Living Layers: Designing Modular E-Skin with Bacterial Cellulose

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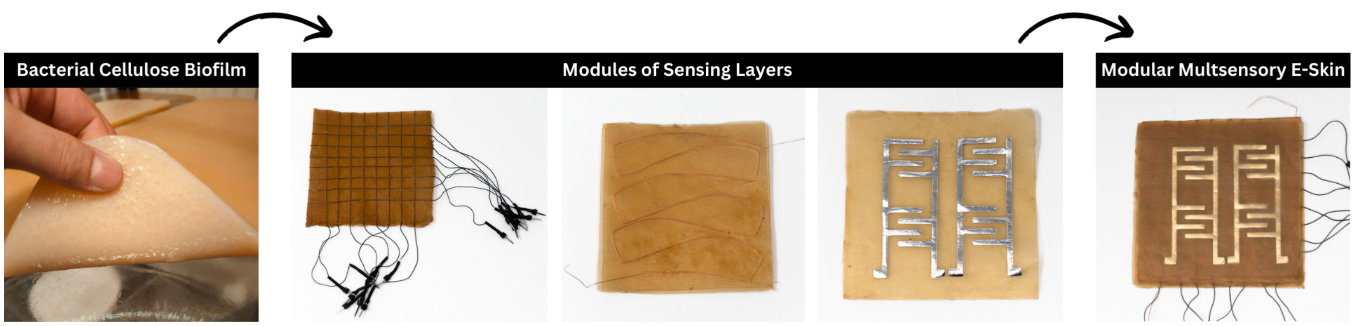

Figure 1: We develop a modular, multisensory e-skin system crafted from bacterial cellulose. Starting from a biofilm substrate, the process integrates layers of sensors, to create a hybrid bioinspired e-skin interface.

ABSTRACT

Due to its flexibility and sensitivity, E-skin is increasingly used in applications in fields such as Human-Computer Interaction (HCI), biomedical engineering, and robotics. However, current e-skin technologies face challenges related to durability, self-healing, and sustainability. Addressing these issues, sustainable materials offer promising alternatives with unique physical properties. In this context, we explore how the inherent characteristics of biomaterials, such as bacterial cellulose, can be utilized for the development of e-skin. We demonstrate the design and use of bacterial cellulose as an e-skin by multilayer assembly, sensor development, and sensor integration into the material.

CCS CONCEPTS

• **Human-centered computing** → **Interaction devices**; • **Hardware** → **Emerging interfaces**; **Bio-embedded electronics**.

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1 INTRODUCTION

Human skin translates pressure, temperature, and texture into actionable information, being a critical feedback mechanism in Human-Computer Interaction research. Mimicking these capabilities, e-skin interfaces are thin, flexible, and slightly stretchable surfaces designed to replicate the properties and sensing functions of human skin. They integrate these sensory functions and feedback into digital systems to enable more natural and intuitive interactions in fields such as robotics and wearable devices. Despite significant advancements, current e-skin technologies often rely on synthetic polymers or metal-based components, very difficult or impossible to recycle. Therefore, while offering high performance, this makes them less viable for large-scale or long-term use applications.

Within HCI and material science, biomaterials have emerged as promising solutions to the environmental limitations of conventional synthetic materials. Derived from natural or renewable sources, biomaterials such as bacterial cellulose stand out due to their biodegradability, flexibility, and mechanical robustness. These characteristics, combined with biocompatibility and self-healing properties open up possibilities for the development of biomimetic self-healing e-skins, particularly relevant for dynamic and responsive interfaces exposed to repeated stress and damage. However, despite these advantages, its potential as a modular platform integrating multiple sensory functionalities for e-skin systems remains underexplored.

Building on prior work, this paper investigates bacterial cellulose as a substrate for e-skin development, combining the biomaterial's inherent properties—flexibility, durability, and environmental friendliness—with the functional needs of interactive systems. More precisely, we develop three types of sensors (touch, temperature, and humidity) which, through the self-adhesion properties of bacterial cellulose can be integrated into multi-layered assemblies. This approach creates a versatile, multi-sensing sustainable e-skin. Thus, this work seeks to expand the design space for bio-hybrid materials in HCI and to explore new forms of interaction that prioritize both usability and sustainability.

2 RELATED WORK

2.1 Bio-materials in HCI

Biomaterials have become a new key element of sustainable innovation in HCI, increasingly gaining traction [4, 5]. The potential of these materials for interaction has been studied from various perspectives from more-than-human design [20] to care-based interactions[15] and fabrication of on-skin interfaces [12, 26]. Particularly, various works using fabrication with living materials, i.e., materials produced through self-assembling by living organisms, have introduced biological growth as an alternative fabrication process compelling with digital fabrication. Previous work demonstrates the viability of bacterial cellulose for creating biohybrid systems through a large range of applications from wearable garments [3, 18] to interactive devices [19] and robotics [22]. Further fabrication techniques have been explored to introduce conductive properties [6, 9], create circuits [1] and their integration into various applications [7]. Although these techniques involve complex processes and specialized material, they provide a further vision expanding the potential applications of bacterial cellulose and establishing a fundamental approach for the development of bio-hybrid devices for both aesthetic and functional applications.

2.2 Synthetic E-Skin and Sensor Development

In Human-Computer Interaction (HCI), researchers have explored synthetic e-skin as a medium for novel interaction paradigms. For instance, Weigel et al. [29] introduced *iSkin*, a flexible and stretchable touch sensor designed for on-body interactions, emphasizing visual customizability and wearability, thus enabling new input methods for mobile computing. Expanding this concept, Teyssier et al. [27] proposed *Skin-On Interfaces*, which integrate artificial skin onto interactive devices, providing a bio-driven approach to tactile feedback and improving the naturalness of interactions. Alongside *ecSkin* by Panigrahy et al. [21], these works emphasize low-cost fabrication methods or DIY approaches, making them highly relevant for democratizing e-skin technology in maker communities and beyond. Recent advancements in synthetic e-skin also focus on enhancing functionality, such as mimicking thermal pain sensing, as demonstrated by Neto et al. [17], or developing self-healing pressure sensors for tactile feedback, as explored by Yang et al. [30]. Liu and Lorenzelli [14] review flexible sensing systems that revolutionize next-generation wearable technologies, while Wang and Gao [28] introduce synthetic e-skin applications in immersive virtual and augmented reality environments. In robotics, synthetic e-skin has progressed toward mimicking the sensory and neuro-inspired capabilities of biological skin. Liu et al. [13]demonstrate how such designs can enable advanced tactile sensing by integrating neuro-inspired architectures. Similarly, capacitive sensing advancements, as explored by Qin et al. [25], enhance the adaptability of synthetic e-skin for deformable and stretchable robotic surfaces, allowing seamless integration into soft robotics. These developments bridge the gap between the biological complexity of human skin and the functional demands of robotics, paving the way for smarter, more adaptive robotic interfaces capable of nuanced environmental interactions. While these works demonstrate significant progress in synthetic e-skin development, our approach offers a complementary perspective by combining modular sensor integration, self-healing/self-repairing properties, and sustainability through the use of bacterial cellulose, all within an accessible and scalable fabrication process for next-generation e-skin systems.

2.3 Biohybrid E-Skin Using Living Cells

Biohybrid e-skin leverages living cells and biological materials to create systems that are adaptive, regenerative, and environmentally sustainable. Unlike synthetic e-skin, these systems integrate the inherent properties of living organisms—such as self-repair, growth, and interaction with their environment—to enable lifelike interfaces. While Kawai et al. [11] pioneered this field by culturing human skin cells onto robotic surfaces, providing tactile and regenerative capabilities, Adamatzky [1] demonstrated the potential of microbial cultures by embedding electronic circuits onto kombucha mats, highlighting their functionality and sustainability. These innovations align with the use of bacterial cellulose as a versatile biohybrid material for robotics and adaptive systems, as explored by Pataranutaporn et al. [23] and Kalantari et al. [10]. In health monitoring, Zhao et al. [31] and Hosseini et al. [8] explore soft bioelectronics and biodegradable materials, emphasizing their role in creating sustainable and multifunctional e-skin systems. Building on these advancements, our work uses bacterial cellulose to create a biodegradable, modular e-skin with adaptable, self-adhesive layers for touch, temperature, and humidity sensing. This design simplifies repairability and maintenance, offering a scalable and sustainable solution for next-generation systems.

3 DESIGN RATIONALE

While high sensitivity and resolution are key performance parameters in e-skin research, we argue that there are scenarios such as large-scale surfaces or environments prone to frequent wear and tear, where sustainability should be prioritized over sensing performance. For example, in applications where large areas need to be covered the e-skin is likely to experience frequent wear or damage. Therefore, producing and replacing cost-effectively and with low environmental footprint are key priorities.

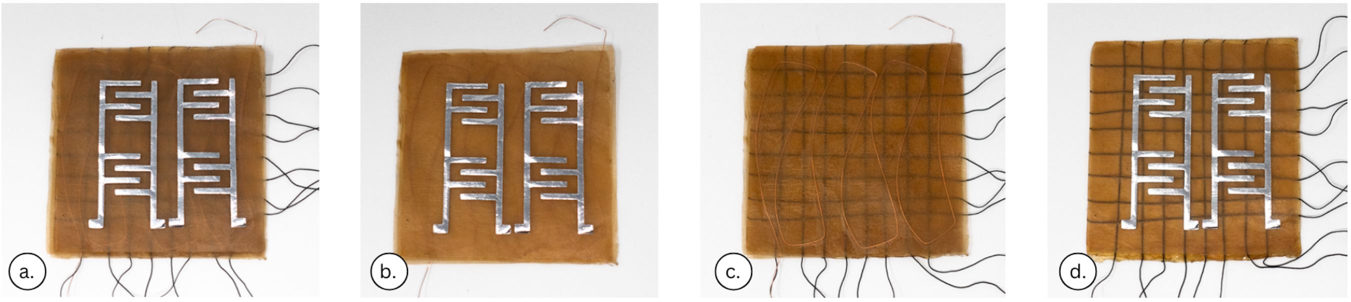

Figure 2: Different combinations of assemblies: a) Touch matrix, temperature sensor, and humidity sensor, b) Temperature sensor and humidity sensor, c) Touch matrix and temperature sensor d) Touch matrix and humidity sensor.

3.1 Material

Among the common biomaterials used in HCI, bacterial cellulose—a natural biocompatible polymer produced through fermentation by a symbiotic culture of bacteria and yeast—is selected as the base biomaterial for this exploration due to its inherent properties. First, being a growing material, conductive elements can be integrated at different stages of the life cycle [19], notably during stabilization, allowing, therefore, the creation of assemblies through water evaporation without additional adhesives. Next, the thickness of each layer, as well as its mechanical and textural properties, can be easily controlled by the designer according to the needs using passive fabrication processes such as forming or pleating [3, 18]. Third, the fermentation and metabolic activity transforming the carbon- and sugar-rich medium into nanocellulose make it an easily scalable, renewable material that can be sustainably produced in large quantities even from waste [24].

It is important to clarify that while bacterial cellulose has potential applications in various domains, the e-skin presented in this work is not primarily intended for direct human use. Instead, this application focuses on its use in mechanical and environmental systems, such as robotics or sensing devices. Furthermore, the term "biocompatible" in this context refers to the material's compatibility with the environment, being biodegradable and sustainable.

3.2 Sensing Integration

Drawing direct inspiration from the layered structure of human skin, where each layer (i.e. epidermis, dermis, and subcutaneous layers) performs distinct sensory functions, this exploration focuses on the integration of touch, temperature, and humidity sensors into the biomaterial. Each bio e-skin layer inherits, therefore, one of the three sensor types. As human skin's sensing capabilities are heterogeneous across the body, each bio-e-skin layer should act as a building block to allow for different combinations of layered assemblies.

The integration of electronics into the bacterial cellulose does not alter the material's composition. Its innate biodegradable properties remain intact and the electronic components can be recovered and reused after the bacterial cellulose's degradation. This ensures that the e-skin retains its environmental sustainability even with functional enhancements such as sensing capabilities.

3.3 Opportunities

This fabrication approach enables fast and simple prototyping of individual sensors, allowing them to be used independently or in assemblies. This modularity reduces the need for unnecessary materials and allows for a generative and adaptive design as new layers or sensors can be added asynchronously over time, enabling incremental improvements or repairs without having to rebuild the entire system. Therefore, the ability to prototype and expand the system layer by layer opens up opportunities for large-scale applications, where the e-skin needs to evolve dynamically with changing requirements.

3.4 Possible Scenarios

Environment-Reactive Architecture : In a modern eco-friendly pavilion, kombucha leather e-skin membranes are used to sense the environment, monitor the integrity of the structure and adapt the architecture to environmental changes in real-time (Fig. 3 a). Temperature sensors embedded in the material detect rising heat, triggering systems that adjust their tension to provide shade or increase airflow and cool the interior. Humidity sensors track moisture levels, prompting the structure to increase ventilation when needed. At the same time, the kombucha skin collects data on air quality, temperature, and humidity, sending it to the building's monitoring system. Hence, bacterial cellulose e-skin acts as an adaptive membrane that not only responds to the environment but also provides valuable data for improving future designs.

Animatronics In an amusement park, user experience is enhanced by animatronics equipped with bacterial cellulose e-skin, enabling safe interactions with visitors (Fig. 3 b). The smooth, flexible, amber-toned e-skin encourages touch interactions, such as holding hands. Embedded sensors continuously monitor the environment, ensuring both visitor safety and the animatronic's integrity in the face of destructive behavior or extreme weather conditions. For instance, if damaged by a user or when an approaching storm or excessive heat is detected, the animatronic autonomously adjusts its behavior, retreating to seek shelter. This ensures both its longevity and the safety of park visitors.

Figure 3: Images generated using OpenAI's DALL-E 3 model for image generation illustrating the two scenarios of a) Environment-Reactive Architecture and b) Animatronics.

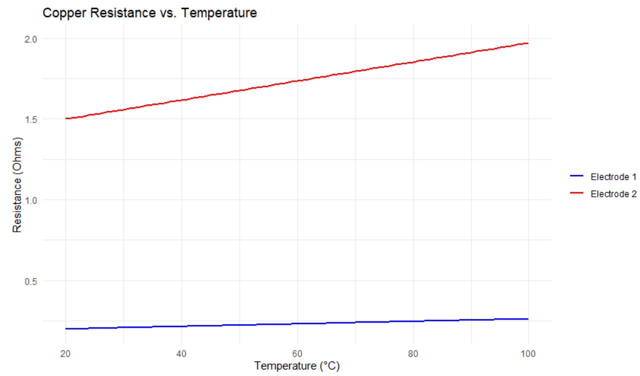

Figure 4: Resistance change of two different copper electrodes.

4 IMPLEMENTATION

4.1 Growing the bacterial cellulose

Bacterial cellulose biofilms were grown using the fermentation process described by Nicolae et al. [19] optimized using growth information provided by [2]. A medium consisting of 6g/L of black tea, 10% brown sugar, 10% vinegar and 10% blended scoby is prepared and left to ferment in GN1/1 polycarbonate trays at 27°C for 7±1 days. This resulted in sheets with thicknesses of approx. 5mm wet and approx. 0.50 mm dry which was deemed optimal for use in e-skin applications.

4.2 Sensors fabrication

Three types of sensors—touch, temperature, and humidity—were developed in thin form factor using off-the-shelf materials and embedded within the bacterial cellulose substrate.

Touch/Pressure : We create a touch matrix, using a mutual capacitance-based approach [19, 27] with conductive yarn layered between cellulose sheets. This matrix mimics the epidermis, which is responsible for sensing pressure and touch in human skin. The matrix is 70mm x 70mm with a thickness of < 1mm.

Temperature sensor : Employing a copper wire electrode shaped as a square wave and encapsulated between two cellulose sheets, we create a temperature sensor [16], that mimics the dermis, the skin layer where temperature regulation and sensing occur. The sensor with a thickness of < 1mm relies on measuring the micro changes in resistance using the Temperature Coefficient of Resistance (TCR) of copper, an Analog to Digital Converter (ADC) with 16 Bit resolution and a Wheatstone bridge circuit. For the same length, the copper wire has a higher resistance than copper or aluminum foil electrodes, which facilitates the detection of changes.

The sensor's thickness could be reduced using methods such as inkjet printing or stencil printing. However, this needs further investigation as our test showed that the irregular surface and porosity of the bacterial cellulose could impact the conductivity of the electrodes, especially when hydration happens.

Humidity Sensor : The humidity sensor aims to mirror the subcutaneous layer, which plays a role in moisture retention and regulation. However, as humidity is one of the most damaging factors of biomaterial-based interactive systems, we consider that this layer should be placed the outermost, contrary to human skin, where the subcutaneous layer is the innermost layer of the skin. Therefore, we tested several materials (conductive bio-paste, copper foil and aluminium foil) to create "F"-shaped electrodes on the surface of the bacterial cellulose biofilm. Among these, we selected aluminum foil electrodes as the most suitable : they are less sensitive to high humidity (e.g. rain) and more resistant to repetitive bending than biopaste-based electrodes and less prone to oxidation than copper-based electrodes.

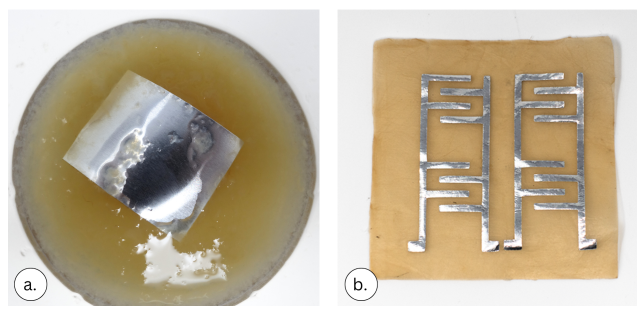

Figure 5: Tests of the a) compatibility between the aluminum tape and bacterial cellulose biofilm and medium and the resulting b) plotter cut electrodes on biofilm.

The electrodes were cut using a Brother ScanNCut CM750 plotter cutter and transferred on the dry biofilm. However, if desired, they can be embedded into the bacterial cellulose biofilm during growth using the *Grow Around* method described by Nicolae et al. [19] as according to our compatibility tests, the copper foil does not biologically or chemically interact with the growing biofilm (Fig. 5).

4.3 Assembling

The previous subsection described the fabrication of independent sensors. However, the assembling of the e-skin consists of embedding the electrodes into or onto the grown bacterial cellulose sheets

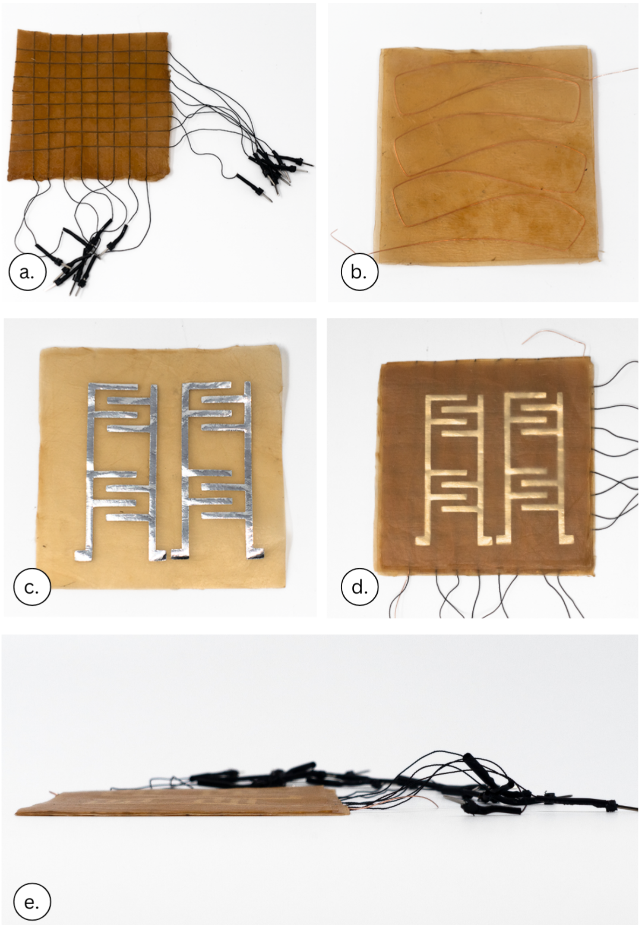

Figure 6: Individual sensory layers a) Touch matrix, b) Temperature sensor, c) Humidity sensor and d) Final assembly from top and e) side (all 70mm x 70mm, thickness 1mm).

using a bottom up approach and the self-adhesiveness of bacterial cellulose wet biofilms. The process can be done following two workflows. The first workflow (Fig. 7 top) starts with using a wet biofilm, on which we place the matrix wires for the touch sensor or the copper wire for the temperature sensor and a 2nd wet biofilm. Once dry, other elements can be added, followed by another wet biofilm, and the process can be repeated. However, if the layout of the different sensors of the whole structure is known in advance, then the process can be fastened up by starting directly by embedding the sensing components during growth of the biofilms following Nicolae et al.'s method [19] or by placing the touch sensor or the copper wire for the temperature sensor between several wet biofilms (Fig. 7 bottom). Thus, using wet biofilms, this approach offers several advantages :

- allows to decrease the number of bacterial cellulose layers needed
- new sensors can be easily integrated into the e-skin over time
- outermost sensors can be removed and cost-effectively replaced if damaged by moisturizing the bacterial cellulose

5 EVALUATION AND TESTING

Our e-skin segment evaluation procedure was centered on testing each element to determine the design's viability and functionality. These tests examined material compatibility, the touch sensor's performance using calculations of Signal to Noise Ratio (SNR), and the reliability of the temperature and humidity sensors.

5.0.1 Compatibility. An important factor to take into account when choosing materials for bio-hybrid systems based on living materials such as bacterial cellulose, is the biological and chemical compatibility. We tested this compatibility by exposing the copper wire coated with acrylic lacquer and aluminium foil to wet, living bacterial cellulose and its medium (Fig. 5 c).

The goal was to assess whether the materials could maintain their structural integrity when in direct contact with bacterial cellulose. The setup was left untouched for two days. Upon examination, no noticeable changes were observed, indicating that it remained unaffected. This result suggests that both materials can be used in combination with bacterial cellulose in bio-hybrid systems without risk of material breakdown.

5.0.2 Touch matrix. We carried out a number of recordings aimed at determining and evaluating the accuracy of the touch matrix integrated into the e-skin prototype. Four distinct 1-minute recordings of raw sensor values were done using an Arduino Mega and a Muca board, without any touch being applied to the sensor and with a steady object touch. A visualization was generated using Processing and no significant noise was observed which could impact the accuracy of touch detection.

The SNR was calculated using the following formula:

$$\text{SNR (dB)} = 10 \times \log_{10}\left(\frac{\left(\frac{1}{N}\sum_{i=1}^{N} S_i^2\right)}{\left(\frac{1}{M}\sum_{i=1}^{M} N_i^2\right)}\right)$$

5.0.3 Temperature sensor. The evaluation of the temperature sensor aimed to assess its responsiveness to both gradual and rapid changes in temperature, which are essential for ensuring that the sensor can accurately track temperature variations in real-world scenarios. Therefore where two different tests conducted. In the first test, the sensor was gradually heated using a heat plate, with temperatures rising up to 80°C. During this test, raw sensor values were recorded over a 10-minute period. The goal was to observe how the sensor responded to a steady increase in temperature (Fig. 8).The sensor's reaction during the process of gradual heating is depicted in Figure 8 a. Resistance measurements on the sensor showed a linear response, rising gradually with temperature. This tendency is consistent with metals Temperature Coefficient of Resistance (TCR), which states that resistance rises proportionately with increasing Celsius temperature. The sensor functions as anticipated for consistent temperature fluctuations, as demonstrated by its reliability in detecting and measuring the slow heating. The results (Fig.8 b) of the second test, in which the sensor was subjected to rapid heat using a lighter, demonstrate the sensor's swift responsiveness to rapid thermal changes.

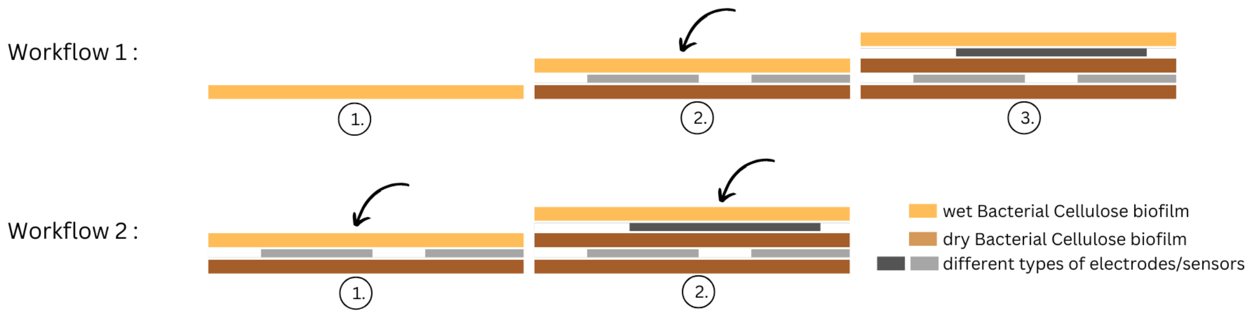

Figure 7: Schematics of the two workflows that can be used to assemble asynchronously, adapt over time and repair bacterial cellulose e-skin.

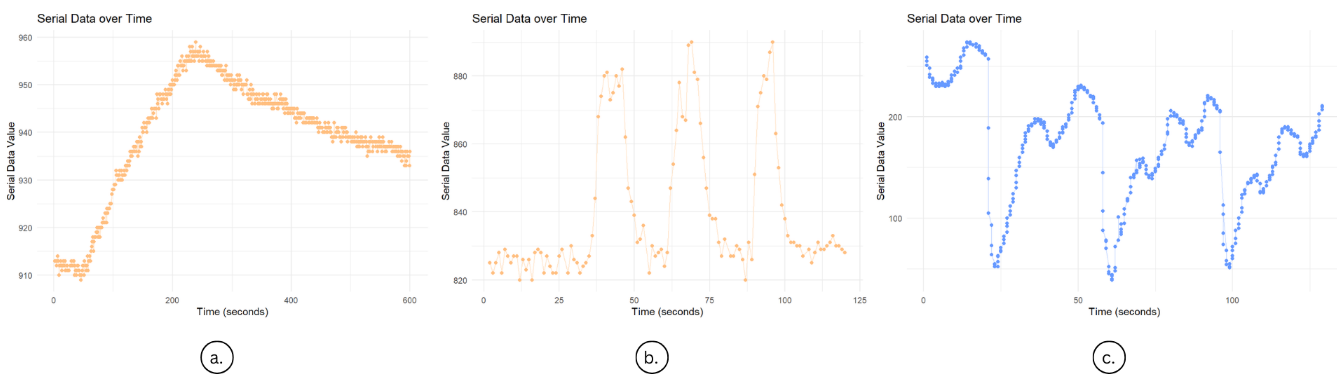

Figure 8: Evaluation graphs of temperature and humidity sensor in different setups: from left to right, gradual prolonged heating, repetitively touching a hot surface and repetitive breathing in proximity of the sensor

Overall, to increase the sensitivity of the sensor, we recommend selecting the highest possible electrode resistance at a given reference temperature, typically around 20°C. Since the TCR influences resistance changes proportionally, a higher base resistance results in more pronounced variations, making temperature changes easier to detect.

5.0.4 Humidity sensor. The purpose of this test was to evaluate the humidity sensor's responsiveness to changes in environmental moisture levels. Therefore, human breath was used to simulate short bursts of humidity to assess how quickly and accurately the sensor could detect these changes.

The sensor was exposed to human breath multiple times over short intervals, and raw values were recorded during the procedure. This allowed us to measure the sensor's sensitivity to increased humidity and how swiftly it could return to baseline values once the moisture source was removed (Fig. 8 c). The plot in Fig. 8 shows that the sensor consistently responded to the introduction of moisture from human breath. Each time the sensor was exposed to humidity, there was a clear change in the recorded values, demonstrating correct detection.

6 LIMITATIONS AND CONCLUSION

In this paper, we present an exploration of the potential of bacterial cellulose as an e-skin substrate. By developing touch, temperature, and humidity sensors that can be modularly and generatively assembled and adapted over time, we demonstrate the potential of this technology in scenarios where sustainability is as important as performance.

However, there are certain limitations and constraints associated with this approach. While bacterial cellulose is created using a living process, the resulting material compounding the applications is inanimate and biodegradable. This biodegradability is both a benefit and a challenge. On one hand, it provides a sustainable alternative to synthetic materials; on the other, it necessitates constant care to maintain its properties. For example, bacterial cellulose tends to degrade over time, losing flexibility through drying or molding. To mitigate this, treatments such as the application of antifungal oils, hydration routines, and waxing are required to preserve its water-repellent and mechanical properties [19].

It is also worth noting that bacterial cellulose has a lower elongation at break compared to human skin. Remarkably, human skin is highly responsive to mechanical loading and can easily double its initial area when subject to mechanical stretch. In contrast, bacterial cellulose has been reported to stretch only up to approximately

2% [3], which limits its use in highly dynamic or mechanically demanding environments.

Despite these challenges, we hope that our work contributes to advancing the understanding of bacterial cellulose as a viable material for sustainable e-skin applications. Moreover, we aim to inspire future research and development into this material, fostering innovation and awareness of sustainable solutions with unique and beneficial properties.

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