Next Steps in Epidermal Computing: Opportunities and Challenges for Soft On-Skin Devices

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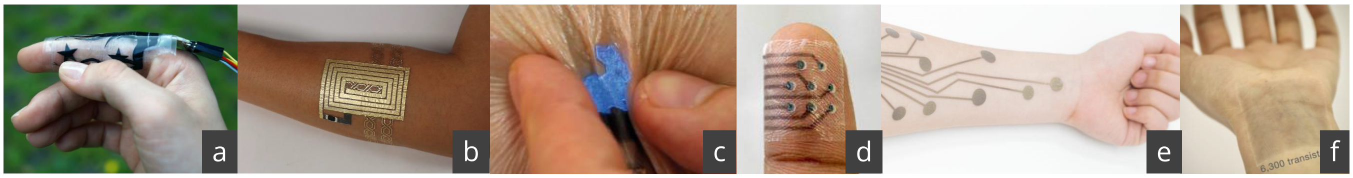

Figure 1: Examples of Epidermal Computing Devices for a) eyes-free touch input [230], b) wireless communication through aesthetic on-skin tattoos [97], c) displaying notifications through ultr-thin displays [232], d) feel-through haptics [234], e) sensing physiological signals [155] and f) skin stretchable large scale transistor array for on-skin computing [225]

ABSTRACT

Skin is a promising interaction medium and has been widely explored for mobile, and expressive interaction. Recent research in HCI has seen the development of Epidermal Computing Devices: ultra-thin and non-invasive devices which reside on the user's skin, offering intimate integration with the curved surfaces of the body, while having physical and mechanical properties that are akin to skin, expanding the horizon of on-body interaction. However, with rapid technological advancements in multiple disciplines, we see a need to synthesize the main open research questions and opportunities for the HCI community to advance future research in this area. By systematically analyzing Epidermal Devices contributed in the HCI community, physical sciences research and from our experiences in designing and building Epidermal Devices, we identify opportunities and challenges for advancing research across five themes. This multi-disciplinary synthesis enables multiple research communities to facilitate progression towards more coordinated endeavors for advancing Epidermal Computing.

CCS CONCEPTS

• **Human-centered computing** → **Interaction devices**; **HCI theory, concepts and models**; **Empirical studies in HCI**.

KEYWORDS

wearable devices; epidermal devices; survey; soft wearables

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1 INTRODUCTION

The extraordinary properties of skin make it an appealing user interface. First, the presence of mechanoreceptors that capture nuanced tactile sensations afford dexterous tactile input techniques and rich haptic output, which can be further enhanced using the materiality of soft and deformable skin. Moreover, as skin is the largest human organ, it offers a large real-estate for input and output. It is always with us and easily accessible supporting direct, subtle, and discreet interactions. This is applicable for a variety of mobile activities, including walking, running, carrying shopping bags, riding a bike, or driving a car. Lastly, skin is inherently multimodal. In addition to its haptic aspects and its function of visual display, it can also act as a biological interface for sensing biosignals.

The HCI community has explored diverse technical approaches for turning human skin into an interface Amongst others, these comprise optical [67], bio-acoustic [69, 149], magnetic [26, 75], radar-based [224] and ultrasound imaging techniques [145]. A recent stream of work, at the intersection of material science, biomedical engineering, and HCI, has created the foundations for Epidermal Computing – a new form of wearable computing platform that is characterized by ultra-thin devices which are noninvasive, offer intimate integration with the curved surfaces of the body and have physical and mechanical properties that are akin to skin.

These Epidermal Devices, often also referred to as Electronic Skin or Epidermal Electronic Systems (EES), open up a wide range of possibilities by augmenting the human skin with electronic functionality. They enable sensing of tactile input [157, 230], highly-articulated body movements [103, 260], and physiological signals [15, 47, 91, 264]. They provide haptic output [234, 249, 252] or augment the body with visual displays [97, 232]. Moreover, Epidermal Devices enable non-invasive testing of contagious viruses such as COVID-19 [209] and offer non-invasive drug delivery [221]. Last but not least, they can harvest energy from bio-mechanical activities like walking [242] or even human sweat [88].

Prior work in HCI has synthesized challenges in related areas, notably wearable computing [196], skin-based interaction [17, 132], human-computer integration [148] and shape-changing displays [1]. Epidermal Computing Devices present orthogonal key challenges and opportunities that focus on the characteristic technology, new materials and fabrication of these devices, which offer unique opportunities for on-skin functionality and applications. The number of publications on soft on-skin devices in major HCI venues has been rapidly increasing in the past few years, forming a new field; however, almost all work contributes research focused on an individual prototype. There is a need for going beyond individual technical and empirical contributions and identifying a more overarching set of opportunities and challenges that can help direct future research in the field.

While there are a few survey articles and state-of-the-art reports for various types of Epidermal Devices that have been published in other communities [10, 108, 178, 244], this work presents the first multi-disciplinary analysis of Epidermal Devices contributed across multiple research disciplines (HCI, Materials Science, Nanotechnology, Bio-medical, Electronics) and focuses on the HCI-specific questions and research directions that other works have not reviewed. By comparing and contrasting research from prior work, we identify challenges and opportunities across five major themes that are central for the development of Epidermal Computing Devices from an HCI perspective: (1) Materials, (2) Fabrication, (3) Devices and their functionality, (4) Technical and Empirical studies, and (5) Applications and real-world deployments (Figure 3.

We envision this article will guide researchers and practitioners from various disciplines to: (1) understand the state-of-the-art capabilities of Epidermal Devices and identify areas of opportunity from an HCI perspective; (2) situate their work within the broader Epidermal Computing research agenda and identify new research directions for their research communities, (3) allow practitioners in industry and government agencies to better understand the field and potential applications for accelerating the real-world deployment of Epidermal Devices.

2 WHAT IS EPIDERMAL COMPUTING

The vision for Epidermal Computing is to intimately couple sensing, computation, and interaction to the outermost layer of the human body (the epidermis) by means of Epidermal Devices. These devices are soft, of minimal thickness, highly stretchable and flexible, to adapt to complex body geometries and ideally conform to the relief of the skin's surface. Furthermore, Epidermal Devices are non-invasive and should be made of bio-compatible materials. They leverage on perceptual, biological, social and emotional properties associated with human skin, in order to support multimodal interactions, physiological sensing, health diagnostics and treatment.

One of the key properties that define *Epidermal Interfaces* is skin conformality. This is a crucial property that defines how well a device or interface adapts to the complex relief of the skin. Figure 2 shows SEM (scanning electron microscope) scans of devices of various thickness levels and their skin-conformable property. Figure 2(a) shows the SEM scan of a skin replica without any overlay. Figure 2(b) is the SEM scan when a thin layer of spray-on bandage ($\sim$ 20 nm) is applied on the skin. As can be observed, the highly conformable layer is unnoticeable in the scan. When a device of $\sim$ 100 μm is applied on to the skin (Fig. 2c), the device very well adapts to the contours of the skin but fails to penetrate into the deepest creases and pits. Reducing the thickness by ten times, to 10 μm, significantly improves the conformality, as shown in Figures 2(e) and 2(f).

Skin-conformal contact has many advantages in various domains. Firstly, from an ergonomics perspective, skin-conformal devices can be very comfortable and minimally invasive, promoting long-term use [104]. Secondly, a device that is highly skin-conformal minimally attenuates our natural tactile perception capabilities. Tactile cues can be transmitted through these devices to the underlying mechanoreceptors, which enables us to feel natural tactile sensations despite the presence of these interfaces on the body [156]. Thirdly, many bio-signals such as EEG, ECG or EOG are captured with skin-mounted sensing electrodes that need to be in close contact with the skin for acquiring high-quality signals. Similarly, this is a very attractive property for applications in sports and fitness where devices need to be tightly coupled to the body for measuring athletic performance [239].

The degree of skin conformality allows to broadly subdivide Epidermal Computing Devices into two groups: (a) *Skin stickers* are somewhat thicker ($\sim$ 100 μm–700 μm) and therefore can be easily worn, removed from the body surface, and re-applied. A few examples of such devices that have been presented in the HCI literature are iSkin [230], Electrodermis [140], Springlets [64] and Multi-Touch Skin [157]. (b) *Skin-conformal devices* are ultra-thin (ranging between $\sim$ 1μm and 100 μm). This enables them to be tightly coupled to the skin, in some cases even without any additional adhesives by van der Waals forces alone. They are extremely stretchable, flexible, and adapt very well onto strongly curved and deforming body geometries. Few examples of such devices in the HCI literature are Skintillates [133], DuoSkin [97] SkinMarks [232], Tacttoo [234] and Tip-Tap [101].

2.1 Research Themes and Analysis

The field of HCI has seen rapid growth in the development of Epidermal Devices in the past few years. Starting with iSkin [230] which introduced Epidermal Devices in HCI and enabled touch input on the body, the devices have become slimmer [97, 133] and adapted to complex body geometries [232], have enabled high-resolution touch sensing [157] and novel haptic sensations [64–66, 234], and included monitoring of bio-signals [140, 155]. The physical sciences research community has been investigating Epidermal Devices for more than a decade longer than HCI. The majority of their work focuses on creating and formulating new materials, advanced fabrication techniques, and developing sensors and actuators, which typically involve using sophisticated lab equipment. The learnings

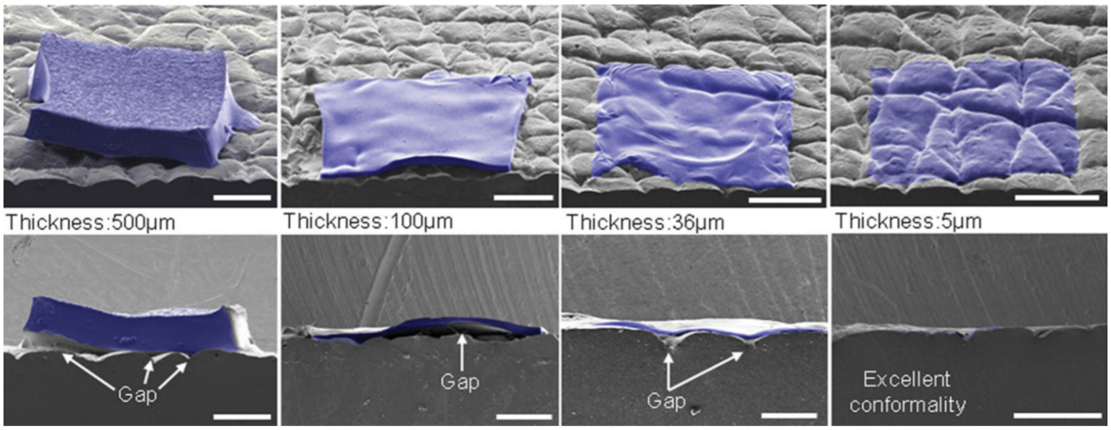

Figure 2: SEM images of epidermal devices of different thickness, showing its effect on skin conformality, reproduced with permission from [86]. Copyright 2013 Wiley-VCH and John Wiley & Sons - Books.

and research innovations from those communities have in parts been taken up by the HCI community, which in turn has led to the development of new interactive devices, along with more accessible fabrication techniques.

To synthesize the opportunities and challenges, we performed a literature analysis across multiple disciplines by analyzing research articles published at top-tier journals and conferences which include: Nature (Nature, Nature Communications, Nature Electronics, Nature Nanotechnology, Nature Materials), Science (Science, Science Advances), Wiley (Advanced Materials, Advanced Functional Materials, Advanced Healthcare Materials), American Chemical Society (ACS Sensors, ACS Applied Material Interfaces, ACS Nano), Royal Society of Chemistry and the ACM Digital Library for research articles in HCI/Computer Science.

Our method of literature analysis is informed by prior work [57, 188]. We conducted a full-text search in the following online repositories: ACM Digital Library, Nature, Science, Wiley, American Chemical Society, Royal Society of Chemistry, using these keywords: "Epidermal Devices; Epidermal Interfaces; Epidermal Electronics; E-Skin; E-Tattoos; Epidermal Electronic System". This resulted in a total of ~4400 publications. From this large pool of articles, the authors selected publications that have potential direct relevance for HCI, by proposing a fabrication process, by demonstrating functional devices, by proposing applications relevant for HCI, or a combination thereof. Papers with abstracts that did not match any of these three inclusion criteria were dismissed. Furthermore, publications other than main track conference papers and journal articles were dismissed (such as work-in-progress, workshop publications, or demos).

This resulted in a total of ~250 that were retained for further analysis. These articles were then analysed through an open-coding scheme. In an initial analysis of a subset of publications, we identified five themes central for the opportunities and challenges that were subsequently used for categorizing all publications:

- Functional Materials: We analyze the functional materials that commonly are used for building Epidermal Devices across disciplines. Based on this, we identify opportunities and challenges for sustainable materials, stretchable conductors, safety and handling of materials.
- Fabrication and Design Workflows: By analyzing and understanding the fabrication mechanisms and design workflows used for realizing Epidermal Devices, we identify potential opportunities and challenges for devising new techniques that better support rapid prototyping, require only simple lab equipment and enable easy fabrication of devices.
- Devices and their functionality: We compare and contrast the devices across disciplines based on their functionality and the interactions that are supported. By understanding and analyzing several device types, we identify future device functionalities that can be developed by the HCI community.
- Evaluation Methods and Strategies: We compare methods of evaluating technical aspects, human factors and user interaction of Epidermal Computing Devices across disciplines. We identify the next steps with regard to fundamental empirical experiments for understanding skin-specific interactions, social acceptability and in-the-wild studies of Epidermal Computing.
- Applications and Real-World Deployments: By comparing and contrasting the applications and deployments that have been targeted, we identify opportunities for potential applications that future Epidermal Devices can target.

In the following sections, we will discuss these thematic areas in turn.

3 MATERIALS

Epidermal Devices are typically fabricated as a multi-material sandwich. Selection of materials is critical, as they need to comply with the demanding mechanical requirements (notably, being soft, stretchable, mechanically robust despite a very low diameter, and adhering to the skin) and offer the required functional properties for the embedded electronics. We will now discuss materials for substrates and functional layers and identify opportunities for future work.

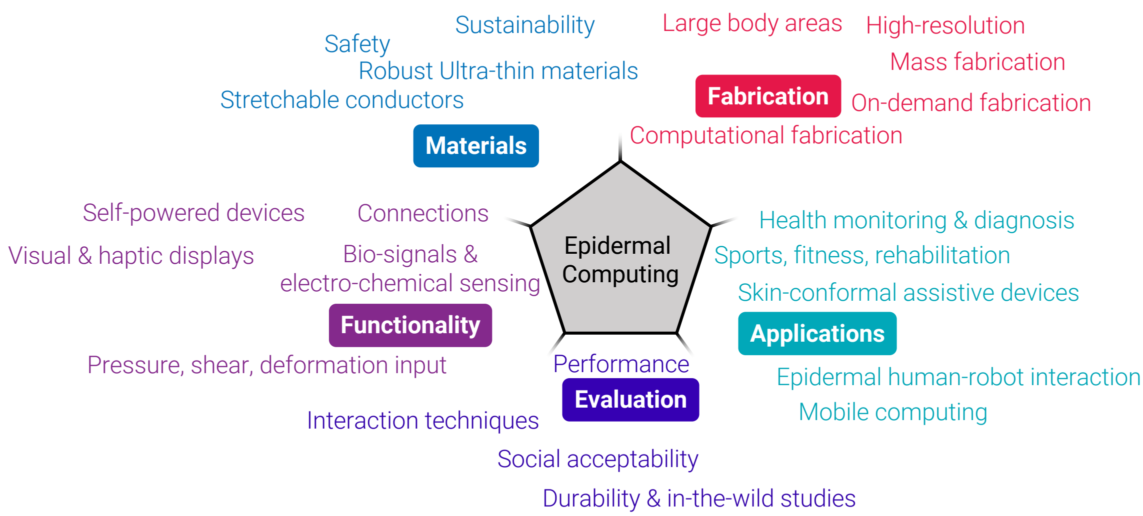

Figure 3: Opportunities and challenges for Epidermal Computing span aspects of materials, fabrication, functionality, evaluation methods and applications.

3.1 Substrates

Substrates usually form the base material onto which functional materials are coated for creating the device sandwich.

3.1.1 PDMS. PDMS (poly (dimethyl) siloxane) is one of the most commonly used substrate materials for fabricating epidermal devices. It is optically transparent (240 − 1100 nm wave length) [23, 144, 195], flexible [90, 235], highly stretchable and bio-compatible [62, 235]. It can be fabricated in a range of thicknesses between $\sim 10 - 700\mu$m for Epidermal Devices, allowing for trading-off between conformality and mechanical durability for a given application case.

PDMS offers additional advantages because of its low cost and rapid prototyping capability. This makes PDMS not only widely used in physical sciences research [36, 87, 104, 166], but it has also been used in the HCI community to create epidermal touch sensors [230], thermochromic displays [227] and for creating haptic sensations using micro-fluidic channels [66].

3.1.2 Tattoo Decal Paper. Tattoo Decal or Temporary Tattoo paper is another commonly used substrate material for fabricating ultrathin Epidermal Devices. The main constituents of tattoos are polymers, having low Young's modulus [47, 142] and the overall thickness is submicrometric [47]. These two peculiar characteristics make it an ideal substrate material for obtaining conformal adhesion to the skin [104]. Temporary Tattoo paper is composed of ultrathin (<1μm) carrier film, water-soluble polyvinyl alcohol (PVA) layer, and backing paper for ease of handling. Functional layers can be easily created on the substrate through inkjet printing [102, 135] or screen printing [133, 232]. Once the devices are printed they can be transferred to the human skin through water transfer: when water is applied to the temporary tattoo paper, the carrier film separates from the paper leaving behind an ultrathin layer composed of functional layers that easily adapt to the body surface.

Temporary tattoo paper has been extensively used in physical sciences research for fabricating various devices such as skin-conforming electrodes for electrophysiology [15, 47, 91, 135, 204], emotion sensing [81], transistors and edible electronics [21], wireless communication [213], energy harvesting on skin [88] and for organic indoor photovoltaics [169]. Temporary tattoo paper has also been extensively used in the HCI community for creating various devices such as touch sensors [133, 232], 2D touch matrices[97, 157], battery-less 2D touch input [101], electro-tactile actuators [234], physiological sensing [155], displays [97, 133, 232], and on-skin PCBs [96].

3.1.3 Hydrogels. Hydrogels and ionogels are another promising class of stretchable active materials, noteworthy because they closely mimic the mechanical, chemical, and optical properties of biological tissues [240]. Due to the advantages of their 3D structure, biocompatibility, and biodegradability, hydrogels have been used for a wide variety of applications such as tissue engineering [129], and highly stretchable printed electronics [253]. We are seeing first explorations of hydrogels in the HCI community for epidermal devices which change their texture and stiffness through joule heating [95].

3.1.4 Substrate-Less or Water-Soluble Substrates. Depositing functional materials directly onto the skin has been another way that has been explored in physical sciences research. This is typically done through a water-soluble substrate that dissolves during wet transfer [228, 229].

3.1.5 Textile Patches. While e-textile research is a substantial research area on its own with multiple research communities actively exploring the field, a few research works in HCI have investigated the use of e-textiles as on-skin interfaces.

This includes augmenting the skin by adhering soft textile patches [197, 198] as well as using weaving or machine embroidery for creating patches with unique visuo-haptic properties [77, 89, 200].

3.2 Functional Materials

3.2.1 Conductors. Epidermal Devices typically require one or more conductive layers on a base substrate for performing a specific function. Multiple approaches and materials have been explored for coating conductive layers. The most commonly used functional materials are:

- Metallic Conductors: Metallic conductors are one of the most commonly used functional materials because of their high conductivity and ease of processing. Silver and gold have been used very commonly in the HCI community either in form of screen-printing pastes [133, 232] or through thin films [97]. These are also very commonly used materials in physical sciences research [147, 228]. Metallic conductors in the form of Silver nanoparticles (AgNp) can also be deposited through ink-jet printing methods [102]. Additionally, the are also used in the form of nanowires and nanoparticles [72, 113].
- Intrinsically Stretchable Polymers: By comparison to metallic conductors that have high Young's modulus and hence are very brittle, intrinsically stretchable polymers have attractive mechanical properties such as high stretchability and deformability. A well-studied conductive polymer is poly(3,4-ethylenedioxythiophene) polystyrenesulfonate (PEDOT:PSS) [223]. It has been widely used in physical sciences research community for creating Epidermal Devices which measure physiological signals such as EMG, ECG and EEG [47, 126]. PEDOT:PSS has also been widely used in the HCI community for creating stretchable interactive devices [56, 233], pressure sensing foils [181] and epidermal devices [157, 232, 234]. Physical sciences research has also explored other stretchable polymers that offer superior deformability, such as a compound material formed from the copolymerization of poly(3-hexylthiophene) (P3HT) and polyethylene (PE) to obtain (P3HT-PE) which offers up to 600% stretchability [150].
- Carbon Composites: Carbon and its composites like graphite, graphene or activated charcoal have been successfully used for creating Epidermal Devices [91, 111, 237]. Carbon composites have received lesser attention in the HCI community, with only a few works using them [230]. A key advantage is that they are low-cost when compared to metallic conductors which have limited reserves and are expensive. Some of the allotropes of carbon used for fabrication purposes are graphite [180] and graphene [48]. Graphene has received wide attention because of its electrical conductivity, mechanical properties [179] and the"thinnest" known material [48] and as result has been used in realizing a number of Epidermal Devices [76, 91, 122]. However, since graphene is expensive [48], Graphite has been viewed as another alternative since it is a low-cost material, and offers the advantage of bio-compatibility [27]. It has relatively low conductivity but is also a popular choice to develop devices for biomedical applications [151].
- Nanowires, Nanomeshes, and Nano-Tubes: Nano particles typically in the form of nanowires (NWs), nano-meshes or nano-tubes are another class of conductive materials that have been extensively used [24, 243]. Multi-walled carbon nano-tubes have also been recently introduced in HCI for realizing self-healing interfaces [153, 177]. A key advantage of using nanomeshes is that they can be realized in highly thin form factors while being stretchable and achieving superior conformal contact in comparison to the planar polymeric substrates [92, 226]. However, a key challenge for using nanomeshes and nanowires is the complex fabrication process which often requires sophisticated equipment.
- Liquid Metals: Liquid metals are another class of conductors that offer the benefits of high deformability [261]) and high electrical conductivity [263]. Most prior research that utilized liquid metals have employed gallium-based liquid metals to develop epidermal devices that measure strain [167] and pressure [246]. They have also been used for creating capacitive touch and pressure [4] sensors, resistive strain sensors [161, 168], for measuring the angle of body joints [146] and for self-healing robots [141]. Liquid metals are also becoming increasingly popular in the HCI community [187, 206, 207, 219], however with only very little work investigating their use in Epidermal Devices [152].

3.2.2 Insulators and Dielectrics. Dielectrics and insulating materials are necessary for creating devices that are composed of multi-material layers and for insulating the device from its environment.

One common approach is to embed silicone elastomers as flat or textured sheets [230, 243]. Another approach is to print fine layers of dielectric materials [102, 232] or use multiple layers of the base material as an insulating material.

3.2.3 Skin Adhesives. Skin adhesives are typically used to achieve stronger adhesion of the device onto the skin. In some cases, the high stretchability and very low thickness levels of the devices make them bond to the skin through just van der Waals forces without the need for external adhesives [104]. Other approaches typically include using commercially available solutions such as water-soluble tape [85], commercial medical grade adhesives [140, 156], tattoo-paper adhesive [97, 133, 232], acrylic [107], spray bandage [247], and mastic [230].

3.3 Opportunities and Challenges

3.3.1 Sustainable Materials. Most materials used for Epidermal Devices today are not sustainable. For instance, rare metals are precious resources, most polymers do not biodegrade well, and multi-material sandwiches are hard to recycle. Considering that many devices are intended for one-time or short-term use, this is an issue. Here, bio-based and bio-degradable materials can open up new design space for epidermal devices, which is beginning to be explored in Materials Science [111] and HCI [215]. By using fully bio-degradable materials like gelatin, agar-agar, etc., one might ultimately have Epidermal Devices that after use can be simply composted.

3.3.2 Stretchable Conductors. A common challenge is the trade-off that exists between highly conductive materials and their stretchability. Intrinsically stretchable conductors such as PEDOT:PSS are stretchable, but typically suffer from a rather low conductivity. In contrast, metallic conductors such as silver and gold possess high conductance levels, however, they are brittle because of their high Young's modulus. A common strategy that has been employed in the Materials science community is to have composite materials, e.g. mixing liquid metals with silver particles to have highly stretchable and conductive material composites [204]. However, a downside of this approach is that the formulation process is complex and the composite material (e.g. liquid metals) might not be bio-compatible. Another approach has been to use carbon in the form of nano-tubes or nano-particles. These have been successfully demonstrated in materials and HCI research works. However, they need meticulous safety practices and a lab environment that might not be available to a large community of makers, hobbyists, and practitioners. The next step in this direction is to identify the suitable materials that are easy to handle, are bio-compatible, stretchable, conductive, and require minimal safety equipment and measures. Carbon-based composites such as graphene and graphite show a promising direction in this regard [27, 48]. Another approach that has been used is to fabricate multi-material layers composed of intrinsically conductive polymer (e.g. PEDOT:PSS) and highly conductive metals (e.g. Silver) so that the conductive polymer bridges the cracks that occur in the metal layer [232].

3.3.3 Robust Ultra-Thin Materials. While tattoo-papers are ultra-slim and conform to complex geometries, they suffer from limited mechanical robustness. PDMS substrates on the other hand offer can be fabricated to custom thickness levels offering and can be more mechanical robust [156]. However, a key challenge that needs to be addressed is to identify substrate materials and their compositions that are ultra-thin and stretchable while being mechanically robust for a long duration. The same holds true for functional materials, and new explorations on functional carbon composites which include graphene and its compounds in materials science offer a promising direction in this regard [27, 48].

3.3.4 Technical and Safety Challenges for Handling Materials. Epidermal Devices are present on the surface of the human body and hence the functional materials that are used in the device should not harm the human body. While there have been several explorations of using sophisticated materials such as carbon-nanotubes and liquid metals in the HCI literature, special consideration should be taken with respect to the handling of these materials as they are toxic and hence not compatible with the typical standards applied in DIY processing. While safety standards and training do exist in maker spaces and fab labs, these usually cover the safe handling of machines, rather than the safe handling of materials. In the HCI and maker communities, we see the need to increase the awareness of potential hazards associated with materials and their processing and recommend lab managers to establish formal safety standards and dedicated training on material safety.

Another opportunity here is to identify, explore and investigate completely safe-to-use and bio-compatible materials. For instance, recent work in physical sciences research has demonstrated Epidermal Devices using a pencil [237].

4 FABRICATION

The fabrication of Epidermal Devices not only involves identifying the right set of methods, tools, and equipment for creating the multi-material sandwich. It also involves challenges regarding the design of layouts that are fabricable and comply with a user's aesthetic preferences.

4.1 Fabrication Methods

4.1.1 Additive Methods. : Typical additive fabrication methods use printing to pattern a sheet of substrate material with functional ink. The arguably most commonly used approach is screen printing, as it allows for convenient deposition of a very wide range of materials with fine-tuned layer thicknesses and sufficiently good resolution [78, 128, 257]. Due to the simplicity of fabrication, it has been widely used in the HCI community [133, 232, 233]. However, the approach is manual and requires creating a negative mask, which makes it slower than alternative techniques.

A rapid approach for creating high-resolution patterns is inkjet printing with functional inks. Physical sciences research typically uses specialized industrial inkjet printers [47], which are very expensive and not easily accessible to hobbyists, practitioners, and many HCI research labs. Recent research in HCI has contributed inkjet printing and transfer approaches that are simple and can be deployed with inexpensive commodity inkjet printers [30, 102]. In addition to these, *Direct On-Skin Printing* techniques involve directly printing functional layers on the skin [59]. Recent research in HCI has demonstrated this via pen-based devices which used computational guides for inking [171] and through wearable plotters that deposit ink based on the target design provided through a design tool [34].

4.1.2 Subtractive Methods. : Typical subtractive methods involve cutting a substrate or film of functional materials into a patterned structure, by cutting out residual materials and leaving behind the desired pattern on the substrate. Commonly used tools are mechanical plotter cuts [97] or more advanced laser cutting such as CO2 [136, 230] or UV laser micromachining [140].

4.1.3 Mixed Methods. : Another recently introduced technique that uses a mix of additive and subtractive methods is the "cut-and-paste" method [241] which involves using a mechanical plotter to cut a specific design on a functional layer. The resultant functional layer is then transferred onto the desired substrate. This technique has been widely used in the Materials Science community with variants of this approach being actively pursued [228]. A similar approach uses a doctor blade to incrementally add functional layers and use CNC milling to have the device in custom shape [227].

While the HCI community majorly focuses on fabrication techniques that are easy, rapid, and can be performed with simple lab equipment, the physical sciences research community employs various other approaches involving more complex procedures and equipment such as electrospinning and vacuum depositions [147], microfabrication, and thermal deposition techniques [71].

4.2 Computational Design and Optimization

Optimizing designs for targeting a specific functionality is a common practice in HCI and physical sciences research communities. This involves optimizing electrical, physical and mechanical parameters, for instance for withstanding high strain [85], or for specific electronic functionality such as the design of antennas for near-field communication (NFC) [107].

One of the areas, where the HCI community has made rapid advances in the use of computational design approaches for creating personalized device designs that are optimized for a user's body,

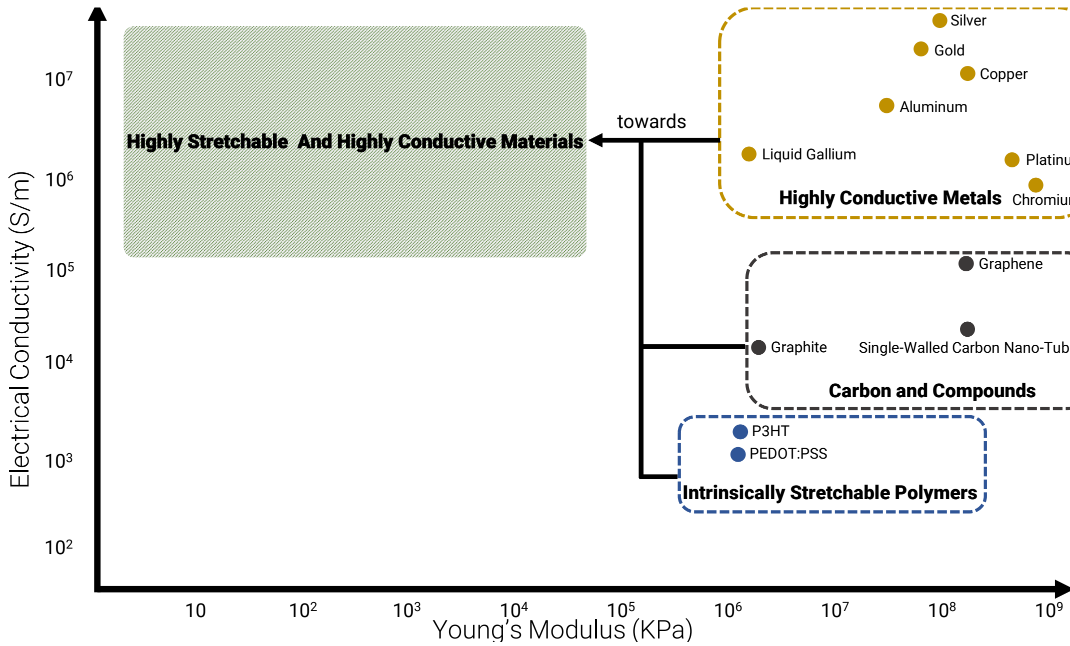

Figure 4: Most commonly used functional materials for epidermal devices, plotted against their respective electrical conductivity and Young's modulus. A key opportunity for further research is to develop highly stretchable materials that possess high electrical conductivity. Note: Young's modulus is inversely proportional to stretchability.

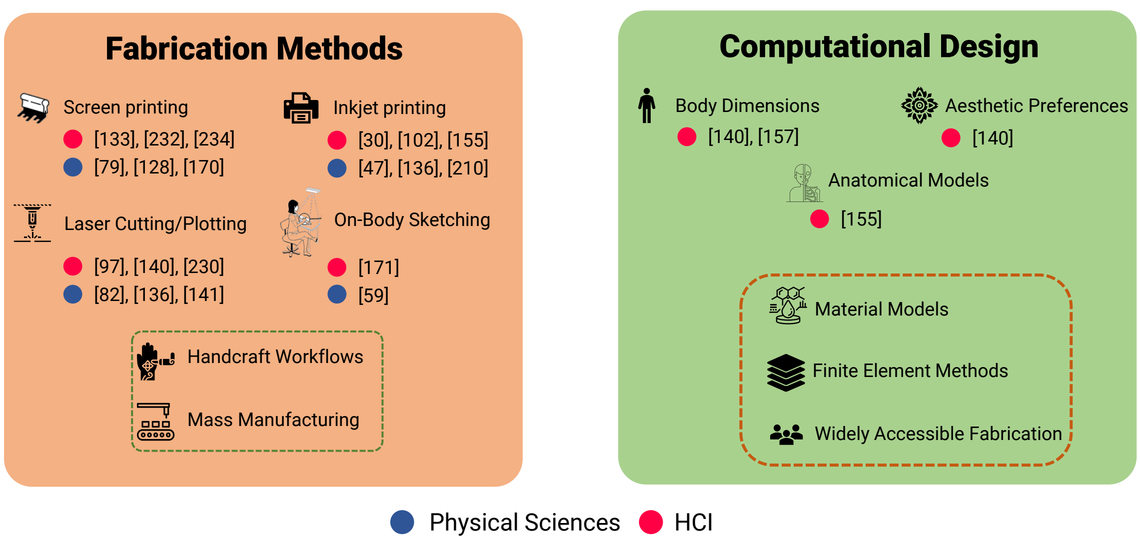

Figure 5: Key research themes for Fabricating Epidermal Devices. A number of rapid and easy-to-perform fabrication methods have been explored in HCI. For each of the fabrication methods and computational design approaches, representative research works from physical sciences and HCI research are shown. Next steps (highlighted) include the exploration of fabrication methods that leverage on traditional art and handcraft based workflows (e.g. henna tattoos) and exploration of mass manufacturing techniques. For computational design techniques, advanced design tools incorporating material properties, FEM analysis and widely accessible fabrication methods are the next crucial steps.

often using interactive graphical design tools. This includes, for instance, a custom design tool for creating non-rectangular touch sensor designs that fit on desired body parts [157], a design tool for optimizing placement of electrodes based on anatomical models for physiological sensing [154] or a design tool for controlling the aesthetics of an Epidermal Device [140].

4.3 Aesthetics

Skin acts as a social display that signals traits related to personality, demographics, health, and social status [201]. Diverse forms of aesthetic skin decoration, such as henna, make-up, jewellery and tattoos, are wide-spread across cultures [41, 119, 162]. If worn visibly, Epidermal Devices become an element of social display, possibly even a fashion item. Therefore, their visual and material aesthetics are central aspects for user adoption. Research in HCI is considering this aspect increasingly, while it still remains rarely addressed in materials science and physical sciences [58].

The current state of the art of fabrication incorporates aesthetics in the following ways:

- Using Aesthetic Materials: Metallic materials such as gold or silver have been used for decorative purposes. Using these materials for fabricating Epidermal Devices has enabled the devices to be intrinsically attractive. A common way to use them is with temporary tattoos [97] or through interactive cosmetics and make-up materials [137, 216].
- Art Layers: Art layers are one of the commonly used techniques to add aesthetically pleasing graphics on top of the device, which is typically hiding the device's internal structure. This is often done by using a dedicated layer of temporary tattoo [133, 137, 157, 232] or molded onto the device[140].
- Aesthetic Functional Designs: A third approach does not hide the device's inner functional structure, but rather designs it to be visually attractive. Electrical circuits or functional elements of sensors are laid out in ornamental shapes that create a desired visual aesthetics [230]. Prior work has achieved this through laser cutting [230], CNC milling [227], a cutting plotter [97], and free inking [171].
  Recent work in HCI involves interactive computational tools for creating aesthetic on-skin devices, such as creating devices decorated with custom Voronoi patterns [140], or creating functional and aesthetic epidermal circuits with computer-assisted free-form sketching [171].

4.4 Opportunities and Challenges

4.4.1 Computational Fabrication. An important direction for future work is to devise new computational design techniques that assist the designer in customizing the design for individual users, their body dimensions, and aesthetic preferences. Such techniques will need to take into account anatomical models and operationalize them for automatic optimization. This will be particularly important for functionality that depends on a specific body location, such as monitoring bio-signals. It remains a wide-open challenge of how to capture and model a user's aesthetic preferences, and operationalize them for computer-assisted device designs. These steps will pave the way for the rapid fabrication of epidermal devices that can be customized for form, shape, and aesthetics. Integrating computational design approaches with rapid prototyping techniques can facilitate on-demand mass fabrication of devices. This can enable more widespread and in-the-wild testing and evaluation of device designs, which in turn can guide the computational design and fabrication process. In addition to incorporating human-centered properties such as body dimensions and anatomical models, future tools should also explore integrating material models and finite element analysis methods which allows designers to quickly identify, predict, debug and custom-design the mechanical and electrical properties of the device.

4.4.2 Fabricating for Large Body Areas. Current state-of-the-art devices in HCI are usually designed for relatively small body areas and regions. Scaling up the size of such devices to enable coverage over entire, large regions of the body can open new avenues for physiological sensing. For instance, large-area, body-scale epidermal devices for electromyography (EMG) can provide robust recording capabilities across multiple muscle groups. Full-scalp or full-forehead epidermal devices for electroencephalography (EEG) can monitor electrical activity across the brain with high resolution. However, there remain three major challenges in scaling current epidermal devices in HCI for large-area electrophysiology: Firstly, the current fabrication processes used in HCI limit the size of devices to a few centimeters. Recent work in bio-medical engineering has demonstrated tattoo-like electrodes for full-scalp EEG [229]. However, the microfabrication process on large thin-film wafers is expensive and requires sophisticated equipment. Secondly, without robust encapsulation, extended interconnects in direct contact with the skin can capture unwanted but substantial biopotentials that interfere with the signals collected by the measuring electrodes [32, 70]. Finally, the geometrically non-developable nature of human skin surfaces can cause wrinkles and high levels of strain on the ultrathin electrodes, which can reduce the mechanical robustness or the conformality of the devices [138, 222].

4.4.3 Supporting High Resolution and Complex Aesthetic Patterns. One of the key features of Epidermal Devices that the HCI community has focused on is their aesthetic appearance. While there are custom design tools that enable designers to create 2D aesthetic patterns [140] and support free-form sketching with a pen or a computer-controlled plotter [34, 171], most of these aesthetic designs are limited to line-arts and simple designs. Future work should investigate how more complex aesthetic patterns that are common in traditional handcrafts can be incorporated.

4.4.4 Mass Fabrication Techniques. A big next step for advancing Epidermal Computing for creating devices on a scale and for real-world deployments is to explore and identify mass manufacturing fabrication techniques. While some of the fabrication processes that have been used for Epidermal Devices have been based on mass manufacturing processes such as screen printing, they have not yet been explored on a large scale. Other techniques are not compatible or not suitable for producing devices on a large scale. An analogy that can be compared to here is the growth of interactive textiles that leverage standard practices of mass-manufacturing textiles such as weaving, using of looms, and development of yarns [170].

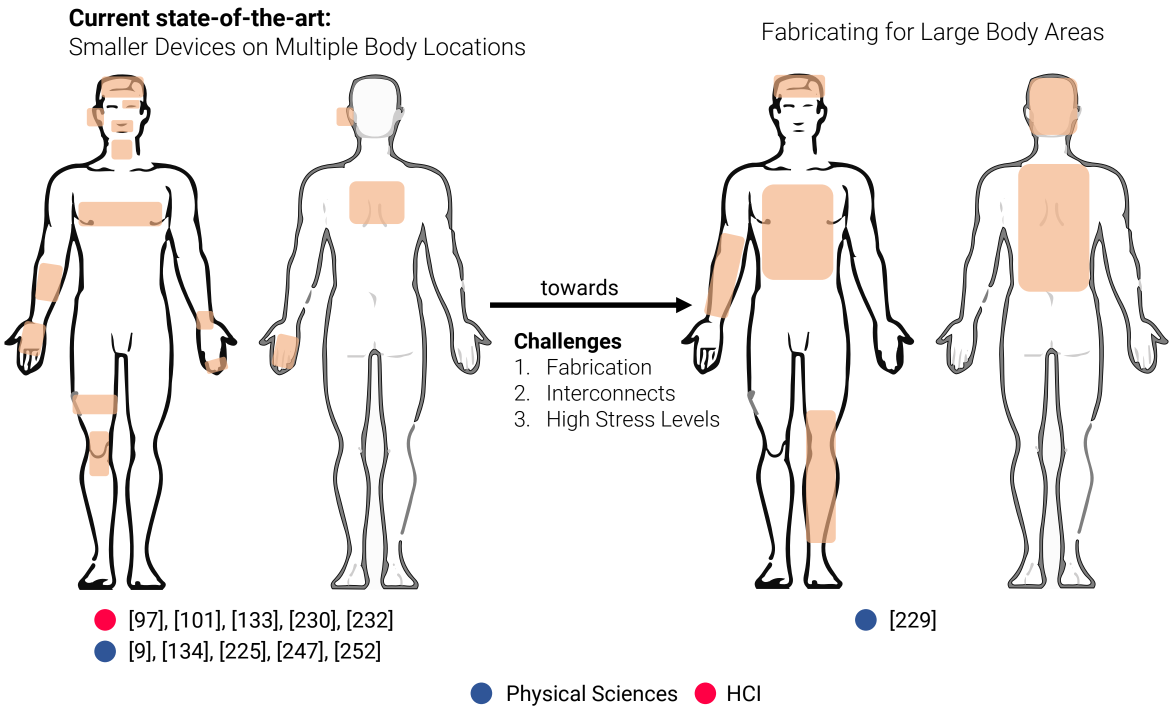

Figure 6: Current Epidermal devices are limited to a few centimeters size. The next step is to create skin-conformable epidermal devices that cover large body areas. Representative research works from physical sciences and HCI research community are shown.

4.4.5 On-Demand Fabrication Techniques. An approach orthogonal to mass-manufacturing is on-demand, on-place fabrication. Epidermal devices that are personalized for a specific user might be fabricated on-demand at a local pharmacy or even at the user's home. Recent work on fabricating epidermal devices with inexpensive commodity desktop printers is making a pioneering step in this direction [102, 155]; however, more work is required until we can ultimately print an entire device on demand.

4.4.6 Promoting Inclusive Design. Previous interactive technologies (e.g. high-end smartphones) have raised concerns over a "Digital Divide", i.e. the technology is not equally accessible to everyone. This can be amplified in the case of Epidermal devices. A simple example is the creation of Epidermal Devices with high-end functionality that currently requires sophisticated infrastructure which is available to only a few labs in the world. Such exclusive means for design and prototyping risk to exclude significant groups of stakeholders from the power to co-define this novel technology, in turn creating new divides that can have new and unexpected consequences. Hence, we advocate for fabrication techniques, materials, and infrastructure that are widely accessible and at a low-cost, to reduce or mitigate new digital divides.

5 FUNCTIONALITY OF DEVICES

Epidermal Devices can serve multiple functions: they can act as input devices through touch, pressure, and gestural input, provide multi-sensory haptic feedback and visual output, monitor physiological signals, and offer a promising platform for health monitoring and diagnostics.

5.1 Input

5.1.1 Tactile Sensing. Touch and pressure contact has been one of the most frequently investigated forms of input for Epidermal Devices in both HCI and physical sciences research [3, 97, 133, 134, 165, 230, 245], realized using self-capacitance, mutual-capacitance, or resistive sensing schemes. Prior work in HCI also includes a high-resolution touch sensing matrices in non-rectangular form factors [157]. While pressure sensing has been explored through a few devices in HCI community [230, 249], higher-resolution pressure sensing matrices need to be investigated.

5.1.2 Kinematic Sensing. Epidermal Devices that capture dynamic motions of the human body can provide critical insights across a broad range of applications, from clinical diagnostics (movement disorders [124, 203], neurological disorders [82]) to athletic performance monitoring [239, 256]. Sensing of body motions through Epidermal devices has also been widely explored in the HCI community [133, 140, 155, 232]. In addition to precise movement tracking, kinematic sensing also allows for using body movements for interactive application such as gesture detection [260]. Typically epidermal kinematic sensing is deployed through strain sensors, IMUs or through EMG approaches.

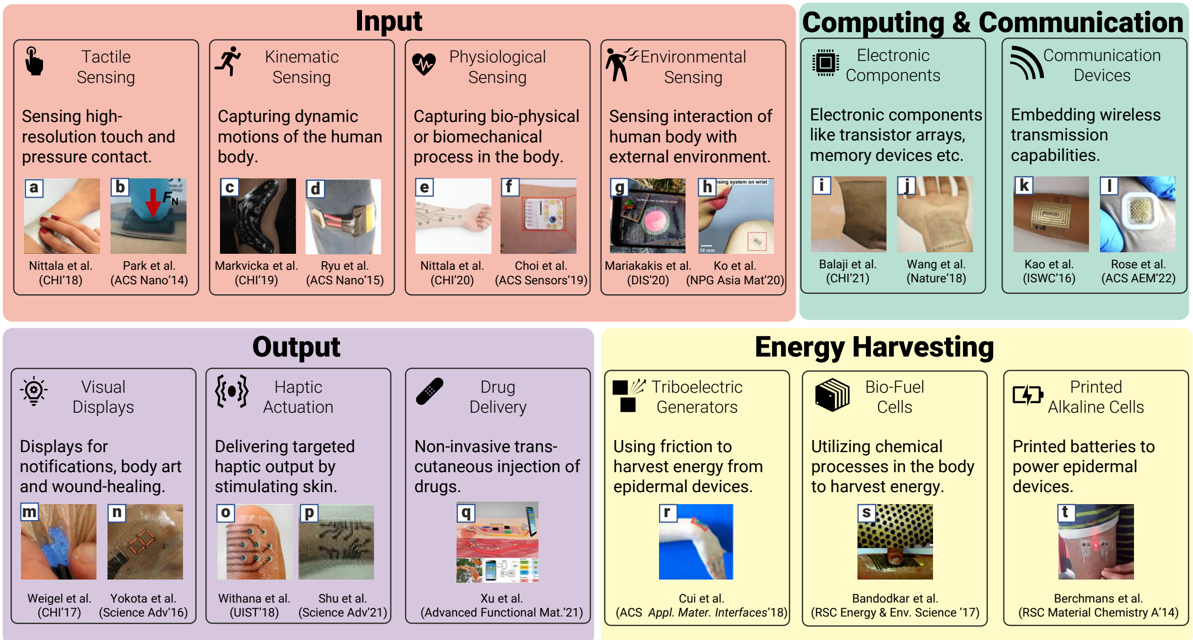

Figure 7: Broad overview of the device classes covered in this survey. For each of the classes, representative devices from the HCI community and physical sciences research community are shown here. (a) Multi-touch sensing on the skin [157] (b) deformation sensing on the skin. Reprinted with permission from ref [165]. Copyright 2014 American Chemical Society. (c & d) capturing dynamic motions of the human body through strain sensors. Reprinted with permission from ref. [140, 186, 239] Copyright 2015 American Chemical Society. (e) physiological sensing on the skin for capturing EMG and ECG signals [155] (f) electro-chemical sensing on the skin for characterization of sweat. Reprinted with permission from ref. [33]. Copyright 2020 American Chemical Society. Environmental sensing on the skin for detecting UV exposure (g) and exposure to harmful gases (h). Reprinted with permission from ref. [139] and ref. [115]. Computing power added to epidermal devices through FPGA arrays [8] and transistor arrays [225]. Reprinted with permission from ref. [8] and ref. [225]. Copyright 2018 Springer Nature. Adding wireless communication capabilities (k & l). Reprinted with permission from ref. [97] and ref. [183]. Copyright 2022 American Chemical Society. Output on the skin through EL displays (m) and LED arrays (n). Reprinted with permission from ref. [248]. Haptic output delivered on the skin through electro-tactile actuation [191, 234]. (q) Non-invasive drug delivery [236]. Reprinted with permission from ref. [236]. Copyright 2021 Wiley-VCH Verlag GmbH & Co. KGaA. (r) harvesting energy from friction [38]. Reprinted with permission from ref. [38]. Copyright 2018 American Chemical Society. Energy harvesting on the skin through bio-fuel cells and printed alkaline cells (s & t). Reprinted with permission from ref. [14] and ref. [16]. Copyright 2017 and 2014, Royal Society of Chemistry.

5.1.3 Physiological Sensing. Physiological signals are readings or measurements that are produced by the biophysical or biochemical processes that happen in the human body. Epidermal electrophysiological sensors have been developed that measure the changes in electrical signals during various processes such as cardiac cycles [47, 155, 229, 237], muscle movements and skin-conductance measurements [102, 155]. In addition to EMG, ECG and EDA signals, the physical sciences community has also explored the design of devices for EEG [126] and EOG [2] measurements.

Electro-chemical sensors are another class of devices that convert information associated with biochemical processes that happen in the body. They can also be used for detecting viruses and pathogens in the body [209]. A wide range of electro-chemical Epidermal Devices have been developed which measure blood glucose levels [108], hemoglobin [110] or characterize sweat [9, 33] with various compounds such as pH levels [39] or trace metals [109].

5.1.4 Environmental Sensing. The interaction of the human body with external environmental signals can be a good indicator of health. These environmental factors include exposure to UV light, pollutants, and gases which can be hazardous.

Prior research has contributed Epidermal Devices for sensing various environmental elements such as UV exposure [51, 139, 210], harmful gases like as nitric oxide [115], humidity levels [211], and exposure to explosives and gun shot residues [13]. While there has been extensive research in physical sciences, environmental sensing so far has received very limited attention in HCI, with pioneering work investigating the fabrication of chemical UV sensors [139].

5.2 Output

5.2.1 Visual Displays. Visual displays on the skin can serve multiple purposes. Firstly they can provide subtle notifications to the user [97, 232]; second, they can be embedded with tattoo art to add further aesthetic value to the devices [133]; third, in a medical context, they can be utilized for healing wounds on the skin [83]. Prior work on epidermal displays from the physical sciences includes a high-resolution display matrix made of LEDs [49, 71], electroluminescent displays [105, 257], stretchable organic LEDs [83, 84], thermochromic [106], and electrochromic displays [35, 164]. Research in HCI built onto some of these findings to focus on more accessible fabrication approaches in a simple lab or DIY settings. Approaches comprise the fabrication of Epidermal Devices that consist of SMD LEDs [133], stretchable electro-luminescent displays [232, 233] and thermochromic displays [97, 227].

5.2.2 Actuation. Stretchable epidermal actuators attached closely to human skin can act as devices that produce haptic output on the body through targeted stimulations. A large number of epidermal haptic output devices have been presented across research communities. Various technologies have been successfully employed. The approach that allows for the most minimal form factor uses electro-tactile stimulation. Two or more electrodes in direct contact with the skin deliver a controlled electrical pulse to directly stimulate nerve stems of mechanoreceptors, which can be perceived as vibrations. These types of actuators have been extensively explored both in the physical sciences [191] and HCI research communities [100, 234]. Various other approaches have been explored for creating haptic sensations based on mechanical movement. These include the use of dielectric elastomers [202, 249], magnetic actuation [143, 252], piezoelectric actuation [258], mechanical actuation with shape memory alloys [31, 64] and actuation through microfluidic channels [65, 66]. A key observation here is that both the HCI community and physical sciences research community are very active in designing actuator devices, with competitive results. However, the communities complement each other in the evaluation approaches: the HCI community's focus on psychophysical studies to validate the actuation principle and corresponding human perception can go hand-in-hand with the materials and fabrication-centered evaluations that are typically performed in the physical sciences research community.

5.2.3 Drug Delivery. Drug delivery devices are another class of output devices that non-invasively and transcutaneously inject drugs. This is achieved through multiple approaches including the use of microneedles [123], electrical methods [236], ultrasound methods [194] and thermal ablation [7]. A more detailed discussion of various types of drug delivery mechanisms (not all are compatible with Epidermal Devices) can be found in [172].

5.3 Computation and Communication

In addition to means for input and output, prior research has also investigated components that are central for on-device computation and communication.

5.3.1 Electronic Components and Fully Integrated Devices. Electronic components such as transistors, memory devices that are building blocks of computing. Prior literature in physical science research community has developed fully printed capacitors [6], transistors [160], dense transistors arrays [40, 225], memory and logic devices [193]. In addition to these components, the design and fabrication of fully-integrated devices is a very active research topic [50, 122, 184]. Self-contained devices are also being actively pursued in the HCI community [140, 152], with even computational capability for running on-device neural network models being imbued into devices via off-the-shelf FPGAs [8].

5.3.2 Communication Components. Often Epidermal Devices are coupled with wireless communication modules to send data to a remote computer or a mobile device for further processing. These strategies typically involve using on-device antennas for wireless communication [104]. Epidermal devices with wireless transmission capabilities have been developed for power transfer [79], near-field communication [97, 107], radio frequency communication [185] and wireless bluetooth communication [77].

5.4 Energy Harvesting

While extensive efforts have been devoted to the development of wearable health and fitness monitoring systems, limited efforts have focused on developing body-worn energy harvesting and energy storage for powering these sensing systems. Most of the work on energy harvesting devices has been contributed in the physical sciences research community by using electro-chemical approaches [12]. Pioneering work from HCI has been using commercial supercapacitors for energy harvesting [77].

Triboelectric generators (commonly termed as TENGs) are one of the most commonly used techniques and utilize the principles of tribocharging to harvest mechanical energy and convert it into electricity in a simple and low-cost manner [38, 46]. Energy harvesting through triboelectric generators has also received attention in the HCI community recently. They have been used for powering paper-based interfaces [28], microphones and acoustic sensing [5] and for interactive cords and textiles [53, 189]. Moreover, biofuel cells (BFCs) have been explored in the physical sciences research community. These are devices that convert chemical energy into electricity through biocatalytic reaction. They are a promising source for generating sustainable electrical energy [12, 61, 255]. Epidermal BFCs have been successfully deployed to harvest energy from human sweat [11, 14, 88, 199]. Finally, thin-film alkaline batteries [259] that use water-based electrolytes can be used for powering on-skin electronics [16, 120].

5.5 Opportunities and Challenges

5.5.1 Pressure, Shear and Deformation Input. While touch contact sensing on Epidermal Devices has been intensely studied in the HCI community [97, 133, 157, 230], there is yet very little investigation of interaction using variations of pressure, shear and deformation. These promise to further enhance the interaction vocabulary by directly building on the softness of human skin. In particular, high-resolution sensing matrices should be investigated alongside the versatile gestures and interactions they enable on diverse body locations. This could be achieved by building onto research from material and physical sciences, and use piezo-resistive materials which have a good response to pressure [182], or employ capacitive approaches with soft dielectric materials, which provide a unique capacitive signature when normal or shear force is applied. Dense microfluidic channels and ionotronic sensing [262] is another promising alternative.

5.5.2 Output with Visual Displays and Haptic Displays. Further improving the quality of visual displays within interactive Epidermal Devices will be an important next step, to move past the limited quality and resolution of thermochromic or electroluminescent displays.

Printed e-ink displays and OLEDs are powerful display technologies that should be explored for Epidermal Devices. E-ink displays have been explored for wearable devices [44]; however, a key challenge is the realization of e-ink displays in skin-conformal form factors, and ideally in a simple lab environment.

Important next steps for epidermal tactile output displays comprises increasing their spatial resolution and scale. Integrating multiple forms of haptic output, for instance, pressure, skin stretch, and thermal output, in one Epidermal Device is another very promising direction, as this directly corresponds to the multi-sensory nature of human skin. Electric muscle stimulation has been widely for providing kinesthetic feedback [99]. However, the vast majority of this work uses either commercial gel-electrodes or textile electrodes [114]. An opportunity for more ergonomically wearable systems is to use Epidermal Devices that encapsulate dry electrodes for EMS output.

5.5.3 Bio-Signals and Electro-Chemical Sensing. Integrating physiological sensing to a greater extent opens up interesting directions for research in HCI, which so far has been mostly concerned with user input and system feedback. For instance, deploying electrophysiological sensors that capture multiple bio-signals (e.g., EEG, ECG, EEG, EOG, EDA) at various body locations can open up opportunities for diverse applications such as continuous activity tracking, gestural interaction, or health monitoring.

Moreover, we identified that the HCI community so far is not using electro-chemical sensing for capturing rich bio-signal data about the electrolyte and metabolite concentrations in the body. For instance, these comprise measuring blood glucose levels or lactate levels in sweat, which are indicators of physical activity. This poses the challenges not only of identifying the appropriate materials for sensing and sensor designs, but also identifying safe and easy-to-perform techniques for rapid prototyping that allow for encapsulating chemicals in the Epidermal Devices.

5.5.4 Energy Harvesting and Self-Powered Devices. Prior work in materials and physical sciences research has shown that energy can be harvested successfully for powering Epidermal Devices. Although fully untethered devices have been contributed in HCI [101, 140], self-powered devices that can harvest energy through biomechanical and physical processes are a natural and important next step for investigation. For instance, this might be achieved through triboelectric generators, which have received attention due to their easy and rapid fabrication [5] and their applicability in self-powered haptic displays [191]. However, designing devices that integrate sensing, display, and energy harvesting capabilities, all in an ultra-thin form factor, is a challenge. Computational design and optimization techniques have strong potential in helping to solve this challenge, finding optimal multi-modal device designs which have been successfully demonstrated in the HCI community can solve these challenges by taking user inputs and constraints for each of the modalities and finding an optimal design.

5.5.5 Connections and Tethering. Connectors and tethering the device remain a challenge, mainly because the slim and stretchable devices are not well compatible with conventional cables, jumper wires, or copper tape. This is a common problem and the most widely used approaches have been to use copper tape [232], conductive z-axis tape to connect the device to an external flexible copper-clad laminated onto a silicone [140] or to a flexible printed cable [157, 234]. The latter two approaches enable easy connection of highly dense connector lines and offer flexibility, but future research should investigate the fabrication of highly stretchable connectors while supporting a large number of I/O pins. Similarly, it remains an open challenge to robustly tether multiple Epidermal Devices that are located at different body sites.

6 EVALUATION METHODS AND STRATEGIES

In all disciplines, empirical studies are conducted to better understand the performance and characteristics of Epidermal Devices. Yet, the research questions, methods, and study designs strongly differ across disciplines. In this section, we will review what are common evaluation methods and will contrast the typical methods and strategies used in HCI with those employed in other disciplines.

6.1 Technical Evaluations

Technical evaluations typically include experiments designed to understand the functionality of the device, its mechanical characteristics, and material behavior.

6.1.1 Evaluating Device Functionality. For input devices involving tactile sensing and physiological sensing, typical measurements representing the quality of signal acquisition include measuring signal-to-noise levels [47, 155, 230] and resolution of sensing [157, 232]. For displays, these involve optical characterization [83]. In the case of actuators, these measurements typically include psychophysical studies to understand the stimulation thresholds and just-noticeable differences(JNDs). Recent work has also been using psychophysical methods to characterize the feel-through characteristics, a key property of Epidermal Devices [65, 156, 234]. In most cases, the methods for measuring device functionality have been similar across the HCI community and physical sciences research.

6.1.2 Microscopic Analysis. Microscopic analyses usually involve SEM (Scanning Electron Microscope) scans of the device to accurately measure the device thickness [241, 247]. These evaluations also show the quality of deposited functional traces and layers in the device. Microscopic analyses are less common in the HCI literature, with only a few works reporting them [133, 232]. Microscopic analyses should be more commonly adopted in HCI work since they can provide insights into various aspects of real-world usage, such as the initial quality of functional layers and for measuring the degradation of the material after continued use.

6.2 Empirical Studies and User Experiments

The HCI community has made fundamental contributions to understanding the use of the human body for interaction. Most of the empirical research and controlled experiments with users are centered around three themes: (a) User Strategies and mappings, (b) elicitation Studies, and (c) social acceptability studies.

6.2.1 User Strategies and Mappings. Understanding on-body interaction is an active research topic in HCI. Several empirical studies focused on the body-centric interaction space [68, 218], identified user strategies for creating on-body gestures [159] and revealed that on-skin input increased the sense of agency [19]. Moreover, previous research has investigated mapping strategies for input elements on the skin. These include salient features on the palm [43, 60, 220], targets placed on the forearm [130], visual and tactile anatomical landmarks [18, 232] as well as mappings between skin and an off-skin display [20].

6.2.2 Elicitation Studies. Several elicitation studies have been conducted to understand gestural interaction on specific body locations such as ears [29], fingers [25, 190], forearm [22, 231], nose [176], belly [217], head and shoulders [214]. In addition to gestural input on body locations, elicitation studies have also been reported for skin-specific input modalities and user preferences for on-skin input [22, 231].

6.2.3 Social Acceptability. In recent years, we witness an increasing focus on social acceptability and social perception of body-worn devices. Social acceptability studies have initially been focused on wearable devices [117, 118] and interactive textiles [42, 98]. They have investigated how e-textiles might alter the wearer's social image and perception by others during everyday activities [42, 114, 173, 208]. More recent work has started to specifically investigate on-skin interfaces, in order to understand the social perception of using such interfaces in public [77, 250, 251]. Work has also studied gestures performed on the body [158, 174], on epidermal interfaces [251] or directly on skin [231] and evaluated appropriate body locations for on-body computing [250, 251, 254].

6.3 Opportunities and Challenges

Most of the empirical work can be categorized into the following classes: Elicitation studies, social acceptability studies. However, very few of these studies actually involve epidermal devices.

6.3.1 Understanding Skin-Specific Interactions. Current mobile and wearable devices have matured because of numerous studies and interaction techniques that have been designed and evaluated for enabling seamless interaction [73]. Similar studies need to be designed and conducted for Epidermal Devices. Skin affords wide variety of rich interactions such as pulling, pushing, squeezing etc [231]. While first technologies enable such interactions, the interaction granularity of skin-specific interactions is still unknown, e.g. what is the comfortable range and resolution with which we can perform a skin pinch gesture. Similar studies have been conducted with e-textiles [63, 98], however these studies do not translate to skin-specific interactions. Studying these questions is further complicated by the strong influence of skin location, body posture, a user's individual body anatomy, and mobility condition. The current state-of-the-art Epidermal Devices offer a viable technical platform for designing and conducting such interaction-specific studies.

6.3.2 Performance Studies. To gain further understanding of Epidermal Devices we need to move on to conducting studies that rigorously investigate interaction performance on Epidermal Devices. Preliminary investigations have investigated how the material stiffness of Epidermal Devices affects tactile perception [156]. Similarly, identifying the appropriate, additional physical and mechanical properties of the devices such as surface friction and roughness to maximize input performance need to be investigated. In addition, advanced simulation studies, e.g., using biomechanical models, and FEM analysis of skin and Epidermal Devices would inform the community and designers about optimal physical and mechanical parameters to increase performance and ergonomics.

6.3.3 Durability and In-the-wild Studies. Typically, Epidermal Devices in HCI have been evaluated with a rather low number of participants and during short durations of use, most often in a lab setting. Testing and evaluating device functionality over multiple weeks is the major next. Preliminary investigations in this regard have been reported in physical sciences research [47, 83, 107, 247]. In-the-wild studies and field deployments help us in identifying technical issues with respect to power consumption, strong skin-conformal contact, and clean signal acquisition, but also in uncovering patterns of use in real-world contexts.

6.3.4 Social Acceptability Studies. Identifying what factors of Epidermal Devices increase or decrease social acceptability will provide important insights allowing to design the next generation of devices that bring Epidermal Computing one step closer to mass adoption. While body locations are well researched [45, 80, 254], other design choices are underexplored. Social cues have been tackled in prior work [42, 74] but not systematically evaluated. Moreover, questions related to self-expression and how personalization of devices can contribute to it [175], but also impression management [52] and also the effect of a device's visibility for bystanders need to be studied [94]. Applying and comparing design strategies for increasing social acceptability that has been presented by Koelle et al. [116] to the field of Epidermal Devices will be another important step for future work on social acceptability.

7 APPLICATIONS AND REAL-WORLD DEPLOYMENTS

Due to their unique form factor, intimate integration with the user's body, and low cost, Epidermal Devices open up a range of opportunities for applications and real-world deployments. These span a wide range of areas, ranging from general mobile computing and communication to supporting a user's bodily activities in sports and fitness, and ranging from health monitoring and diagnosis for the masses to more specialized areas such as assistive technologies. Exemplary application scenarios are one area where the HCI research community trumps over the physical sciences research community.

7.1 Health Monitoring and Diagnosis

A key advantage of Epidermal Devices is that, since they are directly present on the body, they have direct access to the biophysical and biochemical features of the body. Using these devices to continuously monitor bio-signals promises to reduce diagnostic hospital visits and can also facilitate early diagnosis and prevention of illnesses. Epidermal Devices have been deployed for non-invasive drug delivery [7, 123, 194, 221] and wound healing [83, 84, 236].

This application area provides an exciting opportunity, with first interactive physiological devices already being developed in the HCI community [140, 155].

7.2 Assistive Technologies

Assistive technologies and accessibility are key application areas where Epidermal Devices can be deployed for creating societal impact. Studies have demonstrated the benefits of body-based interaction for eyes-free and accessible interaction [60, 159]. Wearable accessories have already been developed in the HCI community for accessible computing on the go [192]. Furthermore, epidermal exoskeletons promise support for applications such as assisting the physically disabled [95] or restoring the ability to pinch and grasp objects after having suffered a spinal cord injury [93].

7.3 Sports and Fitness

Epidermal Devices offer new integrated platforms for continuous monitoring of both biophysical and biochemical signals, which can be of interest in sports analytics and fitness monitoring. Prior work includes strain sensors that can detect human motion [239] and precise body movements during athletic training [256]. Furthermore, traditional electronic components such as accelerometers and strain gauges can be encapsulated within stretchable casings and shells to realize devices that are more mechanically robust and can be deployed for monitoring during a workout [121]. In addition to motion sensing, other physiological parameters such as EMG [241], ECG [125], temperature [212], respiration, and electrochemical signals such as glucose and sweat composition [12] are essential for evaluating an individual's overall physiological state and are thus topics of intense academic interest in sports science and performance.

Epidermal Devices from the HCI community have also demonstrated body motion sensing [140, 155]. However, these are typically limited to a single body location or movement.

7.4 Affective Communication

The multisensory nature of human touch makes Epidermal Devices a promising choice for enhancing affective communication between people over the distance. Propositions from prior research include remote communication with a partner using on-skin multitouch gestures [155, 157] or sending affective haptic signals to a remote user [252]. Sharing of biosignals as a means for intimate communication between users [131] is another promising direction.

7.5 Mobile Computing

A vastly explored application area for Epidermal Devices in HCI is mobile computing. Epidermal Devices have been used for designing novel techniques that enable interaction in demanding mobility conditions. This includes mobile on-body text entry [230, 238], eyes-free microgestures control [101], smart control of IoT devices [112, 157], physical interaction with mobile devices [65], display of subtle notifications [97, 133, 232, 234], and gestures that can be performed when hands are busy holding objects [157]. In addition to supporting interaction in mobile scenarios, Epidermal Devices have also been deployed in the context of other interactive applications such as in AR/VR [234, 252].

7.6 Opportunities and Challenges

We identify a few compelling application domains where deploying Epidermal Devices can not only reveal new insights but also can have a long-term societal impact. Epidermal devices present strong opportunities in several domains, where deploying Epidermal Devices can not only reveal new insights for future generations of devices but also can have a long-term societal impact.

7.6.1 Assistive Technologies. The fields of assistive and accessible computing provide opportunities for further expanding the deployment of Epidermal Devices. For instance, epidermal haptic devices can be used for providing braille output through subtle localized vibrations. In this respect, empirical investigations aiming at understanding the specific needs and preferences of the target population (visually impaired, deaf and hard of hearing, or users with motor impairments) with respect to Epidermal Devices can uncover rich design guidelines. Additionally, exoskeletons are an active research area covering multiple disciplines; the development of epidermal exoskeletons that are skin-conformal and stretchable can open up opportunities for novel assistive technologies in areas such as prosthetic control, neuromotor training, and rehabilitation.

7.6.2 Health Monitoring and Diagnosis. Health monitoring and diagnosis is an application area that is promising and has a large potential for large-scale deployment of Epidermal Devices. When manufactured on large scale, Epidermal devices can be very cost-effective and serve as useful tools for non-invasive measurement of health parameters. For example, recent research has successfully used Epidermal Devices for non-invasive COVID-19 testing [209]. We identify multiple opportunities for the HCI community to advance the state-of-the-art with respect to health monitoring: (1) using computational approaches for placement of devices and optimizing device designs to incorporate multiple sensing modalities, possibly even for individual users, (2) advanced signal processing and recognition algorithms for deployment in the wild and (3) machine learning techniques to continuously understand user's health from noisy or sparse sensor data. We anticipate that coupling the powerful physical capabilities of Epidermal Devices with the strengths of software-centered data processing will significantly enhance the quality and availability of data for long-term health monitoring and open up previously unseen opportunities for medical diagnosis.

7.6.3 Sports, Fitness, and Rehabilitation. Sports, fitness, and rehabilitation can serve as promising avenues for deploying Epidermal Devices. Research in rehabilitation studies has shown initial deployments of Epidermal Devices[163] for tracking precise body movements. Higher resolution and denser sensing patches, including full-body suits, should be developed for enabling detailed whole-body activity tracking, which can have applications in sports, fitness, and rehabilitation studies. Another area that has received limited attention in the field deployment of Epidermal Devices for athletic and sporting activities.

7.6.4 Human-Robot Interaction. Human-robot interaction is an active research area across multiple disciplines. We identify two major opportunities where Epidermal Devices can enhance human-robot interaction : (1) Imbuing the robot with human-like sensor capabilities: this involves designing Epidermal Devices for deployment on a robot that can capture a wide range of expressive interactions similar to the perceptual abilities of human skin, as well as devices that imitate the soft material properties of human skin to enhance human-to-robot touch contact [205]. (2) Enhancing control of robots through Epidermal Devices: controlling and manipulating robots is a complex task and this becomes even more challenging for a swarm of robots. Using skin-based interactions is a promising solution because of the human natural proprioceptive capabilities and dexterity. Preliminary work on controlling a drone through Epidermal Devices has already been reported [2].

7.6.5 Mobile Computing. Prior work in HCI has contributed many approaches for enriching and improving the user interaction with existing mobile and wearable devices. These explorations provide a good foundation and important lessons learned for moving to the next phase of transitioning from prototypes to commercial products. A first step in this direction is to blend these Epidermal Interfaces with existing wearable devices, for instance, soft interactive watch straps for smartwatches or as beauty accessories. Key challenges for such deployment range from identifying compelling interaction-specific use cases (e.g., eyes-free entry, inconspicuous interaction, subtle notifications without the user having to look at his mobile device or watch) to more social and personal challenges such as the aesthetic customization of the devices.

7.6.6 Ethics, Security, and Privacy. The intimate coupling of Epidermal Devices with the body opens up new concerns for security, privacy, and ethics. Firstly, epidermal Devices can capture highly privacy-critical biological data about a user's body and health status. Currently, no security or privacy-based features are incorporated into device designs. In contrast to mobile devices which rely on security measures such as fingerprint authentication, patterns, pins, or passwords, the body provides a more sophisticated means for authentication. Biological signatures such as bio-signals and bio-impedance [37, 127] can be used for authentication and adding another layer of security for Epidermal Devices. Additionally, since Epidermal Devices are present on the body, they are already in the private space of the user, which adds another level of privacy.

Secondly, the body-based output capabilities of Epidermal Devices open up new threats and ethical questions. For instance, who should be allowed to alert the user with haptic messages, and on what body locations? Under what circumstances is it legitimate to influence the user's mood through scents that are automatically disposed from Epidermal Devices? How can one avoid a hacker is getting access to an Epidermal Device that through electrical muscle stimulation can control the sensorimotor functions of the victim? While Epidermal Computing promises an exciting future, it is crucial to identify and counter these threats and potential dark patterns [54, 55] where users are deceived by this technology.

8 CONCLUSION

Across disciplines, there has been a rapid growth of Epidermal Devices in the last few years, embracing new technological developments and deployed in multiple domains, leading to the development of a new era of Epidermal Computing. Despite being a highly multi-disciplinary area, the field is beginning to close in on common areas, encircling new materials and fabrication, new device types, theoretical and empirical foundations, and application domains.

The golden opportunities taken together across all of these themes include: (1) Exploring sustainable materials and robust ultra-thin stretchable conductors. (2) Integrating computational design practices into the current fabrication workflows. (3) Fabricating for large-area devices which involves solving challenges in fabrication, encapsulation methods for interconnects, and the ability to withstand high levels of mechanical stress. (4) Extending the input and output capabilities in sensing touch, pressure and providing high-resolution visual and haptic output. In addition to sensing bio-signals, the HCI community can also explore techniques for energy harvesting and connections/tethering approaches. (5) From an empirical research perspective, pressing next steps to include in-the-wild studies, social acceptability studies, and studies measuring the interaction performance. (6) Finally, exploring promising application areas in assistive technology, health monitoring, and fitness, human-robot interaction, and mobile computing can unearth the vast potential of epidermal devices for widespread use.

Our analysis builds on our own practical experiences and on an in-depth analysis of the literature that exists across multiple disciplines and research communities. This cross-disciplinary angle brings a unique perspective and helps in identifying the overarching scientific goals that transcend the boundaries of a single research community. We, therefore, believe that the challenges and opportunities presented in this paper will resonate with scientists and researchers from disciplines inside and beyond HCI, leading to coordinated efforts across disciplines. We hope that engineers, practitioners, and industry experts will recognize them for the successful commercialization of the devices. We also invite new researchers and practitioners entering the area of Epidermal Computing to use this article to identify and work on unsolved challenges and research problems.

In summary, we are excited about the potential of Epidermal Computing and how it transforms the way we may interact with future computing devices in ways that naturally blend in with our human bodies. With the synthesis and articulation of challenges and opportunities, we hope this work will motivate further research efforts in this emerging research area and support the reader in contributing to the future of Epidermal Computing.

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