Wearability Factors for Body-Worn Colorimetric Biosensors

Shuyi Sun
University of California, Davis
Davis, USA
shusun@ucdavis.edu

Ali K. Yetisen
Imperial College London
London, UK
a.yetisen@imperial.ac.uk

Katia Vega
University of California, Davis
Davis, USA
kvega@ucdavis.edu

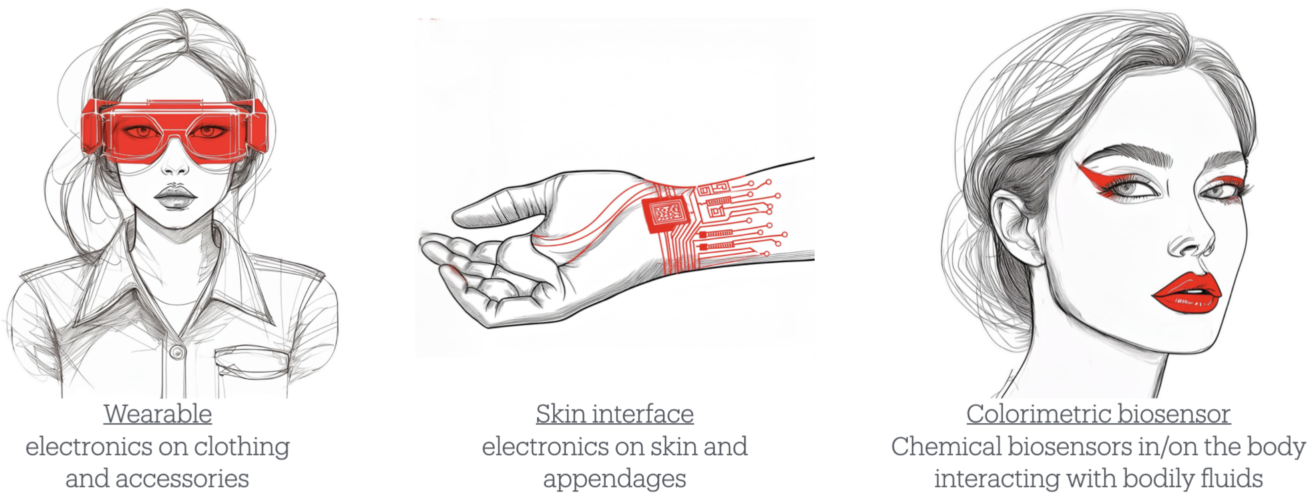

Figure 1: Comparison of Wearable, Skin Interface, and Colorimetric Biosensor

ABSTRACT

Colorimetric biosensors offer significant potential for real-time health monitoring through wearable technologies. However, the design and implementation of these sensors require careful consideration of various wearability factors that are commonly overseen in more scientific and technical approaches. This paper introduces 20 wearability factors specific to body-worn colorimetric biosensors. We compare these factors with skin interfaces and wearable technologies to highlight the unique challenges and considerations when designing colorimetric biosensors. The paper discusses these factors in the context of two applications: a lipstick for salivary analysis and a permanent tattoo that interacts with interstitial fluid. We also introduce the concept of the "Biocosmetic Interface," which combines aesthetic appeal with health monitoring, demonstrating new possibilities for non-invasive, visually appealing biosensors in daily life.

CCS CONCEPTS

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

UbiComp Companion '24, October 5–9, 2024, Melbourne, VIC, Australia

ACM ISBN 979-8-4007-1058-2/24/10
https://doi.org/10.1145/3675094.3678486

KEYWORDS

colorimetric biosensors, chemical biosensing, body fluids, skin interfaces, wearability factors, wearable computing

ACM Reference Format:
Shuyi Sun, Ali K. Yetisen, and Katia Vega. 2024. Wearability Factors for Body-Worn Colorimetric Biosensors. In *Companion of the 2024 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp Companion '24), October 5–9, 2024, Melbourne, VIC, Australia.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3675094.3678486

1 INTRODUCTION

Chemical biosensors are widely used for measuring chemical reactions in fluids through various applications, including medical diagnostics, environmental monitoring, and food safety. They convert biochemical responses into measurable signals and are categorized into colorimetric, fluorescent, and electrochemical types. Colorimetric biosensors provide visual feedback through color changes, making them simple and cost-effective. Fluorescent biosensors use fluorophores for changes in light emission, visible under UV light. Electrochemical biosensors measure electrical signals from interactions with electrode surfaces, offering high sensitivity. Among these, colorimetric biosensors are notable for their ease of use and interpretation without being connected to an electronic device.

Colorimetric biosensors have been developed for detecting analytes in biofluids such as saliva, blood, and sweat [24, 40], essential for monitoring various health conditions[55]. Traditionally used in medical devices, test strips and laboratories, colorimetric biosensors, although not a new concept, have garnered renewed interest among HCI researchers who are exploring various form factors for their integration into wearable technology. For instance, diabetic patches and permanent biosensors [52] are designed to interact with interstitial fluid. Jewelry sensors primarily focus on sweat analysis [45], while temporary tattoos [15, 27, 29, 53], also interact with sweat. Fabric-based sensors [40, 65], available in forms like headbands, shirts, and socks, are adept at monitoring sweat as well. BraceIO [48] created dental ligatures for orthodontics with colorimetric biosensors that interact with saliva. These diverse applications highlight the adaptability and non-invasive nature of colorimetric biosensors in wearable technology for continuous analyte monitoring.

Various factors affecting wearability have been identified, including placement, form language, human movement, proxemics, sizing, attachment, containment, weight, accessibility, thermal aspects, interaction, aesthetics, and long-term use [12]. Dunne identified that 'wearability' in wearable technology lies at the intersection between ubiquitous computing and functional clothing design, including thermal comfort, moisture management, mobility, flexibility, durability, sizing and fit, and garment care [10]. Wearability factors for skin interfaces differentiate between on-the-body and technical factors [30]. Our study provides a new set of 20 wearability factors specifically tailored for colorimetric wearable biosensors, drawing from insights on skin interface factors outlined by Liu et al [31]. These factors include functionality, usability, implementation, and ethical use, as detailed in Table 1. Table 2 provides a comprehensive comparison of wearability factors across different types of wearable technologies, including colorimetric biosensors, wearable computing devices, and skin interfaces.

The main contributions of this paper are:

Wearability Factors Specific to Colorimetric Biosensors: A new set of 20 wearability factors tailored specifically for colorimetric wearable biosensors is introduced. These factors are: Interaction, Actuators, Input Data, Safety of Materials, Response Time, Location, Body Movements, Body Features, Weight, Attachment Methods, Aesthetics, Conductors, Insulation, Device Care, Connection, Communication, Durability, End of Life, Privacy, Social Acceptance.

Comparison with Other Wearable Technologies: The paper provides a comprehensive comparison of wearability factors between colorimetric biosensors, wearable computing devices, and skin interfaces. This comparison highlights the unique aspects and challenges of colorimetric biosensors in terms of functionality, usability, and user experience.

Applications: Lipstick Biosensor and Permanent Tattoo Biosensor: The paper represents this wearability factors into detailed case studies of two applications: a lipstick equipped with colorimetric biosensors for salivary analysis and a permanent tattoo equipped with colorimetric biosensors. These applications demonstrate the practical implementation and user considerations of colorimetric biosensors in biocosmetic interfaces.

Introduction of "Biocosmetic Interface" Concept: We introduce the concept of "Biocosmetic Interface," which integrate biosensing capabilities into cosmetic products. This novel approach combines aesthetics with health monitoring, opening new possibilities for non-invasive, visually appealing biosensors embedded in everyday cosmetic items.

2 WEARABILITY FACTORS FOR BODY-WORN COLORIMENTRIC BIOSENSORS

To ensure the effective design and application of body-worn colorimetric biosensors, we propose 20 wearability factors that are classified into four main themes as shown in Table 1.

Theme	Factors
Functionality	Interaction, Actuators, Input Data, Response Time
Usability	Weight, Attachment Methods, Aesthetics, Location, Body Movements, Body Features, Device Care
Implementation & Maintenance	Connection, Communication, Insulation, Conductors, Durability
Ethical Use	Safety of Materials, Environmental Impact, Social Acceptance, Privacy of Information

Table 1: Classification of Wearability Factors

This section examines these factors in detail, highlighting how they differ from those relevant to traditional skin interfaces and wearable technologies. Table 2 summarizes these factors and the associated comparisons.

1. Interaction: Wearable technologies typically involve electronic sensors and actuators, providing immediate feedback through various modalities such as visual, auditory, or kinesthetic [57]. Skin interfaces also use electronic sensors and actuators but can include direct interactions with the skin. In contrast, colorimetric biosensors rely on chemical reactions when in contact with body fluids such as saliva, tears, interstitial fluids, sweat, urine and blood. These reactions are targeted toward specific analytes, providing visual feedback through color changes [47].

2. Actuators: Wearable technologies provide feedback through visual, tactile, auditory, olfactory or kinesthetic means, often integrated into the garment or accessory. Skin interfaces offer similar feedback but can also include actuators placed directly on or under the skin [36, 52, 56]. Colorimetric biosensors rely on visible color changes, observable through naked eye or mobile apps and devices for interpretation. The color range and intensity must be noticeable and quantifiable to ensure usability and effectiveness.

3. Input Data: Wearable technologies and skin interfaces mostly use physiological inputs such as heart rate, movement, and blend, or gesture-based inputs like touch, press, and swipe. Colorimetric biosensors, however, use metabolic changes as an input. The biosensor requires direct contact with the fluid to sense data through chemical reactions, making the definition of the analyte or analytes crucial for accurate sensing [6]. In addition to deciding the analyte, the biosensor device must define illness or health benefits to monitor [64], amount of fluid in the location, frequency of readouts, sampling time, and composition of analyte in body fluid that interacts.

4. Response time: Wearable technologies typically offer fast response times through electronic sensors, providing immediate feedback. Skin interfaces also offer quick responses via electronic sensors [39, 60]. On the other hand, colorimetric biosensors often exhibit slower response times as they reflect changes in body fluids

Table 2: Wearability Factors Comparison: Wearable Technologies, Skin Interfaces, and Colorimetric Biosensors

WEARABILITY FACTORS	WEARABLE COMPUTING	SKIN INTERFACES	COLORIMETRIC BIOSENSORS
Interaction	Electronics as sensors and actuators	Electronics as sensors and actuators	Chemical reactions when contact body fluids working as sensors and actuators; targeted to the analyte to sense; materials must be non-reactive and safe
Actuators	Visual, tactile, auditory or kinesthetic access on the garment	plus underneath the clothing, accessories, on-skin or surgical	Visible color changes through observation, mobile apps or devices for interpretation; range and intensity must be noticeable and quantifiable
Input Data	Physiological inputs or gesture-based inputs	Physiological inputs or gesture-based inputs	Analytes such as pH, glucose, sodium that are in contact with body fluids
Safety of Materials	Generally safe materials or encapsulated	Generally safe materials or encapsulated	Use of non-toxic, biocompatible chemicals to ensure user safety; microfluidics to avoid non biocompatible materials to interact with the body
Response Time	Usually fast response through electronic sensor	Usually fast response through electronic sensor	Slow response on body fluids reflecting metabolisms changes; target analytes and color change
Location	Clothing and accessories	Skin and its appendages (i.e., hair and nails)	on-skin, within the skin and in the body interacting with body fluids
Body Movements	Micro and macro movements	plus skin movements (stretch, shear, bounce)	Micro and macro, skin movements, plus body fluid drag force
Body Features	Size, shape, muscle strength, constantly evolving	Skin features: moisturizing, types, wrinkles, skin hair, skin tone, injuries or skin conditions	Skin features: moisturizing, types, wrinkles, skin hair, skin tone, injuries or skin conditions
Weight	Heavy devices may be uncomfortable to wear	Heavy devices may cause uncomfort, irritation, injury on skin or falls	Lightweight interfaces with just few layers
Attachment Methods	Garments, accessories, clips	Skin glue, hair accessories, piercing, bands, clothing and accessories	skin glue, microneedles, integration into daily products on or tightly attached to the body
Aesthetics	Electronics could be hidden or visible; shapes, materials, textures and colors	Electronics could be hidden or visible; tattoo, cosmetics, prosthetics, artificial nails and hair	Biosensors can be discreet (tattoos, patches, jewelry, clothing)
Conductors	rigid and flexible PCB, cables; conductive fabric, yarns for clothing applications	Conductive ink, conductive cosmetics, epidermal electronics systems, fluid metal	Not applicable
Insulation	Soft materials and rigid materials	Skin-friendly materials; no electronics directly on skin; body shielding or grounding the body	Skin-friendly products in contact with the skin; encapsulation from fluids with microfluidics, biosensors could be not safe to be in contact with the skin
Device Care	Washability, removing and reattaching; encapsulation, protection from fluids and environmental factors	protection from fluids and environmental factors that can contaminate readaouts	short lifespan; reapplication is expected
Connection	e-textiles; PCB; wires, solders, conductive adhesives, pressure contact	PCB; wires, solders, conductive adhesives, pressure contact	Most do not present connections, or biosensors connected through microfluidics channels
Communication	Wiring; wireless communication: Bluetooth, Wi-Fi, radio	Wiring; wireless communication: Bluetooth, Wi-Fi, radio	Integration with devices for real-time data transmission
Durability	Rechargeable commercial batteries, energy harvesting, long-term use	Rechargeable commercial batteries, energy harvesting, long-term use with some single use componennts	short lifespan and reusability, some biosensors allows reversibility, reusability must maintain accuracy and hygiene
End of Life	Energy consumption, e-waste	Energy consumption, e-waste	Non sustainable materials can generate waste
Privacy	Data protection; usage and privacy terms	Data protection; usage and privacy terms	Data protection; usage and privacy terms; colors can be decoded by observer
Social Acceptance	Hardware can make it noticeable. Discreet when hidden in accessories or using e-textiles techniques.	Hardware can make it noticeable. Discreet if conforming to skin or connected to accessory.	Discreet like makeup or tattoos, but microfluidics may add bulk.

and metabolic processes [1]. The biosensors must target an specific analyte to ensure non-reaction with other analytes interfere, and display prompt color changes, although the speed may vary depending on the analyte and environmental conditions.

5. Location: Wearable technologies are typically integrated into clothing and accessories [11, 18, 62]. Skin interfaces are applied directly to the skin and its appendages [32, 38, 46, 49]. Colorimetric biosensors can be applied on the skin, within the skin, or inside the body, interacting with various body fluids. This flexibility allows for diverse application possibilities, such as tattoos [17], patches, or integration into oral devices and accessories.

6. Body Movements: Wearable technologies must accommodate micro and macro movements of the body. Skin interfaces must handle extra skin movements such as stretching, shearing, and bouncing in addition to body movements [11]. Colorimetric biosensors must handle both micro and macro movements, skin movements, and body fluid drag forces [1, 7]. Flexible and stretchable materials are essential to ensure functionality and comfort[35].

7. Body Characteristics: Wearable technologies must consider size, shape, muscle strength, and the evolving nature of the body. Skin interfaces additionally must account for skin characteristics such as type, wrinkles, pimples, hair, color, moisture, and conditions like eczema [11]. Colorimetric biosensors must also consider these skin characteristics, ensuring the biosensors' effectiveness across different users and scenarios [35].

8. Weight: Wearable technologies can be uncomfortable if the devices are too heavy. Skin interfaces also face issues with heavy devices, which can cause discomfort, irritation, injury, or falls [41, 54]. Colorimetric biosensors benefit from being lightweight [31], consisting of just a few layers such as in bandages or temporary tattoos, or conforming within the body such as in permanent tattoos or makeup.

9. Attachment Methods: Wearable technologies use garments, accessories, and clips for attachment. Skin interfaces utilize skin glue, hair accessories, piercings, bands, and can be placed underneath clothing and accessories [32, 38, 46, 49]. Colorimetric biosensors can use skin glue, microneedles, or be integrated into daily products such as jewelry or clothing [7]. These methods must ensure secure attachment while being skin-friendly and easy to use.

10. Aesthetics: Wearable technologies can be either hidden or visible, offering various shapes, materials, textures, and colors. Skin interfaces can also be hidden or visible, resembling tattoos, cosmetics, prosthetics, artificial nails and hair. Colorimetric biosensors can be discreetly integrated into tattoos, patches, jewelry [7, 45], or clothing, balancing functionality and aesthetics to suit user preferences.

11. Device Care: Wearable technologies require washability, methods for removing and reattaching, and encapsulation to protect from fluids and environmental factors [43, 45, 58]. Skin interfaces have a short lifespan and require protection from fluids and environmental factors. Colorimetric biosensors also have a shorter lifespan, with reapplication expected or frequent maintenance expected [28]. They need protection from environmental factors to maintain sensor integrity and performance.

12. Conductors: Wearable technologies utilize rigid and flexible PCBs, cables, and conductive fabrics or yarns for clothing applications [43]. Skin interfaces employ conductive ink, conductive cosmetics, epidermal electronics systems, and fluid metal. Colorimetric biosensors generally do not require conductors, as they rely on chemical reactions rather than electronic circuitry.

13. Insulation: Wearable technologies use both soft and rigid materials. Skin interfaces prefer skin-friendly materials, avoiding direct electronic contact with the skin and providing body shielding or grounding [59]. Colorimetric biosensors use skin-friendly products for contact with the skin and encapsulate the biosensors from fluids with microfluidics, ensuring non-biocompatible elements do not touch the skin.

14. Connection: Wearable technologies use e-textiles and rigid components adapted to common PCB fabrication processes. Skin interfaces utilize low-temperature solders, conductive adhesives, and direct contact with pressure [57]. Colorimetric biosensors typically do not require traditional electronic connections, often utilizing microfluidic channels to manage fluid redirection.

15. Communication: Wearable technologies use wiring and wireless communication methods like Bluetooth, Wi-Fi, and radio [13, 20]. Skin interfaces employ similar communication methods. Colorimetric biosensors can integrate with mobile devices, often by using computer vision or machine learning for color detection [33].

16. Durability: Wearable technologies are typically designed for long-term use [37]; however, they use short-term electronics such as rechargeable commercial batteries and energy harvesting methods [31]. Similary, skin interfaces can be designed for long-term use with some replacement of components, but some of their components that are in contact with the skin and some attachement methods required a single use such as temporal tattoos, bandages, eyelashes [3]. Colorimetric biosensors generally do not require batteries, relying instead on chemical reactions for functionality [23, 25]. They have a short lifespan due to the interaction with fluids and require re-application of the products on the body and re-filling of the biosensor. Some colorimetric biosensors allow for reversibility and reusability, provided that accuracy and hygiene are maintained [3, 4]. Reusability depends on the specific application and the durability of the analytes.

17. Safety of materials: Wearable technologies generally use safe materials or encapsulate components to prevent harm [63]. Skin interfaces also use safe or encapsulated materials to avoid adverse reactions. Colorimetric biosensors must utilize non-toxic and biocompatible chemicals for sensing reactions to ensure user safety [2, 22]. However, some projects used microfluidics to encapsulate biosensors with irritant materials to not directly interact with the body, adding an extra layer of safety [26].

18. Environment Impact: Usage and End of Life: Wearable technologies and skin interfaces often face sustainability challenges due to electronic and energy waste [18, 19]. Colorimetric biosensors, particularly those designed for single use, must consider eco-friendly materials and disposal methods to reduce environmental impact [34].

19. Social Acceptance: Wearables and electronic skins can be noticeable because of their electronic components and batteries [43, 62]. Colorimetric biosensors, which use microfluidics, can also appear more prominent due to this added bulk. However, when designed to look like makeup [21], tattoos [56], or dental braces [48], colorimetric biosensors can blend seamlessly with the body. The main issue with these biosensors is that their color changes can reveal personal health information if observers understand their function. This visibility poses a challenge for social acceptance, highlighting the need to balance functionality, aesthetics, and privacy in biosensor design.

20. Privacy of Information: Wearable technologies, skin interfaces, and colorimetric biosensors often include concerns about data privacy, especially when collecting sensitive health information and data usage [14, 16, 61]. Colorimetric biosensors also present those challenges when storing data, and, additionally, they present

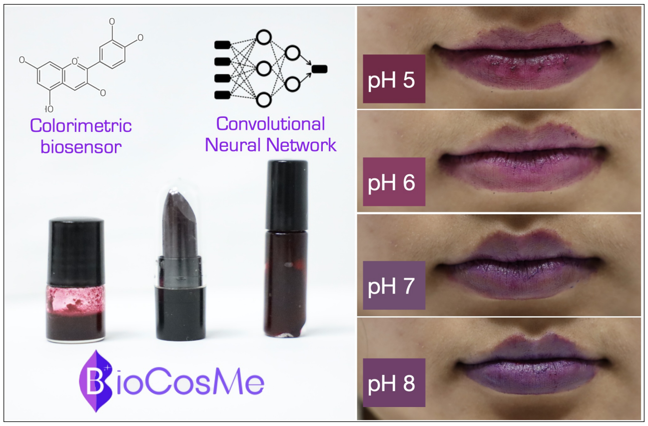

Figure 2: Lip-based products as Colorimetric biosensors[44]

unique challenges as the visible color changes can reveal biodata to observers. Ensuring data privacy through considering the visibility of biosensor output or using other chemicals to encrypt those data is crucial to protect user information.

3 APPLICATION:LIPSTICK BIOSENSOR

3.1 Lipstick as a Biosensor

BioCosMe [44] is a *biocosmetic interface* in the form of a lipstick equipped with colorimetric biosensors for salivary analysis (Figure 1). We define ***biocosmetic interfaces*** as body-worn chemical biosensors that integrate biosensing capabilities into cosmetic products, combining aesthetics with health monitoring. This novel approach allows users to engage in non-invasive health monitoring while maintaining their regular cosmetic routines. Lip products are formulated using skin-safe, food-grade and cosmetic-grade materials. Fabrication process, software and dataset are available at our repository [1].

Interaction occurs through the lip-product changing color in reaction to pH levels. Levels of pH is more alkaline in chronic gingivitis patients and more acidic in chronic periodontitis patients [5], it can provide metabolic, hormonal, and immunological aspects [8], has a relationship with stress levels [9], and changes on pH have been observerd in diabetic patients [42]. It facilitated through user-friendly application methods, ensuring ease of use for consumers who apply and reapply lipstick, lip gloss or lip tint. **Actuators** such as colorimetric biosensors are fused into lipstick materials to detect pH levels (pH 5 to 8) in saliva. **Safety of chemicals** is ensured through the use of cosmetic-grade and skin-safe materials, validated in user study and following the ethics approval from research institution. **Response Time and lifespan** in colorimetric response to pH variations in saliva are optimized for rapid detection, enhancing real-time usability considering user's eating schedules. **Location-based usability** considerations account for application areas on the lips, interaction with saliva, and food and drinks and are customized for pH detection. **Body movements** are considered in the formulation of the product to maintain the integrity of the biosensor during application, re-application and wear.

[1]https://github.com/InteractiveOrganismsLab/ChromaLipSense

Body characteristics and attachment methods like lip shape and size did not influence as process follows traditional lipstick design and fabrication processes. **Aesthetics** are prioritized with formulations that balance cosmetic appeal and biosensing efficacy, maintaining consistent colorimetric properties across different lip products. **Device care and Durability** includes reapplication after long period of usage or contact with food and drinks. Reusability was evaluated to ensure that the biosensor provides reversibility; however, reapplication of the lip product is recommended. **Connection and communication aspects** include integration with a mobile app for pH level detection, enhancing user convenience and data accessibility. **Weight and conductors** follow commercial product consistency, matching the light weight of other lip products. **Insulation materials** can create a soft layer of insulation due to the cosmetic products such as waxes. **Sustainability** is promoted through the use of biocompatible materials. **Social acceptance** User study results presented that participants found the lipstick biosensor comparable with commercial products. **Privacy of information** is ensured by using a similar range of colors as traditional lipsticks, however, other chemicals or combinations with other colors could be considered. Users did not express privacy concerns on using a visible colorimetric biosensor.

3.2 Permanent Tattoo as a Biosensor

We analyze Dermal Abyss [52], a permanent tattoo equipped with colorimetric biosensors to detect pH, sodium, and glucose levels in interstitial fluid. The interstitial fluid, a medium surrounding cells, enables the delivery of biomolecules and intercellular communication. Electrolytes such as sodium ions ($Na+$), chloride ions ($Cl-$), bicarbonate ($HCO3-$), potassium ($K+$), calcium ($Ca2+$), and magnesium ($Mg2+$) are present in the interstitial fluid. Monitoring these analytes can provide crucial information about human metabolism.

Interaction is achieved through color changes that react directly with the interstitial fluid. Needle from the tattoo gun deposits the biosensor in the dermis. **Actuators** are the colorimetric and fluorescence biosensors that provide visual feedback readable with a smartphone. Biosensors for pH, sodium ions, and glucose were selected due to their medical importance. The fundamental metabolite, pH, regulates acid-base homeostasis, with deviations indicating acidosis or alkalosis. Sodium regulates blood volume and pressure, with deviations potentially fatal. Glucose monitoring is vital for diabetes management. For this proof of concept, the **Safety of Materials** was ensured by using an ex-vivo model instead of tattooing human subjects. The **Response Time** depends on the changes in the metabolism occurring in the interstitial fluid, providing a faster response than fluids such as saliva or sweat [40]. **Location** is typically on thin-skin areas like the forearm, though it could be any body part. The tattoo's liquid form ensures functionality during various **Body Movements**. **Body Characteristics** considerations include the effectiveness of the ink on different body types, skin types and tones, which should be further evaluated. Some users presented allergies and reactions to traditional tattoo, thus a living cell test must be considered. The tattoo is **Weightless**, consisting only of ink in the dermis. **Attachment Methods** involve traditional tattooing techniques, with cross-section tests confirming the ink's location within the dermis. **Aesthetics** blend visually appealing

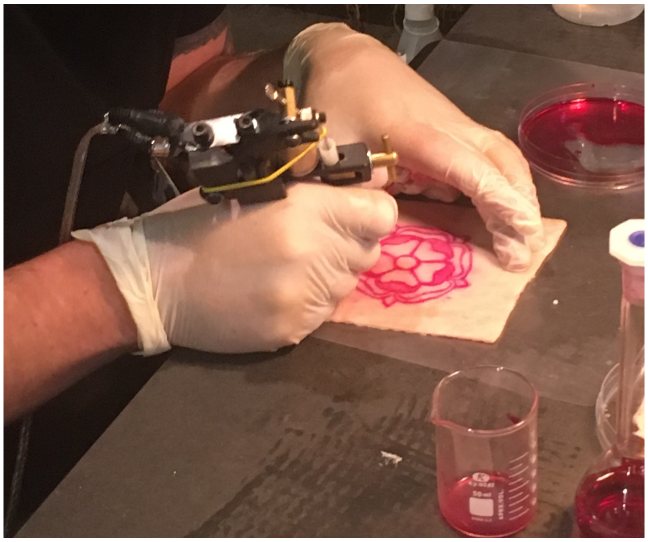

Figure 3: Permanent Tattoo as colorimetric biosensors (The Dermal Abyss demonstration [52])

designs with subtle color changes. **Device Care** is minimal, with the tattoo enduring daily activities, sunlight, and water, though its long-term durability was not evaluated. **Communication** occurs through visual color changes, with a smartphone app providing detailed analysis. The tattoo's **Durability** allows for continuous monitoring with reversible color changes, but further evaluation is required for permanent use. **Sustainability (End of Life)** is addressed as no materials are discarded after use. **Social acceptance** was not evaluated but biosensor inks have similar colors as traditional inks. To increase its discreet aspect, several inks with different biosensors could be applied to the same tattoo, expanding the possibilities of tattoo designing, similar to traditional ones. **Privacy of Information** is maintained through discreet color changes, with app data kept secure, though encryption is necessary to protect it from observers. **Conductors**, **Connection**, **Battery Life**, and **Insulation** are not needed.

4 DISCUSSION

The integration of colorimetric biosensors into wearable technologies introduces unique considerations for HCI researchers, spanning design, material science, chemical engineering, and biotechnology. The application of these biosensors in everyday items such as cosmetics and tattoos offers promising opportunities for enhancing user engagement and compliance, providing insights into bodily fluids through chemical interactions. However, achieving a seamless integration of these biosensors without compromising functionality or aesthetics remains a significant challenge.

Health Monitoring Opportunities. Colorimetric biosensors present an innovative approach to health monitoring, moving beyond traditional lab-based methods. By capturing biochemical information from body fluids, these biosensors enable the development of interactive devices that respond to metabolic cues. Unlike conventional wearables that depend on electronics and batteries, colorimetric biosensors function through chemical reactions, offering a more integrated and discreet solution that aligns closely with human physiology.

Interaction and Actuation: Wearable technologies and skin interfaces can provide feedback through various sensory modalities. In contrast, colorimetric biosensors rely on chemical reactions with body fluids to produce visual feedback, often interpreted through mobile apps. This method enhances accessibility but introduces challenges such as ensuring accurate color detection under varying conditions (lighting, skin tone, body movements) and expanding the limited color range of current biosensors. Selecting the right biosensor involves balancing factors like target illness, accuracy, color range, analyte concentration, and commercial availability.

Data and Communication: While wearable and skin interfaces rely on physiological or gesture-based inputs with data transmitted via wired or wireless methods, colorimetric biosensors detect analytes in body fluids and transmit data through integrated devices. The response time needs to be in consideration as the color response will be affected on readout. This approach, though slower in response, provides valuable insights into the body's internal data and offers unique advantages to have access to the inner self.

Material Safety and Privacy: The safety and biocompatibility of materials used in colorimetric biosensors are critical due to their prolonged skin contact. Researchers must ensure that materials are safe and transparent about their use to maintain usability and replicability, as well as following current regulations and standards such as MDR 2017/745, IVDR 2017/746, FDA, ISO 13485, ISO 14971, among others. Privacy concerns also play a significant role, as colorimetric biosensors can reveal sensitive health information. Ensuring that data collection and usage are ethical and secure is essential for building user trust. Discreet design is crucial, but microfluidics or visible color changes may still pose privacy challenges if the color codes are understood by observers.

Future Works. Future research should explore wearability factors for other types of biosensors, such as fluorescence and electrochemical sensors. While the current list of wearability factors is based on initial experiences, user studies will be necessary to validate and refine these criteria. Collaborations across disciplines, including fashion, jewelry, and beauty product design, will help co-create innovative user experiences. Addressing issues related to durability, comfort, and aesthetics will be essential for increasing the adoption and effectiveness of interactive biosensors.

Biocosmetic Interface. Previous research has explored Beauty Technology [50, 51] that merges cosmetics with electronics. With this project, we introduce a novel subfield in Human-Computer Interaction (HCI) known as *Biocosmetic Interface,* which integrates cosmetics with biotechnology for health monitoring. This approach transforms the body surface into a dynamic display of biochemical reactions. It aims to enable the development of new *biocosmetic interfaces* that, by using beauty products, will provide access to typically unexplored bodily compartments, such as bodily fluids.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No 2146461.

REFERENCES

[1] [n. d.]. A "Two-Part" Resonance Circuit based Detachable Sweat Patch for Noninvasive Biochemical and Biophysical Sensing. https://www.researchgate.net/publication/365819976_A_Two-Part_Resonance_Circuit_based_Detachable_Sweat_Patch_for_Noninvasive_Biochemical_and_Biophysical_Sensing

[2] Bilge Asci Erkocyigit, Ozge Ozufuklar, Aysenur Yardim, Emine Guler Celik, and Suna Timur. 2023. Biomarker Detection in Early Diagnosis of Cancer: Recent Achievements in Point-of-Care Devices Based on Paper Microfluidics. *Biosensors* 13, 3 (March 2023), 387. https://doi.org/10.3390/bios13030387

[3] Ananta Narayanan Balaji, Chen Yuan, Bo Wang, Li-Shiuan Peh, and Huilin Shao. 2019. pH Watch - Leveraging Pulse Oximeters in Existing Wearables for Reusable, Real-time Monitoring of pH in Sweat. In *Proceedings of the 17th Annual International Conference on Mobile Systems, Applications, and Services*. ACM, Seoul Republic of Korea, 262–274. https://doi.org/10.1145/3307334.3326105

[4] Sharmila Baliga, Sangeeta Muglikar, and Rahul Kale. 2013. Salivary pH: A diagnostic biomarker. *Journal of Indian Society of Periodontology* 17, 4 (July 2013), 461–465. https://doi.org/10.4103/0972-124X.118317

[5] Sharmila Baliga, Sangeeta Muglikar, and Rahul Kale. 2013. Salivary pH: A diagnostic biomarker. *Journal of Indian Society of Periodontology* 17, 4 (2013), 461–465. https://doi.org/10.4103/0972-124X.118317

[6] Mohammad Mahdi Bordbar, Mahboobeh Sadat Hosseini, Azarmidokht Sheini, Elham Safaei, Raheleh Halabian, Seyed Mosayeb Daryanavard, Hosein Samadinia, and Hasan Bagheri. 2023. Monitoring saliva compositions for non-invasive detection of diabetes using a colorimetric-based multiple sensor. *Scientific Reports* 13, 1 (2023), 16174. Publisher: Nature Publishing Group UK London.

[7] Oğuz 'Oz' Buruk, Çağlar Genç, İhsan Ozan Yıldırım, Mehmet Cengiz Onbaşlı, and Oğuzhan Özcan. 2021. Snowflakes: A Prototyping Tool for Computational Jewelry. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3411764.3445173

[8] Silvia Chiappin, Giorgia Antonelli, Rosalba Gatti, and Elio F. De Palo. 2007. Saliva specimen: a new laboratory tool for diagnostic and basic investigation. *Clinica Chimica Acta; International Journal of Clinical Chemistry* 383, 1-2 (Aug. 2007), 30–40. https://doi.org/10.1016/j.cca.2007.04.011

[9] Miri Cohen and Rabia Khalaila. 2014. Saliva pH as a biomarker of exam stress and a predictor of exam performance. *Journal of Psychosomatic Research* 77, 5 (Nov. 2014), 420–425. https://doi.org/10.1016/j.jpsychores.2014.07.003

[10] L. Dunne. 2008. Wearability in Wearable Computers. In *Wearable Computers, 2008. ISWC 2008. 12th IEEE International Symposium on*. 125.

[11] Jutta Fortmann, Wilko Heuten, and Susanne Boll. 2015. User requirements for digital jewellery. In *Proceedings of the 2015 British HCI Conference (British HCI '15)*. Association for Computing Machinery, New York, NY, USA, 119–125. https://doi.org/10.1145/2783446.2783573

[12] Fabian Gemperle, Christopher Kasabach, John Stivoric, Martin Bauer, and Richard Martin. 1998. Design for Wearability. In *Wearable Computers, 1998. Digest of Papers. Second International Symposium on*. 116–122.

[13] Bruno Gil, Salzitsa Anastasova, and Guang Z. Yang. 2019. A Smart Wireless Ear-Worn Device for Cardiovascular and Sweat Parameter Monitoring During Physical Exercise: Design and Performance Results. *Sensors* 19, 7 (Jan. 2019), 1616. https://doi.org/10.3390/s19071616 ZSCC: 0000032 Number: 7 Publisher: Multidisciplinary Digital Publishing Institute.

[14] Omer Granoviter, Alexey Gruzdev, Vladimir Loginov, Max Kogan, and Orly Zvitia. 2023. Face Recognition Using Synthetic Face Data. http://arxiv.org/abs/2305.10079 arXiv:2305.10079 [cs].

[15] Tomàs Guinovart, Amay J. Bandodkar, Joshua R. Windmiller, Francisco J. Andrade, and Joseph Wang. 2013. A potentiometric tattoo sensor for monitoring ammonium in sweat. *The Analyst* 138, 22 (2013), 7031. https://doi.org/10.1039/c3an01672b

[16] Neilly H. Tan, Richmond Y. Wong, Audrey Desjardins, Sean A. Munson, and James Pierce. 2022. Monitoring Pets, Deterring Intruders, and Casually Spying on Neighbors: Everyday Uses of Smart Home Cameras. In *CHI Conference on Human Factors in Computing Systems*. ACM, New Orleans LA USA, 1–25. https://doi.org/10.1145/3491102.3517617

[17] Amay J. Bandodkar, Vinci W. S. Hung, Wenzhao Jia, Gabriela Valdés-Ramírez, Joshua R. Windmiller, Alexandra G. Martinez, Julian Ramírez, Garrett Chan, Kagan Kerman, and Joseph Wang. 2013. Tattoo-based potentiometric ion-selective sensors for epidermal pH monitoring. *Analyst* 138, 1 (2013), 123–128. https://doi.org/10.1039/C2AN36422K Publisher: Royal Society of Chemistry.

[18] Jeyeon Jo, Doyeon Kong, and Huiju Park. 2021. BLInG: Beads-Laden Interactive Garment. In *Proceedings of the 2021 ACM International Symposium on Wearable Computers (ISWC '21)*. Association for Computing Machinery, New York, NY, USA, 189–193. https://doi.org/10.1145/3460421.3478827

[19] Lee Jones, Sara Nabil, Amanda McLeod, and Audrey Girouard. 2020. Wearable Bits: Scaffolding Creativity with a Prototyping Toolkit for Wearable E-textiles. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '20)*. Association for Computing Machinery, New York, NY, USA, 165–177. https://doi.org/10.1145/3374920.3374954

[20] Alexandra Ling Ju and Mirjana Spasojevic. 2015. Smart Jewelry: The Future of Mobile User Interfaces. In *Proceedings of the 2015 Workshop on Future Mobile User Interfaces (FutureMobileUI '15)*. Association for Computing Machinery, New York, NY, USA, 13–15. https://doi.org/10.1145/2754633.2754637

[21] Cindy Hsin-Liu Kao, Bichlien Nguyen, Asta Roseway, and Michael Dickey. 2017. EarthTones: Chemical Sensing Powders to Detect and Display Environmental Hazards through Color Variation. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI EA '17)*. Association for Computing Machinery, New York, NY, USA, 872–883. https://doi.org/10.1145/3027063.3052754

[22] Hsin-Liu Kao, Manisha Mohan, Chris Schmandt, Joseph A Paradiso, and Katia Vega. 2016. Chromoskin: Towards interactive cosmetics using thermochromic pigments. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. 3703–3706.

[23] Huisung Kim, Olumide Awofeso, SoMi Choi, Youngkee Jung, and Euiwon Bae. 2017. Colorimetric analysis of saliva–alcohol test strips by smartphone-based instruments using machine-learning algorithms. *Applied Optics* 56, 1 (2017), 84–92.

[24] Jayoung Kim, Gabriela Valdés-Ramírez, Amay J. Bandodkar, Wenzhao Jia, Alexandra G. Martinez, Julian Ramírez, Patrick Mercier, and Joseph Wang. 2014. Non-invasive mouthguard biosensor for continuous salivary monitoring of metabolites. *Analyst* 139, 7 (2014), 1632–1636. https://doi.org/10.1039/C3AN02359A Publisher: Royal Society of Chemistry.

[25] Sungbong Kim, Boram Lee, Jonathan T. Reeder, Seon Hee Seo, Sung-Uk Lee, Aurélie Hourlier-Fargette, Joonchul Shin, Yurina Sekine, Hyoyoung Jeong, Yong Suk Oh, Alexander J. Aranyosi, Stephen P. Lee, Jeffrey B. Model, Geumbee Lee, Min-Ho Seo, Sung Soo Kwak, Seongbin Jo, Gyungmin Park, Sunghyun Han, Inkyu Park, Hyo-Il Jung, Roozbeh Ghaffari, Jahyun Koo, Paul V. Braun, and John A. Rogers. 2020. Soft, skin-interfaced microfluidic systems with integrated immunoassays, fluorometric sensors, and impedance measurement capabilities. *Proceedings of the National Academy of Sciences* 117, 45 (Nov. 2020), 27906–27915. https://doi.org/10.1073/pnas.2012700117 ZSCC: NoCitationData[s0].

[26] Ahyeon Koh, Daeshik Kang, Yeguang Xue, Seungmin Lee, Rafal M. Pielak, Jeonghyun Kim, Taehwan Hwang, Seunghwan Min, Anthony Banks, Philippe Bastien, Megan C. Manco, Liang Wang, Kaitlyn R. Ammann, Kyung-In Jang, Phillip Won, Seungyong Han, Roozbeh Ghaffari, Ungyu Paik, Marvin J. Slepian, Guive Balooch, Yonggang Huang, and John A. Rogers. 2016. A soft, wearable microfluidic device for the capture, storage, and colorimetric sensing of sweat. *Science Translational Medicine* 8, 366 (Nov. 2016), 366ra165–366ra165. https://doi.org/10.1126/scitranslmed.aaf2593 Publisher: American Association for the Advancement of Science.

[27] Chi-Jung Lee, David Yang, Pin-Sung Ku, and Hsin-Liu Cindy Kao. 2024. SweatSkin: Rapidly Prototyping Sweat-Sensing On-Skin Interface Based on Microfluidics. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 7, 4 (Jan. 2024), 166:1–166:30. https://doi.org/10.1145/3631425

[28] Yongjiu Lei, Wenli Zhao, Yizhou Zhang, Qiu Jiang, Jr-Hau He, Antje J. Baeumner, Otto S. Wolfbeis, Zhong Lin Wang, Khaled N. Salama, and Husam N. Alshareef. 2019. A MXene-Based Wearable Biosensor System for High-Performance In Vitro Perspiration Analysis. *Small* 15, 19 (2019), 1901190. https://doi.org/10.1002/smll.201901190 _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/smll.201901190.

[29] Weiyi Liu, Huanyu Cheng, and Xiufeng Wang. 2023. Skin-interfaced colorimetric microfluidic devices for on-demand sweat analysis. *npj Flexible Electronics* 7, 1 (2023), 43.

[30] X. Liu, K. Vega, P. Maes, and J.A. Paradiso. 2016. Wearability Factors for Skin Interfaces. In *Proceedings of the 7th Augmented Human International Conference 2016*. 1–8.

[31] Xin Liu, Katia Vega, Pattie Maes, and Joe A. Paradiso. 2016. Wearability Factors for Skin Interfaces. In *Proceedings of the 7th Augmented Human International Conference 2016 (AH '16)*. Association for Computing Machinery, New York, NY, USA, 1–8. https://doi.org/10.1145/2875194.2875248

[32] Elle Luo, Ruixuan Fu, Alicia Chu, Katia Vega, and Hsin-Liu Kao. 2020. Eslucent: an eyelid interface for detecting eye blinking. In *Proceedings of the 2020 ACM International Symposium on Wearable Computers*. 58–62.

[33] Öykü Berfin Mercan and Volkan Kılıç. 2020. Deep learning based colorimetric classification of glucose with au-ag nanoparticles using smartphone. In *2020 Medical Technologies Congress (TIPTEKNO)*. IEEE, 1–4.

[34] Galina Mihaleva and Pat Pataranutaporn. 2018. Sense: coral reef inspired and responsive dress. In *Proceedings of the 2018 ACM International Symposium on Wearable Computers (ISWC '18)*. Association for Computing Machinery, New York, NY, USA, 290–294. https://doi.org/10.1145/3267242.3267294

[35] Jihong Min, Jiaobing Tu, Changhao Xu, Heather Lukas, Soyoung Shin, Yiran Yang, Samuel A. Solomon, Daniel Mukasa, and Wei Gao. 2023. Skin-Interfaced Wearable Sweat Sensors for Precision Medicine. *Chemical Reviews* 123, 8 (April 2023), 5049–5138. https://doi.org/10.1021/acs.chemrev.2c00823 Publisher: American Chemical Society.

[36] Rosalia Moreddu, Mohamed Elsherif, Hadie Adams, Despina Moschou, Maria F. Cordeiro, James S. Wolffsohn, Daniele Vigolo, Haider Butt, Jonathan M. Cooper, and Ali K. Yetisen. 2020. Integration of paper microfluidic sensors into contact

lenses for tear fluid analysis. *Lab on a Chip* 20, 21 (2020), 3970–3979. https://doi.org/10.1039/D0LC00438C

[37] Ana Moya, Roberto Pol, Alfonso Martínez-Cuadrado, Rosa Villa, Gemma Gabriel, and Mireia Baeza. 2019. Stable Full-Inkjet-Printed Solid-State Ag/AgCl Reference Electrode. *Analytical Chemistry* 91, 24 (Dec. 2019), 15539–15546. https://doi.org/10.1021/acs.analchem.9b03441 Publisher: American Chemical Society.

[38] Marie Muehlhaus, Jürgen Steimle, and Marion Koelle. 2022. Feather Hair: Interacting with Sensorized Hair in Public Settings. In *Designing Interactive Systems Conference (DIS '22)*. Association for Computing Machinery, New York, NY, USA, 1228–1242. https://doi.org/10.1145/3532106.3533527

[39] Andrew Piper, Ingrid Öberg Månsson, Shirin Khaliliazar, Roman Landin, and Mahiar Max Hamedi. 2021. A disposable, wearable, flexible, stitched textile electrochemical biosensing platform. *Biosensors and Bioelectronics* 194 (Dec. 2021), 113604. https://doi.org/10.1016/j.bios.2021.113604

[40] Nadtinan Promphet, Pranee Rattanawaleedirojn, Krisana Siralertmukul, Nipha-phun Soatthiyanon, Pranut Potiyaraj, Chusak Thanawattano, Juan P Hinestroza, and Nadnudda Rodthongkum. 2019. Non-invasive textile based colorimetric sensor for the simultaneous detection of sweat pH and lactate. *Talanta* 192 (2019), 424–430.

[41] Nasuha Rohaizad, Carmen C. Mayorga-Martinez, Filip Novotný, Richard D. Webster, and Martin Pumera. 2019. 3D-printed Ag/AgCl pseudo-reference electrodes. *Electrochemistry Communications* 103 (June 2019), 104–108. https://doi.org/10.1016/j.elecom.2019.05.010

[42] C Seethalakshmi, RC Jagat Reddy, Nisha Asifa, and S Prabhu. 2016. Correlation of salivary pH, incidence of dental caries and periodontal status in diabetes mellitus patients: a cross-sectional study. *Journal of clinical and diagnostic research: JCDR* 10, 3 (2016), ZC12.

[43] Shuyi Sun, Neha Deshmukh, Xin Chen, Hao-Chuan Wang, and Katia Vega. 2021. GemiN' I: Seamless Skin Interfaces Aiding Communication through Unconscious Behaviors. In *Proceedings of the Augmented Humans International Conference 2021 (AHs '21)*. Association for Computing Machinery, New York, NY, USA, 277–279. https://doi.org/10.1145/3458709.3458997

[44] Shuyi Sun, Yuan-Hao Ku, Nicole Unsihuay, Omar Florez, Jae Yong Suk, Ali K. Yetise, and Katia Vega. 2024. BioCosMe: Lip-based Cosmetics with Colorimetric Biosensors for Salivary Analysis. In *Proceedings of the 2024 ACM International Symposium on Wearable Computers*. Association for Computing Machinery, to appear. In press.

[45] Shuyi Sun, Alejandra Ruiz, Sima Pirmoradi, and Katia Vega. 2023. BioSparks: Jewelry as Electrochemical Sweat Biosensors with Modular, Repurposing and Interchangeable Approaches. In *Adjunct Proceedings of the 2023 ACM International Joint Conference on Pervasive and Ubiquitous Computing & the 2023 ACM International Symposium on Wearable Computing*. 315–320.

[46] Yuiko Suyama and Tetsuaki Baba. 2022. Extail: a Kinetic Inconspicuous Wareable Hair Extension Device. In *Adjunct Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology (UIST '22 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 1–4. https://doi.org/10.1145/3526114.3558648

[47] Defita Andri Tusilowati and Nining Sugihartini. 2023. Rosella (Hibiscus sabdariffa L.) extract lip balm: optimization of the composition of beeswax and paraffin wax as a base. *Journal of Halal Science and Research* (2023). https://api.semanticscholar.org/CorpusID:257062397

[48] Eldy S Lazaro Vasquez, Ali K Yetisen, and Katia Vega. 2020. BraceIO: biosensing through hydrogel dental ligatures. 87–89.

[49] Katia Vega, Marcio Cunha, and Hugo Fuks. 2015. Hairware: The Conscious Use of Unconscious Auto-contact Behaviors. In *Proceedings of the 20th International Conference on Intelligent User Interfaces (IUI '15)*. Association for Computing Machinery, New York, NY, USA, 78–86. https://doi.org/10.1145/2678025.2701404

[50] Katia Vega and Hugo Fuks. 2013. Beauty technology as an interactive computing platform. In *Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces (ITS '13)*. Association for Computing Machinery, New York, NY, USA, 357–360. https://doi.org/10.1145/2512349.2512399

[51] Katia Vega and Hugo Fuks. 2016. Beauty Technology Definition. In *Beauty Technology: Designing Seamless Interfaces for Wearable Computing*, Katia Vega and Hugo Fuks (Eds.). Springer International Publishing, Cham, 9–15. https://doi.org/10.1007/978-3-319-15762-7_2

[52] 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 (ISWC '17)*. Association for Computing Machinery, New York, NY, USA, 138–145. https://doi.org/10.1145/3123021.3123039

[53] Bo Wang, Chuanzhen Zhao, Zhaoqing Wang, Kyung-Ae Yang, Xuanbing Cheng, Wenfei Liu, Wenzhuo Yu, Shuyu Lin, Yichao Zhao, Kevin M. Cheung, Haisong Lin, Hannaneh Hojaiji, Paul S. Weiss, Milan N. Stojanović, A. Janet Tomiyama, Anne M. Andrews, and Sam Emaminejad. 2022. Wearable aptamer-field-effect transistor sensing system for noninvasive cortisol monitoring. *Science Advances* (Jan. 2022). https://doi.org/10.1126/sciadv.abk0967 ZSCC: NoCitationData[s0] Publisher: American Association for the Advancement of Science.

[54] Yiran Yang and Wei Gao. 2019. Wearable and flexible electronics for continuous molecular monitoring. *Chemical Society Reviews* 48, 6 (2019), 1465–1491. https://doi.org/10.1039/C7CS00730B

[55] Ali K. Yetisen, J. L. Martinez-Hurtado, Burak Ünal, Ali Khademhosseini, and Haider Butt. 2018. Wearables in Medicine. *Adv Mater* 30, 33 (June 2018), e1706910. https://doi.org/10.1002/adma.201706910 _eprint: 29893068.

[56] Ali K Yetisen, Rosalia Moreddu, Sarah Seifi, Nan Jiang, Katia Vega, Xingchen Dong, Jie Dong, Haider Butt, Martin Jakobi, Martin Elsner, et al. 2019. Dermal tattoo biosensors for colorimetric metabolite detection. *Angewandte Chemie* 131, 31 (2019), 10616–10623.

[57] Jessica Yin, Ronan Hinchet, Herbert Shea, and Carmel Majidi. 2020. Wearable Soft Technologies for Haptic Sensing and Feedback. *Advanced Functional Materials* 31 (12 2020), 2007428. https://doi.org/10.1002/adfm.202007428

[58] Meredith Young-Ng, Grace Chen, Danielle Kiyama, Anna-Sofia Giannicola, Erkin Şeker, and Katia Vega. 2022. Sweatcessory: a Wearable Necklace for Sensing Biological Data in Sweat. In *Adjunct Proceedings of the 2022 ACM International Joint Conference on Pervasive and Ubiquitous Computing and the 2022 ACM International Symposium on Wearable Computers*. 141–143.

[59] Meredith Young-Ng, Grace Chen, Danielle Kiyama, Anna-Sofia Giannicola, Erkin Şeker, and Katia Vega. 2022. Sweatcessory: a Wearable Necklace for Sensing Biological Data in Sweat. 141–143.

[60] Miguel Zea, Francesca G. Bellagambi, Hamdi Ben Halima, Nadia Zine, Nicole Jaffrezic-Renault, Rosa Villa, Gemma Gabriel, and Abdelhamid Errachid. 2020. Electrochemical sensors for cortisol detections: Almost there. *TrAC Trends in Analytical Chemistry* 132 (Nov. 2020), 116058. https://doi.org/10.1016/j.trac.2020.116058 ZSCC: 0000014.

[61] Dingtian Zhang, Jung Wook Park, Yang Zhang, Yuhui Zhao, Yiyang Wang, Yunzhi Li, Tanvi Bhagwat, Wen-Fang Chou, Xiaojia Jia, Bernard Kippelen, Canek Fuentes-Hernandez, Thad Starner, and Gregory D. Abowd. 2020. OptoSense: Towards Ubiquitous Self-Powered Ambient Light Sensing Surfaces. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 4, 3 (Sept. 2020), 103:1–103:27. https://doi.org/10.1145/3411826

[62] Tengxiang Zhang, Xin Zeng, Yinshuai Zhang, Ke Sun, Yuntao Wang, and Yiqiang Chen. 2020. ThermalRing: Gesture and Tag Inputs Enabled by a Thermal Imaging Smart Ring. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376323

[63] Tengxiang Zhang, Xin Zeng, Yinshuai Zhang, Ke Sun, Yuntao Wang, and Yiqiang Chen. 2020. ThermalRing: Gesture and Tag Inputs Enabled by a Thermal Imaging Smart Ring. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–13. https://doi.org/10.1145/3313831.3376323

[64] Mindi Zhao, Yehong Yang, Zhengguang Guo, Chen Shao, Haidan Sun, Yang Zhang, Ying Sun, Yaoran Liu, Yijun Song, Liwei Zhang, and others. 2018. A comparative proteomics analysis of five body fluids: plasma, urine, cerebrospinal fluid, amniotic fluid, and saliva. *PROTEOMICS–Clinical Applications* 12, 6 (2018), 1800008. Publisher: Wiley Online Library.

[65] 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*. 1–11.