# Demonstration of BIOral: Fabricating Intraoral pH Sensor for Continuous Health Monitoring


Yijing Jiang
Aarhus University
Aarhus, Denmark
y.jiang@cs.au.dk

Junzhe Jin
Aarhus University
Aarhus, Denmark
202402602@post.au.dk

Yunhui Song
Aarhus University
Aarhus, Denmark
202402597@post.au.dk

Haiyang Xu
Aarhus University
Aarhus, Denmark
202402604@post.au.dk

Michael Wessely
Aarhus University
Aarhus, Denmark
michael.wessely@cs.au.dk


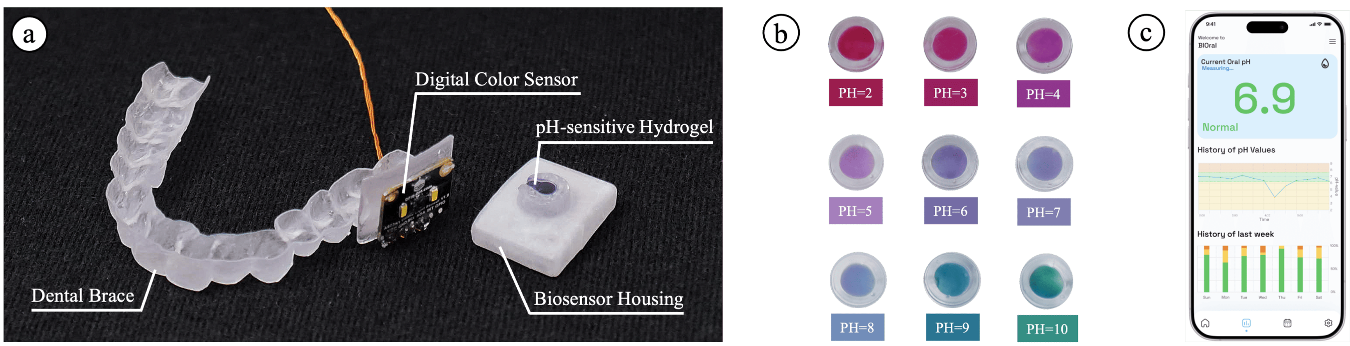


**Figure 1: (a) BIOral consists of four main components: a dental brace, a digital color sensor, and a biosensor housing containing pH-sensitive hydrogel. (b) Colorimetric comparison of the pH-sensitive hydrogel across a pH range of 2 to 10. (c) The design of the BIOral user interface, showcases pH data, a history of pH values, and an overview of the data from the past week.**


## Abstract

Oral pH is a key health indicator, playing a vital role in enamel protection and reflecting systemic conditions. However, existing devices for detecting pH are either one-time tests or require additional extraoral equipment, which fails to capture the dynamic changes in oral pH. This paper introduces *BIOral*, a novel system that integrates pH-sensitive hydrogel with dental braces for continuous oral pH monitoring. *BIOral* combines biocompatible dental braces, edible colorimetric hydrogel, and a digital color sensor to monitor salivary pH levels, offering a new approach to personalized oral care management. We present the fabrication process of *BIOral* and a preliminary technical evaluation to assess the system's performance, reaction time and detection range. We envision *BIOral* as a cost-effective solution for daily use, and could advance preventive healthcare and facilitate early intervention.




*CHI EA '25, Yokohama, Japan*



ACM ISBN 979-8-4007-1395-8/25/04
https://doi.org/10.1145/3706599.3721178



## CCS Concepts

• **Human-centered computing → Interaction devices**; **Ubiquitous and mobile computing**.

## Keywords

Biosensing, Oral Interface, Wearable Computing, Fabrication

**ACM Reference Format:**
Yijing Jiang, Junzhe Jin, Yunhui Song, Haiyang Xu, and Michael Wessely. 2025. Demonstration of BIOral: Fabricating Intraoral pH Sensor for Continuous Health Monitoring. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '25), April 26–May 01, 2025, Yokohama, Japan.* ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3706599.3721178


## 1 Introduction

Oral health is an important indicator of overall health, as an imbalance in the oral environment often signals systemic health issues. Oral pH is one of the key parameters affecting enamel demineralization and caries risk[4]. For example, a pH below 5.5 creates an acidic environment that favors enamel erosion and bacterial proliferation [1]. In addition, fluctuations in oral pH can reflect dietary habits and saliva secretion levels, affecting the balance of the oral microbiome and overall oral health. These changes are particularly important for identifying early signs of caries, periodontal disease, and other diseases such as gastroesophageal reflux disease (GERD) [2].

In recent years, increasing research in the field of Human-Computer Interaction (HCI) has focused on integrating biomarker detection into wearable textiles or directly on the skin. For example, Holo-Chemie [10] uses bio-sourced substrate materials to develop biochemical formulations for both biological and environmental sensing. Dermal Abyss [13] integrates colorimetric and fluorescent biosensors into tattoos to monitor biomarker changes in interstitial fluid. BioWeave [14] and EcoThreads [15] showcase sweat sensors embedded in woven textiles, utilizing colorimetric and electrochemical sensing techniques. These innovations represent advances in the field of non-invasive, wearable biomarker detection and highlight the potential of wearable sensors for health monitoring.

In addition, several studies have explored devices for detecting biomarkers in saliva. For example, Matzeu et al. [7] integrated bioactive materials and colorimetric chemical sensors into oral appliances such as paper points and dental floss. Similarly, BraceIO [12] and BioCosMe [11] embedded colorimetric biosensors with everyday products, such as dental braces and lipstick. Wearable Lab on Body [9] proposes a platform that is worn on the cheek and uses paper-based biochemical sensors to sample biomarkers from saliva continuously. Similar to our work, Organic Primitives[6] utilizes anthocyanins to create food-grade sensor-actuators. These studies highlight the crucial role of monitoring changes in saliva biomarkers, such as pH, in maintaining oral health. However, these devices are either one-time tests or require additional extraoral equipment like a smartphone camera or a handheld microscope, to detect the color change of the reactants. This limits their capability to capture the dynamic nature of oral pH changes throughout the day. Currently, there is a lack of devices that can be fully worn inside the mouth and provide continuous pH monitoring.

We present BIOral, an intraoral system that integrates pH-sensitive materials with dental braces for continuous oral pH monitoring. We propose a novel fabrication method to embed edible colorimetric hydrogel into the 3D-printed dental braces alongside a digital color sensor, allowing continuous pH monitoring in the range of 4 to 8 while the brace is worn. The fabrication process utilizes commercially available materials, and the replaceable pH-sensitive hydrogel ensures easy maintenance, promoting reusability and practicality as a home-based healthcare solution. Our technical evaluation demonstrates the reversibility, performance and reaction time of the system. Finally, we outline two application scenarios showcasing how BIOral facilitates both long-term and short-term health monitoring in daily life.

## 2 Implementation

The design of the BIOral device prioritizes safety, functionality and commercial availability. The hardware part of the system (Figure 1a) is comprised of a customizable brace, pH-sensitive hydrogel and a digital color sensor, while the software includes a mobile application frontend (Figure 1c) and a backend machine learning algorithm for detection. All the materials used to make the brace and biosensors are either food-safe, biocompatible or fully encapsulated.

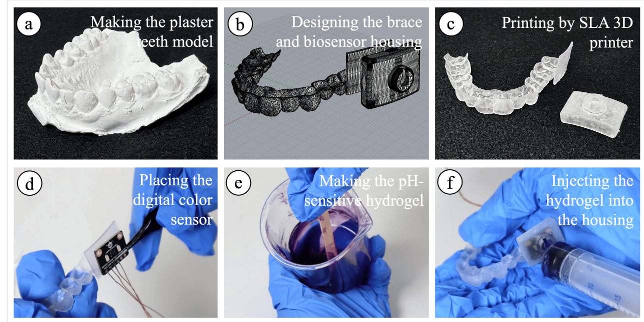


**Figure 2: The fabrication process of BIOral: (a) Making the teeth model of the user with a plaster mold. (b) Designing the brace and biosensor housing in Rhino. (c) Printing the brace and biosensor housing with a resin printer. (d) Placing the digital color sensor on the back plate of the biosensor housing. (e) Making the pH-sensitive hydrogel by mixing the k-carrageenan with the red cabbage solution. (f) Injecting the hydrogel into the biosensor housing.**

**Figure 3: The fully assembled BIOral device after exposure to a solution with a pH of 4.0.**

### 2.1 Design and Fabrication of the BIOral Brace

We base our fabrication method on the MouthIO platform [5]. First, we take the user's teeth impression using alginate[1] and fill the impression with dental plaster[2] to create a teeth model (Figure 2a). Subsequently, this plaster model is scanned with the Polycam app[3] to generate a 3D mesh.

We utilize a 3D modeling software (Rhino[4]) to process the scanned model by removing gum areas and creating a brace model with 1mm wall thickness and rounded corners for enhancing comfort. The design of the biosensor housing features a 25 mm × 20 mm × 6 mm rectangular compartment for the digital color sensor, a cylindrical compartment with a diameter of 10 mm and a thickness of 3.5 mm for the pH-sensitive hydrogel (Figure 2b).

[1]Wagner Silicones Alginat, https://www.zahntechnikshop.de/en/p/alginat-algistar-regular-set-3-4-min-colour-indicator-aroma-tropic-fruits-453-g
[2]Meyco Hobby Modelling Plaste, https://shop.meyco.eu/main/index.php?main_page=index
[3]https://poly.cam/
[4]https://www.rhino3d.com/

We 3D-printed the BIOral brace with biocompatible dental resin[5]. After printing, we cleaned the brace with isopropyl alcohol and cured the brace under UV light to enhance its mechanical stability. Finally, we polish sharp edges using a Dremel rotary tool to ensure comfort (Figure 2c).

We attach the digital color sensor to the back plate of the biosensor housing using resin and cure it under UV light. To obtain accurate pH detection, we align the color sensor with the pH-sensitive hydrogel (Figure 2d). After that, we attach the housing lid with resin to provide waterproofing and insulation, enabling the device to function reliably even during extended use, such as overnight monitoring.

## 2.2 Design and Fabrication of the Biosensor

The pH biosensor consists of hydrogel made from k-carrageenan[6] and anthocyanin, which responds to changes in pH, producing a visible color change (Figure 1b). We utilize the anthocyanins contained in red cabbage powder[7] as the pH-sensitive hydrogel ingredient as it is edible, offers a visible color changes at different pH values, and is easy to process. We chose k-carrageenan as the hydrogel matrix for its colorless, tasteless nature, making it highly suitable for oral use. Its excellent water absorption properties allow it to effectively blend with anthocyanins, forming a stable structure that can react with saliva. Additionally, it is a commercially available and affordable raw material which is straightforward to process.

To fabricate the biosensor, we first mixed red cabbage powder and mineral water in a 3:100 ratio. The red cabbage powder was thoroughly blended with mineral water to form a solution, which was then filtered through filter paper to remove insoluble impurities. Next, we mixed the k-carrageenan with the filtered red cabbage solution in a 1:25 ratio and heated it to a liquid state (Figure 2e). Finally, we inject the mixture into the biosensor housing and let it cool to room-temperature, forming a stable gel matrix (Figure 2f).

## 2.3 Brace Cleaning and Biosensor Replacement

To maintain hygiene, the brace should be rinsed with warm water to remove debris and saliva, and thoroughly cleaned with a mild dental-safe disinfectant before drying.

The pH-sensitive hydrogel can be replaced by submerging the brace in water above 70°C to melt it. Once melted, fresh pH-sensitive hydrogel can be injected and cooled to restore functionality.

## 2.4 Color Sensing

To detect color changes in the pH-sensitive hydrogel, we integrated the AS7341 visible light sensor[8] paired with an external ESP32 microcontroller for data collection. We store the collected data from the sensor's eight visible, scintillation, and NIR channels in a database for analysis. To mitigate interference from sunlight when opening the mouth, the system automatically starts and stops sampling based on incident ambient light detection. This ensures that sampling is only performed in dark conditions, with the user's mouth closed, thus maintaining the accuracy and reliability of the results.

The spectral data is converted into pH values through machine learning algorithms (PCA and Random Forest). To obtain the training data, we prepared 71 solutions with a ph value between 2 and 9 in 0.1 increments. We created these solutions by mixing tap water with citric acid[9], sodium citrate[10] and pure sodium carbonate [11]. Citric acid lowers the pH, while sodium citrate raises it, together forming a buffer system. However, for solutions with a pH above 8.5, pure sodium carbonate is required. For each solution, we collect data from three fresh pH-sensitive hydrogels. We immersed the hydrogel with the housing into the solution until the color change ends. We conducted the measurement by placing the biosensor with the digital color sensor in a black box to avoid any ambient light interference. Finally, we captured 50 readings per biosensor, which we averaged and added to the training set.

## 2.5 User Interface Design

We developed a user interface (Figure 1c) to visualize key oral health data obtained from BIOral in an intuitive way. The application features pH monitoring and two data visualization sections: pH levels change during the last measurement, and the distribution of pH normality rates across the days of the week. These visualizations provide users with a comprehensive overview of their oral health trends.

# 3 Application Scenarios

**Tracking Eating Habits.** Diet is a major contributing factor to tooth decay. Eating habits, such as consuming carbonated beverages like soft drinks or eating chocolate, can impact oral pH levels after meals [8]. BIOral provides an effective solution, allowing users to monitor their saliva pH after eating. BIOral can alert users if the pH deviates from the normal range, ensuring timely awareness and action. This can help them better understand the impact of their dietary choices, promote healthier eating habits, reduce the risk of tooth decay, and support the strengthening of tooth enamel.

**Monitoring Overnight Health.** Gastroesophageal reflux disease (GERD) is a common condition, affecting 44% of U.S. adults monthly[3]. Nighttime reflux can lead to heartburn, disrupt sleep quality, and elevate the risk of tooth decay. GERD often lowers saliva pH to acidic levels, around pH 4.9 [2]. BIOral devices enable overnight pH monitoring. Users can wear the device before sleeping to continuously track pH levels throughout the night, with data processed and stored. In the morning, users can check the app to review pH trends. This can provide insight into potential conditions like GERD and overall oral health during sleep.

# 4 Technical Evaluation

We conducted an experiment to evaluate the BIOral system's pH detection performance, reaction time, and reversibility across solutions with varying pH levels.

[5] FormLabs Dental LT Clear, https://formlabs.com/eu/store/dental-lt-clear-v2-resin/
[6] https://specialingredients.co.uk/products/carrageenan-kappa-e407
[7] https://naturzo.com/product/red-cabbage-powder/
[8] urlhttps://www.dfrobot.com/product-2131.html
[9] urlhttps://www.heitmann-hygiene-care.de/en/heitmann-pure-citric-acid-350-g/
[10] urlhttps://specialingredients.co.uk/collections/sodium-citrate/products/sodium-citrate-100g
[11] urlhttps://www.heitmann-hygiene-care.de/en/heitmann-pure-soda-500-g

**Apparatus and Procedure.** To cover a large range of saliva pH, we prepared solutions with pH values of 2 and 4 (acidic), 7 (neutral), and 8 (alkaline) using tap water, citric acid, and sodium citrate. To simulate the dark environment, we 3D-printed boxes with lids and placed thermos cups inside to maintain the constant temperature of 37°C, replicating human body temperature.

The experimental procedure involved heating 150 mL of each solution to 37°C before pouring it into the thermos cup. Then the BIOral detection device was placed inside and activated to record pH changes. Each test lasted 50 to 150 minutes until the monitoring data stabilized. The device was then immersed in the next pH solution, and the process was repeated until equilibrium was reached. All pH changes were recorded throughout the experiments.

## 4.1 Results & Discussion

**Reversibility & Detection Range.** Figure 4b shows that our biosensor is reversible between pH levels of 4, 7, and 8, but not at pH 2. Normal saliva pH ranges from 6.2 to 7.6, with an average of 6.7 [1]. The results confirm that the BIOral system is effective within the pH range of 4–8, which encompasses most daily use cases.

**System Performance.** We calculated the error in the pH values identified by the system after the first and second rounds of reactions. Excluding the six pH 2 reactions that were not successfully reversed in the second round, the average errors of the first (Figure 4a) and second (Figure 4b) rounds were 0.53 and 0.54, respectively, showing no significant difference. To improve performance, expanding the training dataset for the machine learning algorithm is a potential solution. Furthermore, we observed that the resin spacer between the color sensor and the pH-sensitive material is not fully transparent, which may affect the color detection accuracy. Moreover, despite enclosing the sensor in a black box, the LED from the color sensor introduced ambient light variations, which negatively influenced system performance.

**Reaction Time.** Our average reaction times for the first and second round were 3504 seconds and 3605 seconds, respectively, which are too slow for real-time monitoring. This delay is mainly due to the thickness of the 3.5 mm pH-sensitive material and its limited contact area with the solution. Future improvements will focus on reducing the material's thickness while maintaining its colorimetric performance. Additionally, we aim to refine the biosensor housing design to maximize the contact area between the material and the solution while ensuring robust integration of the pH-sensitive material with the brace.

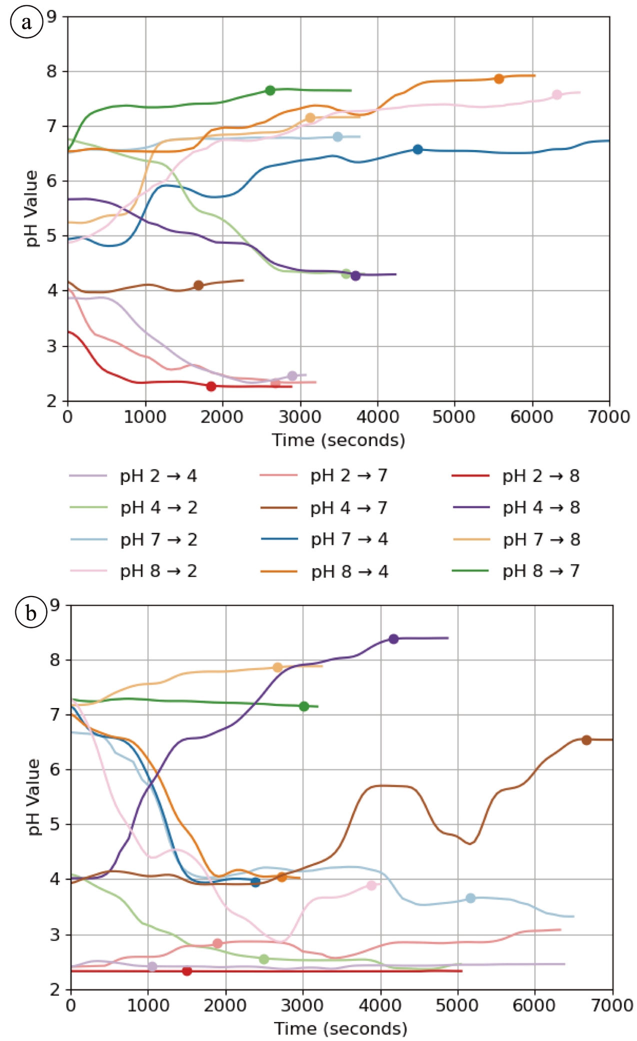


**Figure 4: We conducted 12 sets of experiments, resulting in a total of 24 reactions. (a) presents the results from the first round of 12 reactions, while (b) presents the outcomes from the second round of 12 reactions. The points where the curve approaches equilibrium are marked with dots.**

# 5 Conclusion

This paper introduces BIOral, a novel approach to integrate pH-sensitive hydrogel with dental braces, enabling continuous and less invasive monitoring of oral pH. We presented the fabrication process for the braces and colorimetric biosensors, utilizing commercially available materials that are either edible or biocompatible to ensure safety.

Looking ahead, our goal is to advance BIOral into a wireless, multifunctional health monitoring system. This evolution will involve the integration of additional biosensors, such as glucose and urea, to broaden its applications to conditions such as diabetes, metabolic syndrome, and kidney health. Furthermore, we plan to explore both colorimetric and electrochemical sensors, expanding the system's versatility and enhancing its diagnostic capabilities. We envision BIOral as a cost-effective solution for continuous health monitoring for daily use, and could advance preventive healthcare and facilitate early intervention.

# Acknowledgments

The work presented in this paper is supported by the Novo Nordisk Foundation grant NNF22OC0081352.

## References


[1] Sharmila Baliga, Sangeeta Muglikar, and Rahul Kale. 2013. Salivary pH: A diagnostic biomarker. *Journal of Indian Society of Periodontology* 17, 4 (2013), 461–465.

[2] Farah Bechir, Mariana Pacurar, Adrian Tohati, and Simona Maria Bataga. 2021. Comparative study of salivary pH, buffer capacity, and flow in patients with and without gastroesophageal reflux disease. *International Journal of Environmental Research and Public Health* 19, 1 (2021), 201.

[3] Ram Dickman, Colleen Green, Shira S Fass, Stuart F Quan, Roy Dekel, Sara Risner-Adler, and Ronnie Fass. 2007. Relationships between sleep quality and pH monitoring findings in persons with gastroesophageal reflux disease. *Journal of Clinical Sleep Medicine* 3, 5 (2007), 505–513.

[4] Frank J Dowd. 1999. Saliva and dental caries. *Dental Clinics of North America* 43, 4 (1999), 579–597.

[5] Yijing Jiang, Julia Kleinau, Till Max Eckroth, Eve Hoggan, Stefanie Mueller, and Michael Wessely. 2024. MouthIO: Fabricating Customizable Oral User Interfaces with Integrated Sensing and Actuation. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology* (Pittsburgh, PA, USA) *(UIST '24)*. Association for Computing Machinery, New York, NY, USA, Article 1, 16 pages. https://doi.org/10.1145/3654777.3676443

[6] Viirj Kan, Emma Vargo, Noa Machover, Hiroshi Ishii, Serena Pan, Weixuan Chen, and Yasuaki Kakehi. 2017. Organic Primitives: Synthesis and Design of pH-Reactive Materials using Molecular I/O for Sensing, Actuation, and Interaction. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 989–1000. https://doi.org/10.1145/3025453.3025952

[7] Giusy Matzeu, Gili RS Naveh, Siddhart Agarwal, Jeffery A Roshko, Nicholas A Ostrovsky-Snider, Bradley S Napier, and Fiorenzo G Omenetto. 2021. Functionalized Mouth-Conformable Interfaces for pH Evaluation of the Oral Cavity. *Advanced Science* 8, 12 (2021), 2003416.

[8] Ankit Pachori, Haalaswamy Kambalimath, Satish Maran, Babita Niranjan, Garima Bhambhani, and Garima Malhotra. 2018. Evaluation of changes in salivary pH after intake of different eatables and beverages in children at different time intervals. *International journal of clinical pediatric dentistry* 11, 3 (2018), 177.

[9] Pat Pataranutaporn, Abhinandan Jain, Casey M. Johnson, Pratik Shah, and Pattie Maes. 2019. Wearable Lab on Body: Combining Sensing of Biochemical and Digital Markers in a Wearable Device. In *2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. 3327–3332. https://doi.org/10.1109/EMBC.2019.8857479

[10] Sutirtha Roy, Moshfiq-Us-Saleheen Chowdhury, Jurjaan Onayza Noim, Richa Pandey, and Aditya Shekhar Nittala. 2024. HoloChemie - Sustainable Fabrication of Soft Biochemical Holographic Devices for Ubiquitous Sensing. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology* (Pittsburgh, PA, USA) *(UIST '24)*. Association for Computing Machinery, New York, NY, USA, Article 111, 19 pages. https://doi.org/10.1145/3654777.3676448

[11] Shuyi Sun, Yuan-Hao Ku, Nicole Unsihuay, Omar Florez, Jae Yong Suk, Ali K. Yetisen, and Katia Vega. 2024. BioCosMe: Lip-based Cosmetics with Colorimetric Biosensors for Salivary Analysis using Deep Learning. In *Proceedings of the 2024 ACM International Symposium on Wearable Computers* (Melbourne VIC, Australia) *(ISWC '24)*. Association for Computing Machinery, New York, NY, USA, 32–39. https://doi.org/10.1145/3675095.3676610

[12] Eldy S. Lazaro Vasquez, Ali K. Yetisen, and Katia Vega. 2020. BraceIO: Biosensing through Hydrogel Dental Ligatures. In *Proceedings of the 2020 International Symposium on Wearable Computers (ISWC '20)*. ACM, 87–89. https://doi.org/10.1145/3410531.3414290

[13] Katia Vega, Nan Jiang, Xin Liu, Viirj Kan, Nick Barry, Pattie Maes, Ali Yetisen, and Joe Paradiso. 2017. The dermal abyss: interfacing with the skin by tattooing biosensors. In *Proceedings of the 2017 ACM International Symposium on Wearable Computers* (Maui, Hawaii) *(ISWC '17)*. Association for Computing Machinery, New York, NY, USA, 138–145. https://doi.org/10.1145/3123021.3123039

[14] Jingwen Zhu, Nadine El Nesr, Christina Simon, Nola Rettenmaier, Kaitlyn Beiler, and Cindy Hsin-Liu Kao. 2023. BioWeave: Weaving Thread-Based Sweat-Sensing On-Skin Interfaces. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 35, 11 pages. https://doi.org/10.1145/3586183.3606769

[15] Jingwen Zhu, Lily Winagle, and Hsin-Liu (Cindy) Kao. 2024. EcoThreads: Prototyping Biodegradable E-textiles Through Thread-based Fabrication. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 857, 17 pages. https://doi.org/10.1145/3613904.3642718