BioWeave: Weaving Thread-Based Sweat-Sensing On-Skin Interfaces

Jingwen Zhu
Hybrid Body Lab, Cornell University
Ithaca, USA
jz497@cornell.edu

Nadine El Nesr
Hybrid Body Lab, Cornell University
Ithaca, USA
nme32@cornell.edu

Christina Simon
Hybrid Body Lab, Cornell University
Ithaca, USA
css286@cornell.edu

Nola Rettenmaier
Hybrid Body Lab, Cornell University
Ithaca, USA
ner45@cornell.edu

Kaitlyn Beiler
Hybrid Body Lab, Cornell University
Ithaca, USA
keb282@cornell.edu

Hsin-Liu (Cindy) Kao
Hybrid Body Lab, Cornell University
Ithaca, USA
cindykao@cornell.edu

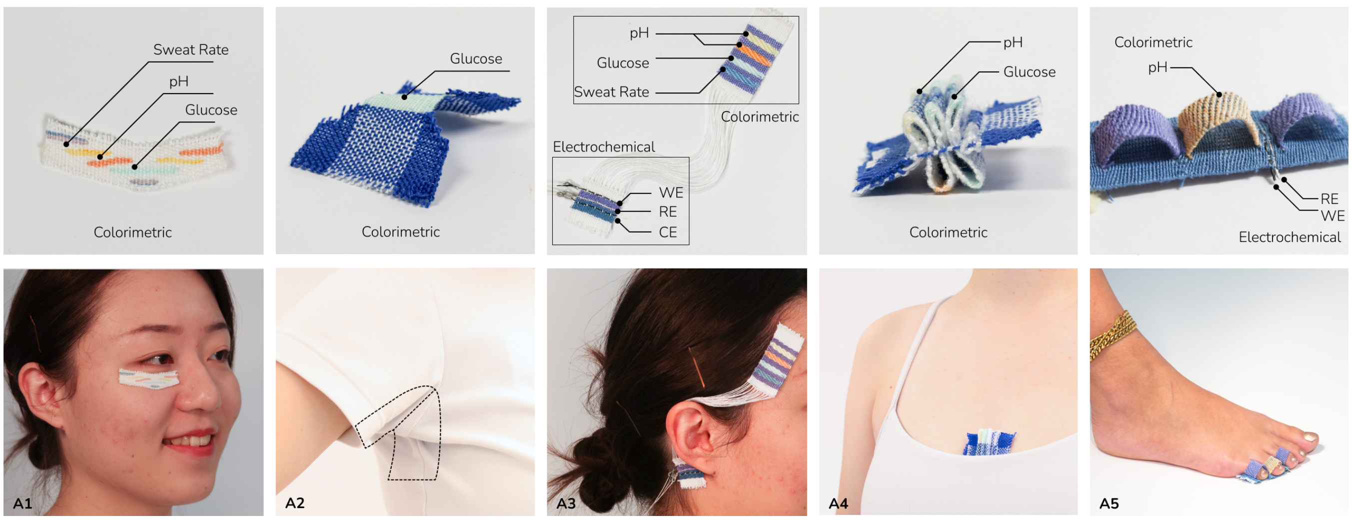

Figure 1: We present BioWeave, a woven textile-based sweat-sensing on-skin interface. We synthesized accessible fabrication approaches to fabricate colorimetric and electrochemical sweat-sensing threads that can be woven into two- and three-dimensional structures conforming to diverse body locals. We demonstrate applications including (A1) Under eye cell patterned pH and glucose sensor, (A2) Under arm glucose sensor, (A3) Forehead and ear glucose sensor with floating warp, (A4) Between chest 3D pH sensor, (A5) Between toes pH sensor.

ABSTRACT

There has been a growing interest in developing and fabricating wearable sweat sensors in recent years, as sweat contains various analytes that can provide non-invasive indications of various conditions in the body. Although recent HCI research has been looking into wearable sensors for understanding health conditions, textile-based wearable sweat sensors remain underexplored. We present BioWeave, a woven thread-based sweat-sensing on-skin interface. Through weaving single-layer and multi-layer structures, we combine sweat-sensing threads with versatile fiber materials. We identified a design space consisting of colorimetric and electrochemical sensing approaches, targeting biomarkers including pH, glucose, and electrolytes. We explored 2D and 3D weaving structures for underexplored body locations to seamlessly integrate sweat-sensing thread into soft wearable interfaces. We developed five example applications to demonstrate the design capability offered. The BioWeave sensing interface can provide seamless integration into everyday textile-based wearables and offers the unobtrusive analysis of health conditions.

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CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**.

KEYWORDS

biosensing, sweat sensing, on-skin interfaces, weaving, wearables, textiles

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1 INTRODUCTION

Sweating is a natural and essential bodily function. The human body has numerous sweat glands, producing sweat containing various substances which reveal conditions in the body [29]. For example, changes in electrolyte levels in sweat can indicate hydration status, while changes in glucose levels can be used to monitor diabetes. In recent years, there has been a growing interest in using wearable on-body sweat sensors for non-invasive sensing and real-time monitoring of various analytes [4, 37]. These sensors have the potential to provide valuable information about an individual's health and fitness and can be integrated into clothing and other wearable devices for easy and convenient use.

While wearable sweat sensors have been thoroughly researched in the materials science and biochemistry fields, there has been comparatively less focus on wearable chemical sensors, as opposed to electrical or biometric sensors, in recent Human-Computer Interaction (HCI) research. There have been explorations into sweat-sensing devices fabricated with flexible printed circuit boards (PCB) [2], and tattoos [49], yet thread-based sweat-sensors are underexplored in the HCI community. Thread-based sweat sensors afford textile integration and can be comfortable to wear like clothing. Furthermore, by combining different fibers and weaving techniques, textiles can obtain a certain level of wicking capability, which is necessary for sweat sensing [51]. Given that woven textiles are already commonly used in garments and have become an emerging form factor for on-skin wear [20, 45], the development of textile-based sweat sensors is a natural next step and converting the raw sweat-sensing material into textiles would allow for easy fabrication within the existing fashion industry processes.

Although recent materials science research has investigated thread-based sweat sensors, the research is mostly focused on thread fabrication [35, 41, 46] and weaving integration in basic plain weave [8, 50]. The full potential of the structural and textural dimensionality that textile weaving can afford has not yet been explored. Through weaving, functional threads can be further constructed into three-dimensional structures and expressive patterns, which can conform to more diverse body locations beyond planar ones such as the arm and wrist.

In this paper, we present weaving thread-based sweat-sensing on-skin interface built on three-dimensional weaving. By combining sweat-sensing yarn with other fibers through weaving, we aim to create flexible and comfortable on-skin interfaces that can provide valuable information about an individual's health and fitness. By focusing on the integration of sweat-sensing technology into textiles, we aim to address this gap in the literature and explore new possibilities for wearable sweat sensors. In summary, the main contributions are:

(1) Two fabrication approaches for colorimetric and electrochemical sweat-sensing threads for the HCI community to adopt with a series of technical evaluations to understand the characterization of the sweat-sensing threads.
(2) The design space of woven structures, and pattern designs for different sensing, attachment, and wearing features.
(3) 5 sample applications demonstrating the capability of the BioWeave design space.

2 BACKGROUND & RELATED WORK

2.1 Sweat Sensing Approaches

Sweat provides a rich repository of important biomarkers within the body, including electrolytes (such as sodium, potassium, chloride, magnesium, and calcium), organic compounds (such as urea, lactate, and ammonia), metabolites, and trace compounds (such as iron and zinc) [29]. As a natural bodily function, sweat sensing offers a great opportunity for unobtrusive sensing for health purposes, and wearable sweat sensors have been widely explored in the biotechnology field [4, 26, 33].

The sensing modalities of wearable sweat sensors can be categorized into two categories: electrochemical sensing and optical sensing [4]. Optical sensing includes colorimetry and fluorometry. Colorimetric assays expose sweat to different chemical reagents pre-designed to exhibit color changes in the presence of specific chemical analytes. On the other hand, electrochemical approaches such as amperometry, potentiometry, voltammetry, and conductometry utilize the electrical properties of the sweat biomarkers to detect and quantify their concentrations, enabling accurate and real-time monitoring of the wearer's health status.

To fabricate colorimetric sweat sensing devices, recent research has explored using polydimethylsiloxane (PDMS) [3, 17], hydrogel [27] and tattoo paper [5]. Colorimetric assays do not require any electronic components, and a number of low-cost colorimetric kits are commercially available to detect biomarkers such as pH and glucose [49]. Among the HCI community, colorimetric sensing assays have been explored in tattoos for biosensing [49] as well as fabricating responsive primitives [22], but further understanding colorimetric assays' capacity for textile-based sweat sensing remains underexplored.

Ion-selective membranes (ISM) are selectively permeable to certain ions through electrochemical sensing modalities, such as potentiometric sensing and amperometric sensing [7, 32, 37]. Since recent research has enabled all-solid-state electrodes, ion-selective sensors no longer need a liquid solution in the electrode [7, 13, 47]. This advancement has expanded the sweat-sensing opportunity from conductometry [14] to ion-selective sweat-sensing capabilities that are comparatively precise and accurate.

BioWeave presents textile-based sweat-sensing approaches that support both colorimetric and ion-selective electrochemical sensing. We take advantage of the commonly available colorimetric sensing reagents, presenting an accessible fabrication approach that uses off-the-shelf colorimetric test strips, in addition to developing an electrochemical sensing thread fabrication approach for the HCI community.

2.2 Textile-Based Sweat Sensing

Textiles are natural close-to-body materials and can be further enhanced for personalized healthcare [31]. In the sweat-sensing context, textiles, especially threads, can function as microfluidic channels for sweat-wicking. Recent research has explored two methods of rendering thread into sweat sensors: colorimetric assays[52, 54] and ion-selective membrane (ISM)[35, 41, 43, 46]. This enables the possibility of textile-based sweat sensing for both on-skin and near-skin wear [29].

In the HCI community, fiber-based and thread-based research has focused on actuators [15, 25] or piezoresistive sensors [38], while dyed or coated fiber or thread with chemical-sensing capabilities remains underexplored. Although there were explorations in conductometry sweat sensing [14, 21] using conductive threads, colorimetric and ion-selective electrochemical textile-based sweat sensors merit investigation.

BioWeave synthesizes the textile-based sweat-sensing approaches into a cohesive design space, presenting textile-based sweat-sensing fabrication opportunities for HCI researchers.

2.3 Weaving Biosensing in On-Skin and Textile Interfaces

Weaving is a technique for creating textile surfaces by interweaving warp (vertical) yarns and weft (horizontal) yarns at right angles to each other. The warp yarns are held on a loom under tension, while weft yarns pass between warp yarns in a specific sequence to create patterns and structures [40, 45]. Different weaving structures can create textiles with different properties, such as varying degrees of flexibility, strength, and breathability. Weaving provides a stable structure for integrating soft or rigid materials, further enabling versatility.

While extensive explorations of integrating electronics into textiles have been explored in HCI community [10–12, 20, 28, 36, 39, 40, 45], the capability of integrating chemical sensing functions into weaving remains underexplored. Meanwhile, woven textiles are already commonly used in garments and have become an emerging form factor for on-skin wear [20, 45, 55], which presents closer-to-skin sensing opportunities in sweat sensing context.

In this project, we explore using weaving as a way to integrate sweat-sensing yarn into on-skin interfaces to create seamless, non-invasive, real-time sweat-sensing devices with the potential for everyday wear.

3 BIOWEAVE DESIGN SPACE

3.1 Theory of Operation

We utilize two common chemical sensing approaches: optical sensing and electrochemical sensing (Figure 2). Each of these approaches targets a range of analytes with their own advantages and limitations.

Optical Sensing: *Colorimetry* is a common optical sensing approach widely used in both lab testing and at-home diagnose scenarios, with off-the-shelf colorimetric saliva and urine test strips widely available for different analytes [4]. Colorimetric sensing provides visible hue and saturation change when colorimetric assays react with analytes. BioWeave colorimetric-sensing approach

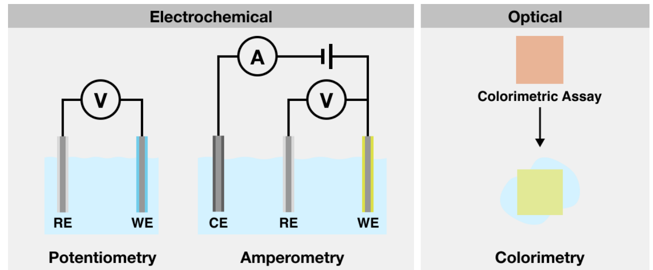

Figure 2: BioWeave utilizes two common sweat-sensing approaches: electrochemical sensing and optical sensing.

harvests colorimetric assays from off-the-shelf test strips and use them to dye commonly available cotton weaving yarn, to fabricate colorimetric woven sensors. The colorimetric sensing approach is intuitive and easy to integrate, as there are no soft circuitry components involved in the weaving process.

Electrochemical Sensing: Electrochemical sensors use electrodes as a transducer element in the presence of an analyte. Two common electrochemical sensing approaches are examined in BioWeave: *potentiometry* and *amperometry*. Potentiometric sensing uses two electrodes: a working electrode (WE) and a reference electrode (RE) to measure the potential change between them. Amperometric sensing uses three electrodes: a working electrode (WE), a reference electrode (RE), and a counter electrode (CE). By applying a potential between the working electrode and reference electrode, electron movements in sweat cause a very low current flow between the counter electrode and working electrode, which can be measured and converted to the analyte concentration. By applying different ion-selective membranes on the working electrode, both potentiometric and amperometric approaches can be used to measure a wide of biomarkers including pH, glucose, electrolyte, etc [35, 46]. Electrochemical sensing approaches offer real-time analysis of biomarkers in sweat, but corresponding analog front-end (AFE) circuitry and batteries are required.

Reusability of Thread-Based Sensors: In general, electrochemical sensing threads are reusable after they are rinsed by deionized water. Colorimetric sweat rate and pH sensing are reusable: the sweat rate sensing thread will return to its original color when the sweat evaporates, while the pH sensing thread will return to its original color when the sweat is rinsed off. Colorimetric glucose sensing threads are not reusable. The different reusability of each type of sensing thread affords their corresponding integration strategies: reusable sensing threads can be integrated into full garments, while single-use sensing threads can be integrated as woven patches, which can be unwoven into weft and warp threads. This would also allow the sensing threads to be recoated and reused.

3.2 BioWeave Design Space

We defined a 5-dimensional BioWeave design space (Figure 3) for fabricating thread-based sweat sensors and integrating them into a variety of weaving patterns and structures targeting different biomarkers and body locations.

Sensing Approach (Figure 3 i.): BioWeave is compatible with colorimetric and electrochemical sensing. *Colorimetric* sensing affords

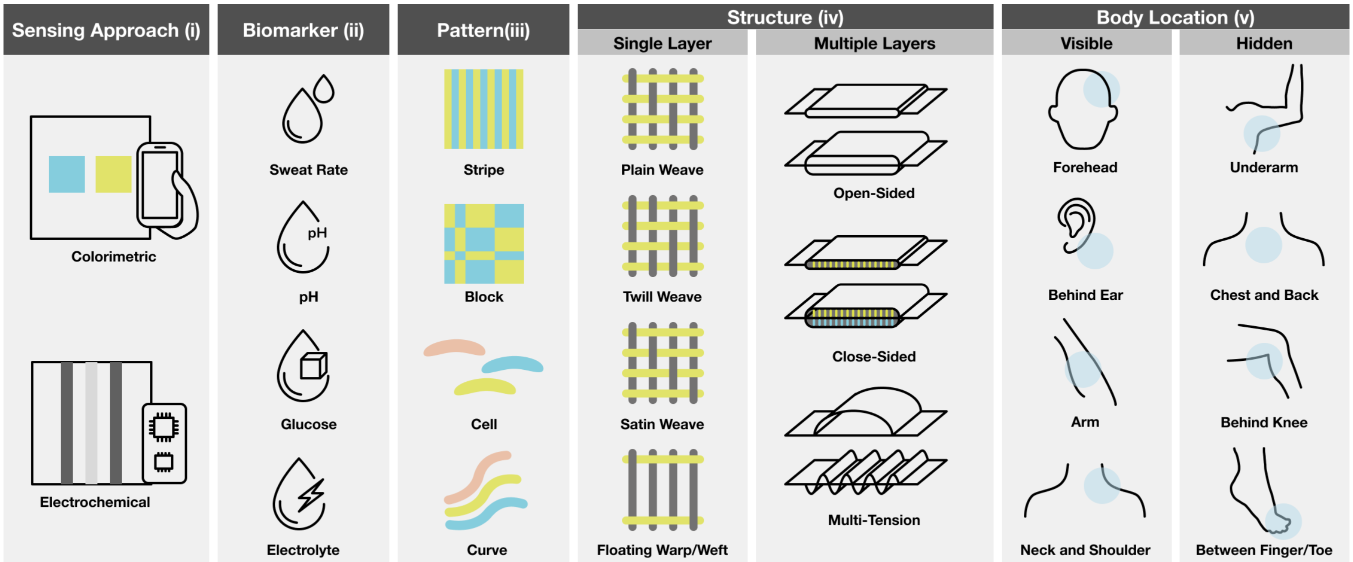

Figure 3: BioWeave Design Space.

comparatively low cost and fewer material and equipment requirements. Colorimetric sensing is suitable for visible body locations to provide immediate analytical feedback, and the color-changing feature offers unique design opportunities. *Electrochemical* sensing provides analytical results of sweat with higher resolutions compared to colorimetric sensing while can be adapted to hidden body locations for unobtrusive sensing.

Biomarker (Figure 3 ii.): BioWeave is compatible with biomarkers including sweat rate, pH, glucose, and electrolytes, and each biomarker can signal different body status and health conditions [29]. The pH level of sweat can be used for indicating skin disease and monitoring wound healing status. Glucose level is critical for people with diabetes, while electrolytes such as sodium and chloride can indicate dehydration.

Pattern (Figure 3 iii.): Weaving affords the integration of diverse materials and patterns[44]. We identified compatible 2D patterns that can form dedicated color blocks for colorimetric sensing while also functioning as decorative patterns for electrochemical sensing. Simple patterns such as *stripe* and *block* can be woven on a 4-shaft floor loom, while complex patterns such as *cell* and *curve* would require 8-shaft floor looms to achieve better results. Each geometric shape within these patterns can be woven with different colorimetric sensing threads, resulting in multiplexed woven sweat sensors.

Structure (Figure 3 iv.): We identified single-layer and multi-layer woven structures for their corresponding sweat-sensing advantages. Woven structure decides to sense thread integration approaches and will result in different sensing efficacy. *Single layer* woven structure includes basic plain, satin, and twill structures. These structures are suitable for woven colorimetric sensing as they can quickly absorb sweat while being visible for users to inspect. Floating weft or warp can further increase the absorbing speed.

On the other hand, *multi-layer* structures can afford component integration and enhance sweat absorption capability. In BioWeave, we explored multi-layer weaving on an 8-shaft floor loom with double back beams. This enables 2 to 4 layers of multi-layer weaving such as double cloth and double weave [40]. *Open-sided* structure provides as weaving electrochemical sensing yarns into the layer close to the skin while providing a housing layer for PCB and battery. *Close-sided* structure affords cushion-like texture when weft yarns are woven as spacer material, providing extra absorption for sweat collection. *Multi-tension* structure can be easily woven on a loom with double back beams. The two warp sets on each back beam can maintain different tension during the weaving process. This will result in protruded dome structures for body locations such as finders and toes, or ripple textures for concave body locations such as the chest.

Body Locations (Figure 3 v.): We identified suitable body locations based on the higher sweat glands density of the body ($glands/cm^2$) [29] and categorized them into visible body locations that are suitable for colorimetric sensing and hidden body locations that are suitable for electrochemical sensing. Hidden body locations can also be used for colorimetric sensing private biomarkers, such as glucose levels that may indicate personal health conditions.

4 FABRICATING BIOWEAVE THREADS

Here, we present the BioWeave fabrication approach of dyeing colorimetric sweat-sensing threads (Figure 4) and coating electrochemical sensing threads.

4.1 Fabricating Colorimetric Sensing Threads

Fiber Content and Thread Weight: We take several factors into fiber choice consideration: absorption property [1], wicking property [30], and dyeing property [42] for colorimetric sweat-sensing context. Natural fibers, such as wool, cotton, and silk, tend to dye more evenly and produce more vibrant colors. Synthetic fibers, such as acrylic and nylon, can be dyed, but the colors may not be as vibrant and may fade over time. Among natural fibers, cotton fiber

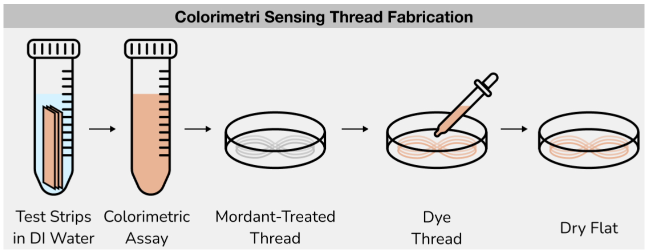

Figure 4: Colorimetric sweat-sensing threads fabrication process

has a high absorption rate and wicking properties compared to silk and is a common weaving material. To weave on-skin interfaces, the thread weight should be in the range of lace weight (10 to 60 yards per pound) to achieve a seamless wearing experience. After completing a wicking property test of available weaving thread [48], we choose mercerized perle cotton thread 10/2 (4,200 yd/lb, two strands) and 20/2 (8,400 yd/lb, two strands) from Woolery as the raw material for colorimetric thread dyeing.

Thread Preparation: Before dying, it is necessary to clean the yarn to ensure that any wax residue from the manufacturing process does not interfere with the dye absorption or coating. Common approaches to treat sewing threads include air plasma treatment [35] or washing with sodium carbonate or sodium hydroxide [54]. However, different from sewing threads, weaving yarns do not have a wax coating and can achieve the same wicking property compared to air plasma-treated threads. For cleaning purposes, we immersed the yarn in isopropanol alcohol for a period of 5 minutes and then air-dried.

Mordanting is a process that enhances the color fastness of natural fiber or its ability to bind dye and hold color after repeated washings. We mordant our yarn to prevent the colorimetric thread from bleeding onto the surrounding woven textile when exposed to moisture. For this process, we used aluminum sulfate, or alum, a common mordant compound. Mordant procedures specify weighing out aluminum sulfate to 12-20% weight of fiber (WOF) [9]. Although mordanting typically involves preparing large amounts of yarn for dyeing, we adapted our mordant procedure to the low volume of fiber. We used 0.2 g of aluminum sulfate (20% WOF, to maximize the saturation and color fastness of our dyed yarn), dissolved in 2.5 mL of boiling deionized (DI) water heated on a hot plate. We then added the small volume of dissolved aluminum sulfate to a flask of DI water heated to 82°C on a hot plate, to which a small magnetic stir bar had been added. We added our fibers to the flask and let them stir in the mordant solution at 82°C for 45 minutes. After this time, we took the flask off the heat, removed the fibers from the mordant bath, and rinsed them with DI water in preparation for dyeing. Fibers were either immersed in colorimetric dye solution immediately after mordanting or stored in the refrigerator for up to 3 days before dying. The mordant solution was reused for several rounds of dyeing before replacement.

Preparing Colorimetric Assay: We adopted an accessible colorimetric sensing fabrication approach by incubating commercial urinalysis test strips in DI water for 2 hours at 37°C according to literature [49]. In this example, we used pH test strips 4.5 to 9.0 for urine and saliva pH testing (Just Fitter Precision pH Test Strip), glucose test strips (Diastix Reagent Strips for Urinalysis), and moisture test strips (Cobalt Chloride Test Paper) at a relative concentration of 10 strips per milliliter. After incubating, we removed the soaked test strips and kept the solution for dyeing in the next step.

Dyeing Colorimetric Sensing Threads: Dyeing textiles using natural dyes typically involves diluting the dye in a large volume of water. In contrast, the volume of sweat-sensing solution used in the present study was much smaller, with a ratio of 1 foot of yarn to 250μL colorimetric assay. By applying colorimetric assay directly onto the prepared thread with a dropper or syringe and laying it flat to dry, we were able to produce colorimetric sweat-sensing threads with even color concentration.

4.2 Fabricating Electrochemical Sensing Threads

Electrochemical sensing threads are fabricated with a procedure adapted from the literature for an HCI context [35, 41, 46]. As the theory of operation is extensible, we focused on using voltammetry for pH sensing and using amperometry for glucose sensing as examples to examine both potentiometric and amperometric sensing approaches as described in the BioWeave design space (Section 3). In total, four different types of sensing threads need to be fabricated, and each sensing thread requires multiple layers of coating as illustrated in Figure 5.

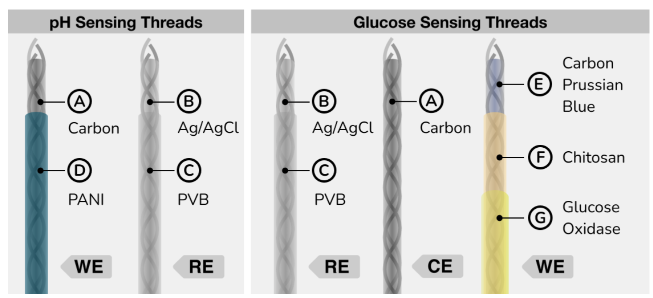

Figure 5: Electrochemical sensing threads contain multiple layers of coatings.

Preparing Coating Materials (Table 1): We summarized seven coating materials needed for coating electrochemical sensing threads for pH and glucose sensing. The formulation of each coating is shown in Table 1(A) to (F). By replacing coating D and G with a different ion-selective membrane coating, we could fabricate ion-selective sensing threads for different biomarkers (for example, replacing coating D with nonactin membrane solution for ammonium sensing [46]). To prepare diluted carbon resistive ink(Table 1 A), we diluted and mixed carbon resistive ink (Kayuku C-250J) with 2% v/w DE Acetate (Thermo Fisher Diethylene Glycol Monoethyl Acetate). The silver/silver chloride ink (Table 1 B, Kayuku AGCL-675) can be directly used without diluting. To prepare the Polyvinyl Butyral (PVB) cocktail (Table 1 C), we mixed 78.1 mg of PVB powder(Sigma-Aldrich P110010) with 50 mg of sodium chloride in 1 mL of methanol. This solution was sonicated in an ultrasonic bath for 30 minutes to achieve a transparent, slightly sticky cocktail.

Table 1: Material formulation for each layer of coating for pH and glucose sensing.

Material Formulation			
A	Carbon Resistive Ink 2g	DE Acetate 40uL	
B	Silver/Silver Chloride Ink 2g		
C	Polyvinyl Butyral Powder 78.1 mg	Sodium Chloride 50 mg	Methanol 1 mL
D	Polyaniline Powder 500 mg	Hydrochloric Acid 20 mL	
E	Prussian Blue Powder 250mg	Carbon Resistive Ink 1g	
F	Chitosan Powder 0.1 mg	0.1M Acetic Acid 100 mL	PBS 100mL
G	Glucose Oxidase Powder 45 mg	PBS 1mL	

For the pH sensing electrode, polyaniline (PANI) is used as the ion-selective membrane. The PANI solution (Table 1 D) is prepared by mixing 500mg PANI powder (Sigma-Aldrich 556386) in 20mL hydrochloride acid (Sigma-Aldrich HX0603-4) and ice bath at 4 °C for 5 hours.

For the glucose sensing electrode, three coating materials need to be prepared. The Prussian blue ink (Table 1 E) is prepared by mixing the carbon resistive ink (Kayuku C-250J) with Prussian blue powder (Sigma-Aldrich 234125) at 25% w/w. The chitosan solution (Table 1 F) is prepared by dissolving 0.1 mg of chitosan powder in 100 mL of 0.1 M acetic acid, then mixed with a magnetic stir bar for 1 hour at room temperature. Then it was diluted in a 1:1 ratio with Phosphate Buffered Saline (PBS, Sigma-Aldrich 806552). The glucose oxidase solution (Table 1 G) was created by mixing 45 mg glucose oxidase with 1 mL of PBS.

Coating Electrochemcial Sensing Threads (Figure 6): For electrochemical sensing, the same reference electrode and counter electrode can be used for each analyte, while working electrodes need to be coated with specific ion-selective membranes. We summarized the coating procedure in Figure 6. All the threads used in this process are 20/2 mercerized perle cotton thread treated under air plasma for 5 minutes.

Coating Carbon Resistive Thread as Counter Electrode. Carbon Resistive Ink (Coating A) is used for coating carbon resistive thread. One end of the cotton thread was threaded through a silicone tube(McMaster Carr 9628T42, 1/8" inner diameter), and the remaining length of the thread was dipped into the carbon resistive ink and slowly pulled through the tube to ensure that the coated thread was roughly an even diameter along the length of the thread. The coated thread was then left to cure in a 60°C oven for 30 minutes. The coating and curing process needs to be repeated three times to achieve an even resistance at $80\Omega/cm$.

Coating Silver/Silver Chloride Thread as Reference Electrode. Silver/silver chloride conductive ink (Coating B) and PVB cocktail solution (Coating C) are used for coating silver/silver Chloride thread.

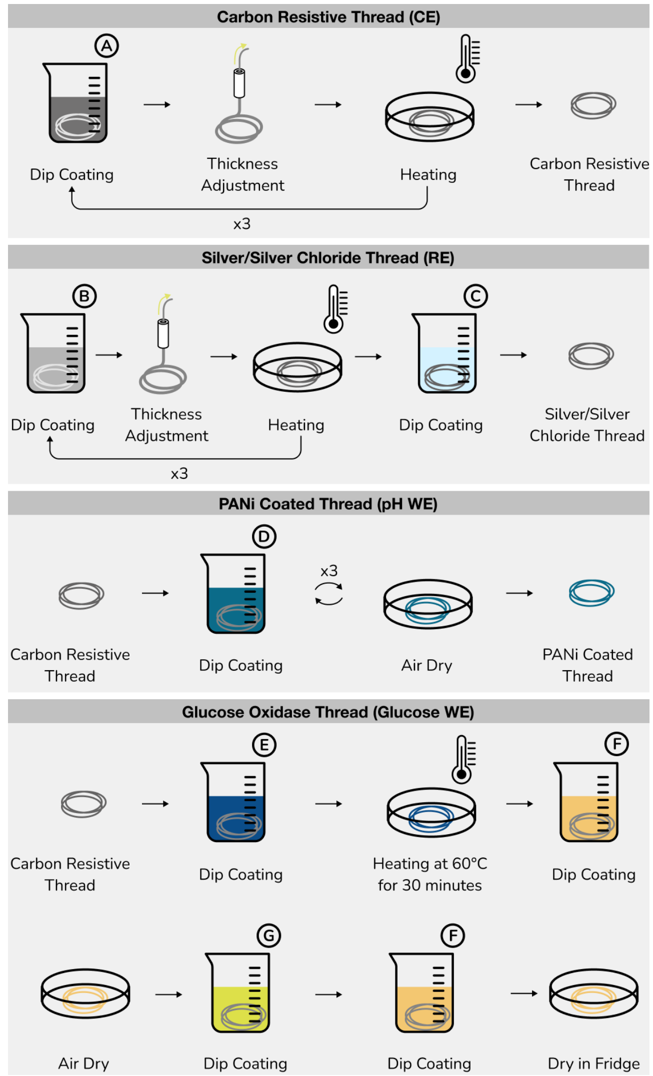

Figure 6: Coating processes of electrochemical sensing threads.

The dip coating procedure is the same as carbon resistive thread, followed by a layer of Coating C as the polymeric membrane. The triple-coated Silver/Silver Chloride thread was then coated with coating C using the same tube-threading process mentioned above, then left to air dry for an hour. The fully coated thread has a low resistance of less than $1\Omega/cm$.

Coating Working Electrode for pH Sensing. The counter electrode in the pH sensing thread was fabricated by dipping the coated carbon resistive thread in coating D three times and air drying completely between each layer. The coated thread needs to be stored in a desiccator until usage.

Coating Working Electrode for Glucose Sensing. The working electrode for the glucose sensing thread is fabricated by applying coating E in the same tube threading process and cured in the oven at 60°C for 30 minutes. Following this, the thread is dipped in coating

F and left to air dry completely. The dried thread was dipped in coating G and immediately dipped into coating F again. The fully coated thread was left in the refrigerator at 4 °C to dry until usage.

4.3 Characterization

We conducted a series of characterizations to understand the performance of our colorimetric and electrochemical sensing threads.
Coating: Figure 7 shows Scanning Electron Microscope (SEM) images of the four electrochemical sensing threads. It is evident from the images that the coating has fully covered the external fiber of the raw cotton thread, while each type of thread presents a surface texture consistent with that observed in the literature [35].

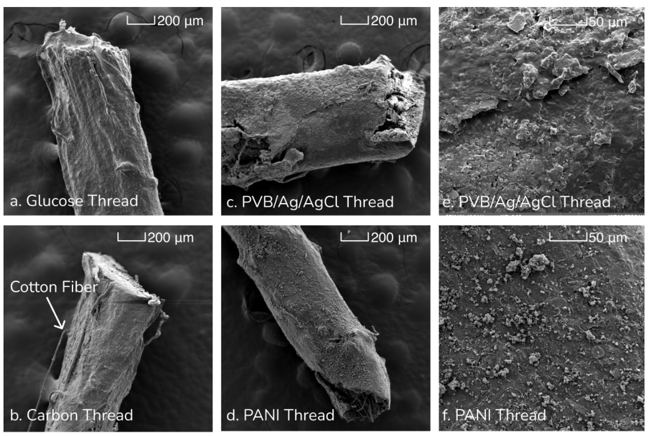

Figure 7: SEM images for coated threads. a,b,c,d (scalebar 200 μm) show that the conductive carbon ink and Ag/AgCl ink base layers along with other external coatings completely wrap around the fibers of the cotton thread, with minimal breakage. Closer images in e,f (scale bar 50 μm) on the right show the PVB and PANi particles on the surface of the coated threads.

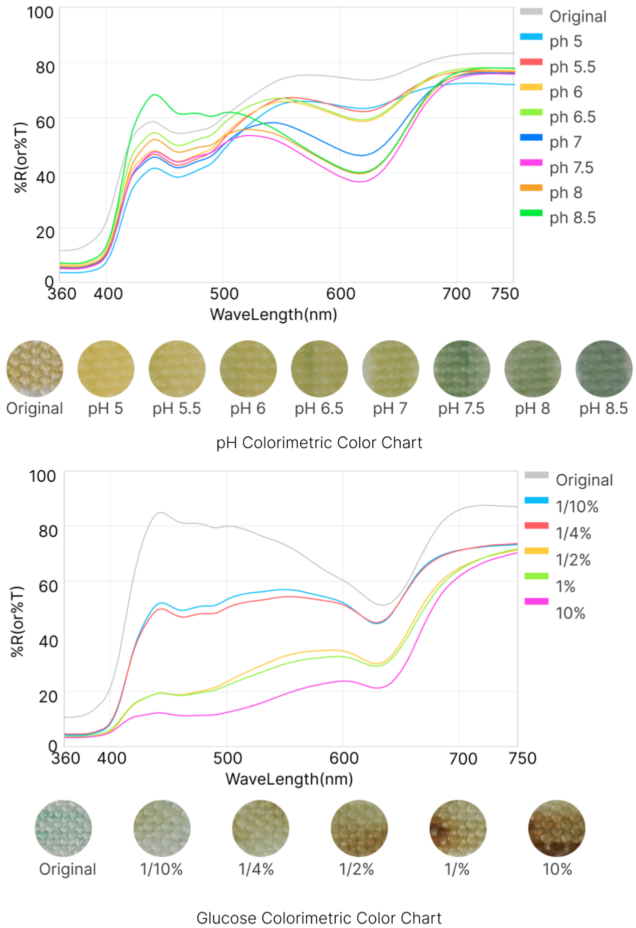

Figure 8: Colorimetric Sensing Threads Characterization

Quantitative Colorimetric Analysis of Woven Sensing Threads: We quantitatively analyzed the woven colorimetric sensing threads through (i)spectrophotometry and (ii) optical images as a function of analyte concentration, following common methods [22, 27].

We fabricated testing swatches by weaving dyed 20/2 mercerized perle cotton thread with the same threads in white color as warp. Individual samples are approximately 20 mm x15 mm, with the colorimetric thread woven portion 6 mm in the center. We prepared pH buffer solutions (pH 5-8.5) and glucose solutions (0.1% - 10%) in the reactive range of the colorimetric assays and used precision syringes to prepare 1mL of each solution, applying them onto samples at the same time. An X-Rite Ci7800 Sphere Benchtop Spectrophotometer was used to find a CIE L*a*b* color value for each sample and the wavelength, as shown in Figure 8. We can see clear weave length differences among each colorimetric activated color.
pH Electrochemical Sensing Thread Characterization: For pH sensing potentiometric characterization, we chose two sets of pH sensing threads from two batches of fabrication processes and used analog front-end (AFE) Texas Instruments LMP91200 with ATMEGA32U4 to measure the open circuit potential. pH buffer solutions are prepared at pH levels from 4 to 9. We rinsed the sensing threads with DI water in between each test. The result in Figure 9 shows a linear decrease in open circuit potential with pH as expected. The sensors exhibit a Nernstian behavior with an average linear sensitivity of 60mV/pH, which matches previously reported values [35], demonstrating the functional pH sensing thread sets.
Glucose Electrochemical Sensing Thread Characterization: For glucose electrochemical sensing characterization, e used programmable AFE Texas Instruments LMP91000 with ATMEGA32U4 to measure the open circuit potential to conduct both amperometric sensings with constant voltage (0.5V) and cyclic voltammetry by sweeping potential from -0.45V to 0.45V. Glucose solutions are prepared at a 0.1% to 10% concentration range. We rinsed the sensing threads with DI water in between each test. The result in Figure 9 shows a clear anodic peak shifting with concentration change, demonstrating the sensing capability of glucose electrochemical sensing threads.

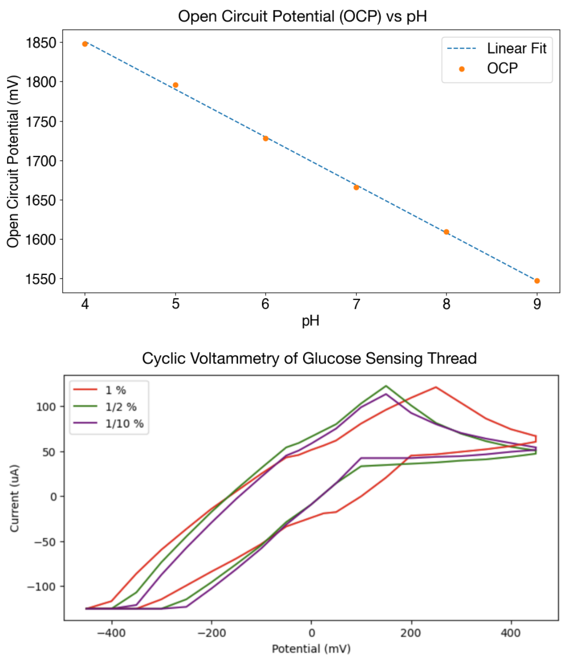

Figure 9: We characterized electrochemical pH sensing threads by conducting open circuit potential measurement at pH levels from 4 to 9 and characterized glucose sensing threads by conducting cyclic voltammetry measurement at glucose concentration from 1/10% to 1%.

5 APPLICATIONS

To demonstrate the BioWeave design space's extensibility, we wove 5 BioWeave example applications to explore the BioWeave design space (Section 3) diverse body locations with high sweat gland density[29] as shown in Figure 1 and their close-up images in Figure 10.

Under Eye (A1 of Fig 1). To explore the expressivity of Patterns in BioWeave design space, we weave a cell pattern on an 8-shaft floor loom. We wove pH, glucose, and sweat rate colorimetric sensing yarns into each individual cell with floating wefts in between each cell. This application explored design opportunities for multiplexed colorimetric sensing, and small sensing zones consume less of the sensing yarn in the weaving process.

Under Arm (A2 of Fig 1). To demonstrate BioWeave can be integrated into existing wearable items, we used floating warp shaping techniques in plain weave to weave the foldable colorimetric sensor that can be attached to the underarm area inside clothing. Fashion tape is used to attach the woven sample to the armhole of a cotton T-shirt. The targeted biomarker is glucose.

Forehead and Ear (A3 of Fig 1). In this example, we explored using floating warp as sweat fluidic channels and combined plain, satin and twill structures for multi-thread integration. The colorimetric sensing zone is woven in the satin structure to maximize the exposed colorimetric wefts and can be worn near the temple area so they are visible in mirrors. The electrochemical sensing zone is woven in the twill structure that can help absorb sweat and can be worn on the side of the neck with easier attachment to circuitry components. Plain weave is used to weave the rest of the device for stable structures.

Between Chest (A4 of Fig 1). This application explores multi-layered woven structures for concave body locations with high sweat gland density. We used a double back beam 8-shaft floor loom to weave a multi-tension structure, while each layer has its own tension adjustments. By tightening and releasing the tension of the layer, we can create the multiple folded structure without the need for post-sewing and stitching. This structure increased thread density in a fixed skin surface, with the potential of absorbing at a higher sweat volume.

Toes (A5 of Fig 1). As electrochemical sensing thread is fabricated in lower volume than weaving yarn in the research lab settings, we explored the design of a very small woven structure that provides reinforced sensing attachments. We designed this application to be worn on the toe for skin condition monitoring. We wove a multi-tension structure and integrated pH electrochemical sensing threads between the layers. We also used colorimetric pH sensing threads to weave one of the toes for visual indications.

Figure 10: Close-up image of applications before and after colorimetric activation: (A1) Under eye cell patterned pH and glucose sensor, (A2) Under arm glucose sensor, (A3) Forehead and ear glucose sensor with floating warp, (A4) Between chest 3D pH sensor, (A5) Between toes pH sensor

6 DISCUSSION, LIMITATIONS & FUTURE WORK

Preliminary Wearability Study We conducted a preliminary wearability study with three participants to gain insight into the device's comfort and feasibility [23]. As shown in Figure 11, all three devices remained attached to the participants' foreheads after 21 minutes of intensive exercise. P1.3, P2.3 and P3.3 present visible pH colorimetric change that aligns with the precision test strip results of their sweat. All participants expressed that the lightweight form factor of the sensor was unnoticeable while wearing and did not cause any distraction during exercise. Our preliminary study also highlights human factor considerations in designing wearable sweat sensors. We observed inconsistent sweat-inducing rates for individual participants, which points to customization needs for more precise sweat rate sensing. In future work, this may be achieved by varying weaving patterns and adjusting the proportion of sweat-absorbing threads.

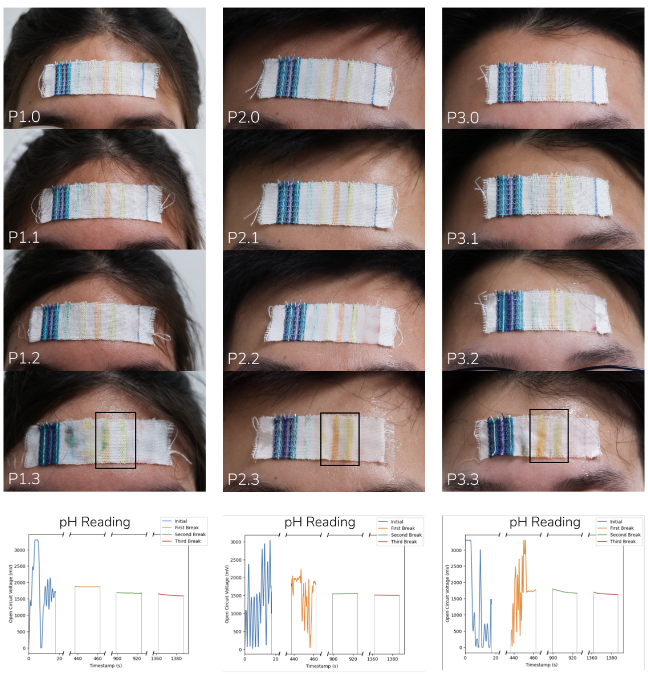

Figure 11: The image depicts the BioWeave interface worn on the participant's forehead. From top to bottom, each photo is taken before they start to exercise, at 7 minutes break, 14 minutes break, and 21 minutes break. The plot shows the pH sensor readings at the same timestamp.

Trade-offs between Accessibility vs. Sensing Performance. Our proposed approach can offer a lower barrier for HCI researchers to prototype and experiment with colorimetric sweat sensing, with room for expanding analyte capabilities by replacing test-strip-harvested colorimetric assays with solutions available from chemical product vendors. We identified the accessible colorimetric thread sensing approach by harvesting colorimetric assays from off-the-shelf saliva and urine test strips. However, this solution presents a trade-off between accessibility and performance, as off-the-shelf colorimetric biomarker sensing strips are limited in the variety of compatible biomarkers and the targeted concentration range that they can sense. For example, certain biomarkers are present at higher concentrations in urine than in sweat, so using colorimetric assays harvested from urine test strips may not sense the lower concentration in sweat. However, off-the-shelf test strips are easy to access and at a lower cost than colorimetric assay solutions available from chemical product vendors.

Similarly, in our electrochemical sensing approach, off-the-shelf analog front-end components and open-source hardware are also adopted. Although this setup lacks a benchtop reference point for the initial evaluation of coating efficacy, we can still achieve characterization aligning with the literature. Moreover, this setup is accessible for HCI research lab settings, as benchtop potentiostat, while affording greater precision, may not be widely available. By developing this multi-step fabrication process, we aim to lower the barrier for chemical sensing in the HCI community and provide a jumping-off point for research and design opportunities in biosensing for personal healthcare.

Visualizing Biosignals Through Woven Sweat Sensing On-Skin Interfaces. The BioWeave design space identified weaving patterns and visible body locations for visualizing colorimetric biosignals in public and private contexts. During our preliminary wearability study, participants expressed their thoughts and concerns regarding visualized biosignals. As the colorimetric woven patterns may appear as a pattern integral to the textile itself, biosensing information can be conveyed to the wearer themselves but be perceived as an *ambiguous social display* [18] by others. This subtle "camouflaged" interaction afforded by the richness of woven patterns could offer a unique opportunity for wearers to monitor their health information without unwanted disclosure of personal data. Furthermore, this chemical reactive color change expands the design pallet of non-emissive displays beyond current thermochromic [18, 19, 24], photochromic [6] and electrochromic [53] color-changing wearable displays for HCI researchers, designers, and makers.

Towards Scalable Woven Sensor Fabrication. In this work, we explored multi-layer and pattern-rich weaving patterns and structures on a double back beam 8-shaft floor loom via hand weaving. With a digital jacquard loom that can individually address each warp, we can achieve a greater variety and complexity of weaving patterns and structures. Meanwhile, the multi-thread sensing approach can leverage weaving software tools [16] to easily integrate functional materials into the woven design. We envision that this approach could pave the way for scalable and affordable sweat-sensor woven sensor fabrication, potentially achieving low-volume production. Although electrochemical sensing threads and certain colorimetric sensing threads are reusable after deionized water rinsing, the machine washability remains unexamined in sweat-sensing textiles. This would be a fruitful area for future evaluation by adopting launderability study methods [34] to explore launderability of the woven sweat sensors.

7 CONCLUSION

We present BioWeave, a novel approach for fabricating thread-based sweat-sensing on-skin interfaces. We defined a five-dimensional design space that enables users to fabricate colorimetric and electrochemical sensing textiles, with options of biomarkers, and rich weaving patterns and structures. We synthesized accessible fabrication processes for colorimetric and electrochemical sensing and characterized the fabricated threads regarding their sensing feasibility. We developed five example applications exploring body locations with high gland density. We reflected on the subtle interaction visualizing biosignals through woven sweat-sensing on-skin interfaces, which offer non-emissive displays beyond current color-changing wearable design approaches. Through our extensive exploration and synthesis of the BioWeave design space and fabrication approach, we aim to lower the barrier for sweat-based chemical sensing in the HCI community to initiate research and design opportunities in biosensing for personalized healthcare.

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