managing diabetes.

8.3 Sweat Loss of Athletes

We present a sweat-loss-indicating patch that offers visual feedback on the amount of sweat lost by the wearer. The device is worn on the arm and may be publically visible when wearing short-sleeved clothing but privately visible when wearing long-sleeved clothing (Fig. 2 (a)). This enables flexibility for the wearer. For instance, during marathon training sessions where real-time monitoring by both the wearer and the coach is essential, public visibility can be chosen. Conversely, during routine workouts, when the wearer solely desires to track personal data without sharing it with others, private visibility can be opted for. The patch is meticulously crafted using silicone rubber (Fig. 2 (b)) and features analysis channels filled with CoCl2 hydrogel (Fig. 2 (c), (d)). The selection of the stretchable polymer-based device is aimed at offering robust support during rigorous training movements. The device is designed in the shape of a water bottle, enhancing its usability and relatability (Fig. 2 (e)). As the wearer perspires, their sweat enters the channels, causing the water level inside a connected bottle to visibly decrease. This direct correlation between sweat loss and the water level provides an intuitive and real-time indication of the wearer's hydration status. This enables effortless monitoring of hydration levels during physical activities or in hot environments.

9 DISCUSSION, LIMITATIONS, AND FUTURE WORK

Paper-based wax barrier method. The fabrication of paper-based microfluidic devices utilizing wax as a hydrophobic barrier encompasses techniques beyond crayon drawing. Researchers have explored alternative methods such as wax printing [9] and screen printing [15]. However, we opted for the crayon drawing method to offer an engaging and readily accessible fabrication approach, thereby reducing the entry barrier for gaining initial insights into the functioning of on-skin sweat-sensing microfluidic devices. Remarkably, many participants of the studies expressed that this approach could serve as an excellent at-home experiment for children.

To enhance the fabrication accuracy of wax as a hydrophobic barrier method, we further investigated the use of a vinyl cutter in conjunction with a crayon drawing. By replacing the blade on the vinyl cutter with a pen holder equipped with a sharpened crayon, precise channels can be drawn. Additionally, to support thinner traces, we experimented with a method similar to screen printing. This involved vinyl-cutting a mask and applying it to filter paper, followed by placing a thin film of the wax sheet on the mask, which was subsequently melted and absorbed by the filter paper. Despite these alternative methods, it is important to note that hand-drawing with crayons remains the simplest and most straightforward approach for fabricating the device.

Polymer-based methods. In order to ensure the comfort and usability of on-skin interfaces, it is crucial to select a polymer material that is soft and flexible. In this paper, we have chosen silicone rubber as our primary material due to its excellent softness and stretchability. Silicone rubber is widely utilized in applications such as special effects makeup and body part mimicry. Additionally, we have opted for soft UV resin as an alternative material choice, primarily due to its transparency. This allows for easy visualization of the colorimetric results within the device. While silicone rubber and UV resin have proven to be effective, it is also worthwhile to explore other soft and clear materials that can be molded for on-skin microfluidic devices. Inspired by the work of Flowcuits [78], we have also experimented with thermoplastic (Oyumaru). However, we found that although devices fabricated using thermoplastic can present colorimetric results clearly, they lack the same level of stretchability as those made with silicone rubber or UV resin. As a result, we are eager to explore and evaluate a wider range of materials to provide valuable insights into the fabrication of on-skin microfluidic devices in the future.

Biomarkers. In addition to the biomarkers proposed in this study, there are numerous other biomarkers that can be analyzed in sweat. For instance, Koh et al. [40] proposed a colorimetric method for measuring lactate concentration in sweat to better understand exercise intolerance and tissue hypoxia. By incorporating different test papers or colorimetric biochemical assays in the chambers or analysis channels, our device can support more measurements. Additionally, many researchers have explored the use of electrochemical sensing methods for sweat sensing [19, 22, 48, 60]. However, in this paper, we focus on developing passive and soft devices without batteries or electronic components for greater user comfort. Nevertheless, exploring further possibilities in the future is also worthwhile.

Wearability. In terms of the materials, the paper-based device is favorably noted for its thinness and robustness. Yet, the device's long-term durability poses a concern. To shed light on this aspect, one of the authors undertook a preliminary experiment of wearing the device for over eight hours while continuing daily activities. By the end of the day, the device remained conformable to the skin and was activated, i.e., showed color change. As this paper primarily centers on the fabrication process, we suggest future research to conduct a wearability study [92], delving deeper into the device's durability. Regarding the polymer-based device, its stretchability is acknowledged for augmenting comfort during wear. Nonetheless, due to its thickness, concerns have arisen about potential peeling when rubbing against the device. In the earlier-mentioned experiment, the polymer-based device consistently adhered to the skin during the entire study. Yet, to bolster the adhesion and counteract the impact of the device's thickness, we recommend using supplementary tape to cover the device.

Various placement options for the device have been presented (Fig. 1 and Fig. 14). Generally, skin areas characterized by minimal hair and wrinkles provide superior adhesion, thereby enhancing the device's efficacy.

Body areas that are relatively flat and exhibit limited movement are better suited for the paper-based device due to its lack of stretchability. Moreover, the slim profile of the paper-based device renders it suitable for locations with greater contact with external objects. This thinness mitigates the device's impact during such contact. On the other hand, the polymer-based device's stretchability makes it ideal for body regions with more movement. While Study 1 (Section 7.1) and Study 2 (Section 7.2) permitted participants to engage in a range of activities during the device tryout session, extreme cases were not tested. To gain more insight into the wearability, selection of materials, and body placement in various scenarios, further field studies with diverse applications are necessary.
Customization. While body size, skin tone, and sweat profile naturally vary among individuals, our proposed platform caters to this diversity through its customizable design. The size of the device can be scaled to fit the size of the body, the decorative channel colors can be tailored to match various skin tones or incorporate diverse decorative patterns to mask the reagents, and the dimensions of the channels and chambers can be adjusted to suit distinct sweat profiles. Although in Study 1 (Section 7.1), we've investigated customization needs based on experts' feedback, we eagerly anticipate conducting further studies in the wild to comprehensively explore the efficacy of customization in meeting individual needs.

10 CONCLUSION

This paper introduces SweatSkin, a microfluidic fabrication process that supports the customization of on-skin interfaces for personalized healthcare through sweat analysis based on colorimetric methods. SweatSkin offers two form factors featuring four low-cost rapid prototyping methods that can be easily implemented using readily available materials, including crayons, paper, silicone rubber, and UV resin, even in home settings. Through technical characterization, the effectiveness of the devices has been validated in measuring various sweat parameters, including sweat loss, sweat rate, pH value, chloride concentration, and glucose concentration. We shed light on the application potential of on-skin sweat-sensing devices via interviews with athletic experts. A two-session workshop study demonstrated the ease of learning and execution of the four fabrication methods by general participants, emphasizing the user-friendly nature of SweatSkin. Finally, three applications illustrate how the SweatSkin platform can facilitate personalized healthcare monitoring and promote well-being. In summary, SweatSkin opens up new possibilities in UbiComp and HCI for non-invasive personalized healthcare monitoring and paves the way for a future where the fabrication of customizable healthcare devices is democratized to broader populations and more seamlessly integrated into our daily lives.

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