

Skintillates: Towards Epidermal Interactions

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ABSTRACT

Skintillates is a wearable technology that mimics tattoos - the oldest and most commonly used on-skin displays in human culture. We demonstrate that by fabricating electrical traces and thin electronics on temporary tattoo paper, a wide array of displays and sensors can be created. Just like the traditional temporary tattoos often worn by children and adults alike, Skintillates flex naturally with the users skin. Our simple fabrication technique also enables users to freely design and print with a full range of colors to create application specific customized designs. We demonstrate the technical capabilities of Skintillates as sensors and expressive personal and private displays through a series of application examples. Finally, we detail the results of a set of user studies that highlight the user experience, comfort, durability, acceptability, and application potential for Skintillates.

Author Keywords

Fabrications; wearable; skin; epidermis; tattoo

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI):
Miscellaneous

INTRODUCTION

Every day, we interact with the world through our skin. The human skin senses important events that happen closest to us, and serves as an expressive medium when adorned with tattoo art. In this paper, we present Skintillates, a class of novel epidermal wearable interactive devices. Skintillate devices can serve as electronic tattoos as passive and active on-skin displays, capacitive sensors and resistive sensor for mobile device control, and strain gauges for posture detection. The combined thickness of the substrate and traces of Skintillates is thinner than human hair - approximately 36μm. The devices move naturally with the users skin and are comfortable to wear for long periods of time. Similar to traditional tattoos, Skintillates can be customized to be a variety of different shapes and colors to

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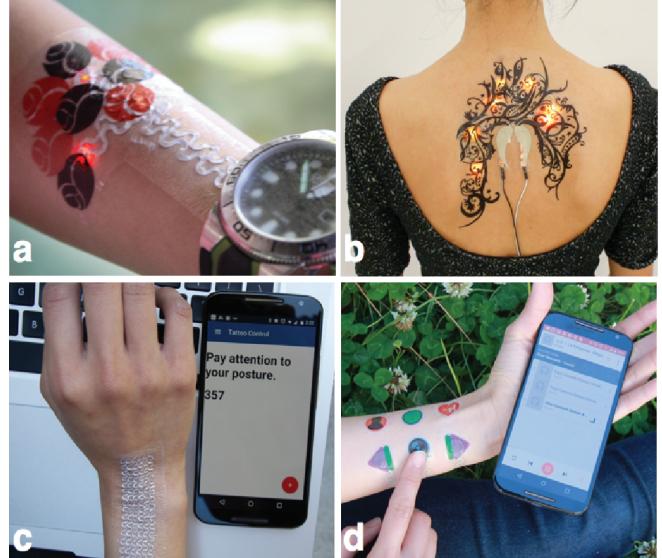


Figure 1. Skintillates is a class of temporary tattoo electronics that can be fabricated with an accessible process. a) A Skintillates point-light display, b) A back tattoo LED display that flashes with music, c) A strain gauge that detects body position, d) capacitive buttons for mobile control

fit the users intended functions. Moreover, we demonstrate an accessible, low-cost fabrication method for Skintillates that uses only commercially-available materials and easy-to-obtain equipment. Skintillates is inspired by a line of research in micron-thin epidermal electronics pioneered by material scientists. Since these epidermal electronics directly contacts the skin, they can be made into extremely accurate, yet comfortable, sensors. However, due to existing devices intricate fabrication method, epidermal sensors remain to be a device mainly used in specialized medical and military applications. Responding to a clear need for ultra-thin on-skin wearable electronics to enable natural and always-available interactions with the electronics and data around us [12–14, 19, 23, 33], we created Skintillates. Skintillates are a class of devices sparked by Epidermal Electronics but tailored for applications that focus more on everyday-interactions, and have a fabrication method much more open to experimentation for sophisticated visual and electrical design. To list a few examples, Skintillates can serve programmable/addressable LED displays with customized aesthetic design (Fig 1a-b), strain gauges that respond to body movement (Fig 1c), and capacitive with visual designs that indicate the applications that they controls in a mobile device (Fig 1d).

MOTIVATION

Skintillates aim to enable a new form of interaction and expression through electronically-augmented temporary tattoos that can be easily designed and fabricated, and comfortably worn. Beyond the technical design of our system, we surveyed the historical, cultural, and deeply personal embedded meaning of tattoos and body art.

Towards Technological Tattoos: A Brief Cultural History

Tattoos are known to have been part of human culture from as far back as the 4th millennium BC and used as forms of religious, tribal, and personal identification and adornment [11]. Expressing ones love for the combination of technology and arts through body-modifications vary in degrees from embedding ferrous materials under ones skin [28]], to tattooing math equations and molecular structure of plants onto ones body [40]. With the increasing popularity of using temporary as a platform for artistic self-expression [5, 9], it is evident that the cultural role of the skin using permanent and temporary tattoos for personal expression aligns well with that of fashion and personal technology. Skintillates explore how visual body elements can become more interactive and expressive by capturing part of the allure of the rich tattoo culture.

Public and Private by Design

Diane Ackerman wrote in *A Natural History of the Senses*, “Tattoos make unique the surface of one’s self, embody one’s secret dreams, adorn with magic emblems the Altamira of the flesh.” [26] Tattoos could serve a dual role as both a narrative to the public and a private message to the wearer [8, 25]. We foregrounded the flexibility and hybridity of these shifting public and private tensions in one of the design features of Skintillates. Skintillates afford a wide range of personal designs varying in size, shape, color, body location, sensing, and electronic properties. We demonstrate and study examples of how customization of Skintillates can allow these wearable devices to serve as both public and private display in this paper.

Aesthetic and Personalization with Wearables

Wearers of tattoos, both permanent and temporary ones, expect control of the aesthetic of the tattoos because body art sends a strong message about the wearer [8, 25]. Contemporary tattoo artist Henriata Nicholas declares that a design portrays a persons “genealogy, specific landmarks, historical events, and Kaitiaki (spiritual guides).” [2]. One could imagine that temporary tattoo, though transient, could be designed as something highly personal and expressive. However, most commercially available wearable systems offer color and few sizes as the only means to personalize their device. Counter to this limitation, Skintillates specifically all the customization of the visual aesthetic and the electronic functionality, enabling open, creative, and personal designs in an on-skin wearable device.

Comfort, Safety, and Biocompatibility

Any wearable, from clothing to electronics to tattoos, must be safe and comfortable to wear for long periods.

Skintillates use materials that have been approved by U.S. Food and Drug Administration (FDA) for safe usage human skin. To minimize the possibility of negative skin-reaction to Skintillates, we used commercially available temporary tattoo paper as the substrate, and a medical electrode grade silver screen-printing ink as the conductive material for the circuitry [1, 6, 31]. In some Skintillate devices where electronic parts such as ICs and LED’s are used, the current is limited to 10mA, which is considered physiological safe [34].

RELATED WORK

Skintillates builds off of a body or related work across Human-Computer Interaction (HCI), flexible polymers, and epidermal elections as we detail below.

On Body Interface

Our own body is our most intimate and familiar interactive device - technological advancements in fields such as optics, materials sciences, and signal acquisition and processing, have enabled HCI researchers to imagine and create sensors and controls directly on the users skin. Many of these projects aim to create an always-on, unobtrusive, responsive, technology that allow users to interact in natural and intuitive ways with their personal devices and environment. Optical projection and careful image processing transforms the users skin into an interactive display screen in work such as Skinput and Skinbuttons [14, 23]. Saponas and his colleagues obtained Electromyography (EMG) from users forearms to create a natural and always-available computer interface [32]. To explore creative input methods addition to vibration and visual, Ion led an effort that created a skin drag display that communicated messages to the user by drawing their skin with a “tactor” [16]. Other researchers imagined an implanted device as an always-available intimate input and output [15]. We designed Skintillates from the inspirations offered by these and similar HCI work in on-body interaction.

Polymeric On-skin Wearables

The flexibility of polymer makes it a great substrate for wearable electronics. Great advances have been made in many applications, including robotic skin that can detect the touch of a fly via capacitive sensing [24], fully-functional on-skin keypads [22], highly-stretchable strain gauge-based wearable interface [4, 27], ultra-flexible sensing circuits that include radio capability [17, 38], and adaptive camouflage skin overlay [39]. The thickness and relatively high tensile modulus of polymeric wearable devices makes them durable and highly reusable, providing the ideal substrate for encapsulating complex electronics.

However, of the same properties that make polymeric wearables functional and reusable also often make them uncomfortable to wear for long periods since they are typically not very breathable on-skin without special device design [17]. Moreover, to fabricate polymeric substrates that are uniformly thin for on-skin wearable applications, specialized, expensive equipment such as a spinner and vacuum chamber are often needed [17, 22, 27, 35, 38, 39].

Additionally, incorporating conductive materials into polymeric wearables, mainly through mixing conductive materials with nonconductive polymer or injecting liquid metal into prefabricated channels, is non-trivial. Mixing a conductive material, such as graphite, into a nonconductive polymeric carrier is a simple process, but the resulting conductivity tends to be extremely poor [10, 37]. Better electrically performing materials such as highly conductive liquid metal are unsuitable for on-skin applications such to their extreme toxicity [4]. These material limitations often make customizing the visual appearance of polymeric wearables difficult as well. One such example of a polymeric wearable device using this technique was iSkin, which addressed these problems by cutting the black graphite-functionalized conductive polymer into visually attractive patterns, thus cleverly turning the electrical layer into an aesthetically customizable layer [37]. Skintillates seeks to expand on this work by broadening the visual design freedom by moving from purely monochromatic art to a full range of inkjet printable colors, as well as developing techniques that can produce thinner, more comfortable on-skin interface that support additional input/output modalities.

Epidermal Electronics

Human skin has natural wrinkles, creases, and pits that are on the order of $15\text{ }\mu\text{m}$ to $100\text{ }\mu\text{m}$ [36]. If the wearable electronics have a thickness smaller or comparable to the natural skin features sizes, the wearer will not feel his/her skin unnaturally restrained [20]. Recent approaches have worked to address these epidermal surface and scale issues. The Epidermal Electronics, as defined by Kim et al, refers to the class of sensors with thickness on the order of natural skin creases, conform to small skin movements such as wrinkling, and present minimal obstructions to users skin sensations [20]. Multifunction electronics, such as capacitive sensors that accurately detect physiological signals down to 0.5V , multilayer coils that enable on-skin RF communications, and strain and hydration sensors that aids in post-operation recovery [3, 18, 20, 21] are possible with these ultra-thin devices. Materials that are structurally stronger, such as polymeric stamp, water-soluble Poly(vinyl alcohol) (PVA), or skin-safe stickers are used as a structural backing to transfer the ultra-thin epidermal electronics devices onto the user's skin [35]. Once transferred, the ultra-thin Epidermal electronics (most less than $60\text{ }\mu\text{m}$), with low Young's modulus that matches with human skin, can be attached to skin through van der Waals force alone without additional adhesive [20, 35].

Despite these the impressive scientific advances made by the development of epidermal electronics, the fabrication process makes them inaccessible to the general public. The flexibility and conformity of epidermal electronics enabled by the ultra-thin geometry comes at the expense of complicated fabrication method and equipment, such as photoresist spinner, e-beam evaporator, mask aligner, and chemical etch bay [20]. The fine electrical traces(down to $1\text{ }\mu\text{m}$ in width), and the ultra-thin conductive and insulation layers (ranges from 500nm to $5\text{ }\mu\text{m}$), though extremely

sensitive and conformal to the human skin, requires highly specialized lithographic equipment, high temperature metal deposition, and etching chemicals to fabricate [20, 21]. In one example application of Epidermal Electronics, a small piece of temporary tattoo paper is used as a backing to transfer the epidermal device onto the user's skin [20]. Unfortunately, the etching process that fabricates the fine gold traces is incompatible with commercially available tattoo paper because the paper cannot withstand the chemical etchants. Skintillates overcomes this barrier by replacing the cleanroom fabrication steps with a low-temperature screen-printing process. As a result, Skintillates enables users to customize the device both electronically and aesthetically. More importantly, this makes Skintillates accessible to a broad range of users since they can be fabricated without cleanroom equipment or extreme temperatures at a much lower cost.

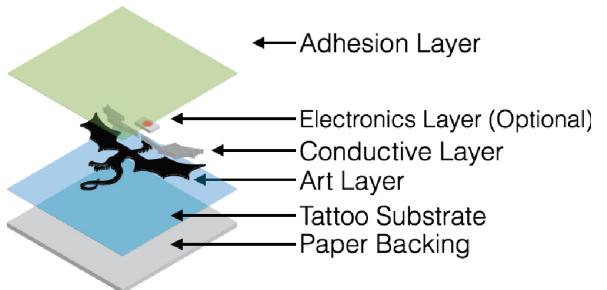


Figure 2. An illustration of the different layers of a basic Skintillate device.

SYSTEMS DETAILS AND FABRICATION

All Skintillate devices are comprised by five basic layers - three of which come as a commercially available package. Skintillate devices are fabricated on temporary tattoo paper, which rests on top of a paper backing before the tattoo is applied. A nonconductive, inkjet printed art layer can be printed on the tattoo substrate before the electrically functional conductive layer is screen-printed on top. Additional layers, such as an electronic layer, can be added to enable more complex interactions and expressivity. Before applying the Skintillate devices onto users' skin, an adhesion layer is applied on top of the Skintillate device.

In designing the Skintillate devices, there were four major goals that guided our decisions.

- **Functional**-provide electronics that are conductive enough to support body based HCI applications such as sensing and output display
- **Comfortable**-fabricate with materials that are thin (ideally under $100\mu\text{m}$ to fit within natural wrinkles), skin conforming, unobtrusive, and can be comfortably worn for hours or days and easily removed
- **Durable**-maintains functionality over typical usage of hours or days.
- **Aesthetically Express**-the substrate has to be easily customizable to enable a broad range of artistic expressions and user personalization

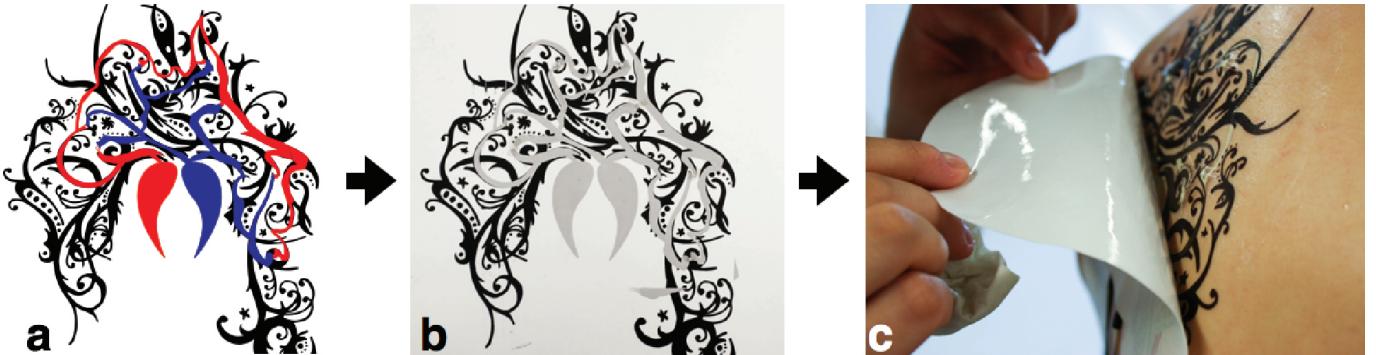


Figure 3. Skintillates fabrication process work flow. a) the art layer (in black) and the electrical traces (in red and blue) are designed in a standard design program, b) the art layer (in black) is inkjet printed and the conductive layer (in silver) screen-printed on the tattoo substrate, and c) the Skintillate device is applied on skin and released from the paper backing.

Similar to epidermal electronics, we aimed for the look and feel of electronic-integrated-with-skin aesthetic in Skintillates. We aimed to design a fabrication process that relies on inexpensive equipment and materials, and we looked to the crafting community for inspirations. Screen-printing, which can be carried out in a relatively simple and inexpensive set of tools, was a great candidate for the Skintillate fabrication process. The screen-printing technique has been used to create work from beautiful arts and craft to fine and complicated flexible electronics by Makers of all skill levels [7, 29, 30]. We chose to directly screenprint the Skintillates circuits and sensors onto commercially available temporary tattoo papers. The silver ink screen-printable ink (\$100 for 25g), which commonly used for fabricating medical devices and electrodes [6, 31]. Although we have successfully created these devices with both conductive inkjet printing and conductive pens, we decided against fabricating the Skintillates devices with them because of the lack of data in the safety and long-term biocompatibility of these inks.

For the device substrate, we choose to use an inkjet-printable temporary tattoo substrates (Silhouette Inkjet Printable tattoo paper, \$7.42). We believe temporary tattoo papers to be a good platform for Skintillates because 1) users can simply inkjet print the visual design of the tattoo directly onto the tattoo paper, and 2) as an existing product their safety and comfort has already been well established. Moreover, temporary tattoos have an application process that is simple and well established. By building on top of a substrate that users are familiar with, we hope to enable Skintillates to be easily incorporated into users everyday active lifestyle.

Fabrication and Applying Skintillates

Skintillates are fabricated using a standard screen-printing process and applied onto users skin the same way temporary tattoos are applied. The full process is detailed below.

1. **Artwork Design**-Design a with any graphic design tool. (Black area of Figure3a)
2. **Electronics Design**-Design the circuit and/or sensors to be screen-printed as the conductive layer. (Blue and red area of Figure3a)

3. **Print Art Design**-Use an inkjet printer to print the art layer design onto the tattoo substrate while it is still attached to its paper backing.
4. **Create Mask**-Cut a negative mask with vinyl cutter for screen-printing the conductive layer.
5. **Attach Mask**-Apply vinyl mask onto the silkscreen.
6. **Silkscreen Traces**-Screen-print the circuit and/or sensors using conductive silver screen-printing ink.(Figure3b)
7. **Populate Circuit**-Mount electronics onto the circuit using z-conductive tape at appropriate locations if needed. Apply copper tape or any desired connector to power the circuit.
8. **Prepare Skintillate Device for Application**-Apply the adhesive layer included in the temporary tattoo paper package.
9. **Apply Tattoo**-Position the Skintillate device on the desired body location. Wet and lift the paper backing (Figure3c)

Figure 4 shows that a basic Skintillates device, which contains the tattoo substrate and a conductive layer, is approximately 36 μ m, which is thinner than an average human hair. Surface mount 0603 LED's and resistors, which have thickness of 500 μ m, were used throughout this study to minimize the added thickness in locations where electronics were mounted (fig.5). Increased complexity in electrical functionality and aesthetic design could be achieved by using deviations of this basic fabrication method. The specific changes will be discussed in the application section.

Cost and Fabrication Time Analysis

We performed a cost and time analysis of fabricating a Skintillates device with some integrated electronics that wrap around the arm. (The same tattoo was used in the user study.) A Skintillate tattoo that measures 6.5 in x 1.0 in would cost \$0.23 in temporary tattoo paper and adhesive. It would take approximately 0.3g of silver screen-printing ink to fabricate the circuit, which cost \$1.2. With \$0.5 allocated for surface mount LED, the total cost of such a device is \$1.83. Such a tattoo would take less than 15 minutes to fabricate. The cost of the Skintillate device will vary with the design. For example, a large Skintillate device with

many electrical silver traces will cost more than the aforementioned example device.

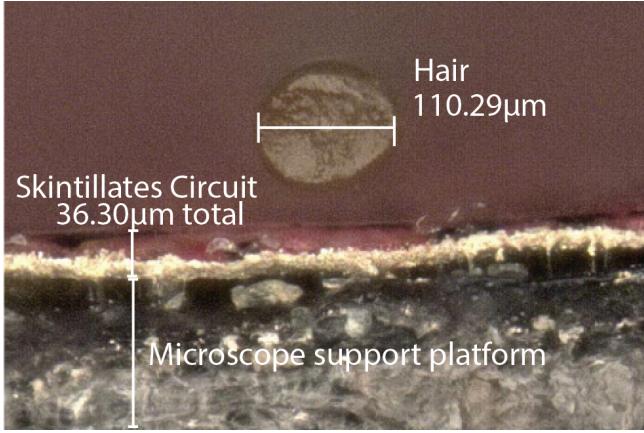


Figure 4. A micrograph of the cross section of a 36 μm -thick Skintillates device compared to a cross section of a piece of human hair (110 μm).

DESIGNING THE VISUAL AESTHETICS OF SKINTILLATES

The visual appearance of Skintillates can be designed using the inkjet printable art layer and the conductive layer. Figure 6 shows a few examples of visual design possibilities. The color and shape of the art layer, which lies on top of the conductive layer when the tattoo is put on skin, can be used to hide or complement the conductive layer. A darker color printed on the art layer that completely overlaps the conductive layer can hide the conductive layer (fig6a). A lighter color printed on the art layer or a shape that does not completely overlap with the conductive layer allows the silver layer to peek through (fig6b). The shape of the functional silver conductive layer can also be used to enhance the art layer by serving as a subtle decoration or a visual element in the design (fig6c-d).

APPLICATIONS

We envision a wide range of applications enabled by Skintillates and detail the technical designs and novel interactions across a set of examples in this section.

On-Skin Display

One of the most important aspects of wearing tattoos, either temporary or permanent, is to express personal identity. Skintillates aims to augment the self-expression of tattoo artwork with electronics. In Figure 7, we show a few examples of public and private decorative Skintillates

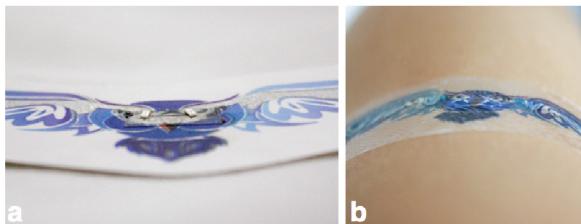


Figure 5. A side view picture of Skintillate device, showing its conformal profile. a) A Skintillate device with 0603 LED electronic. b) The same display worn on skin

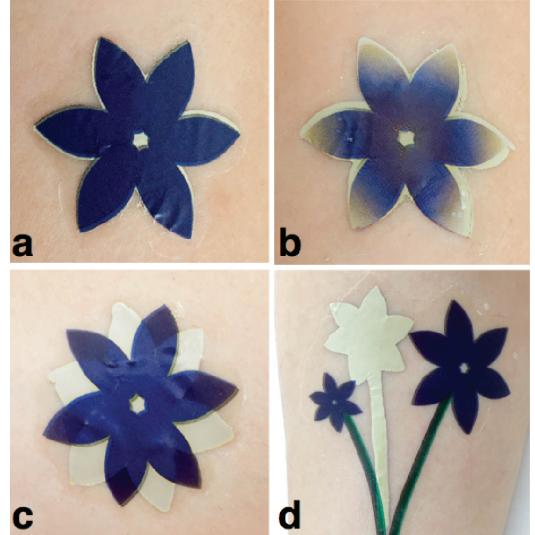


Figure 6. Example of visual design of a Skintillate device. a) A dark colored pattern is printed on the art layer to completely cover the conductive layer, b) A lighter gradient color is printed on the art layer to allow the shape and silver color of the conductive layer to peek through, c) The pattern of the conductive layer is designed to complement the blue flower printed on the art layer, d) The silver conductive layer can be designed to be a design element

displays. Figure 7a shows a Skintillate dragon tattoo with red LED eyes that is electrically connected to the watch, and could potentially serve as a point-light display for a smart watch. Figure 7b demonstrates a back tattoo with LEDs that flash with music, which is controlled by an Arduino hidden under the wearer's clothing. In this example, we also



Figure 7. Example of Skintillates tattoo displays. a) A dragon Skintillate display is powered by the watch and could serve as a point-light display, b) a back Skintillate tattoo that flashes with the pulsation of the music around the wearer, c) a private Skintillate tattoo flashing according to ECG signals, d) a Skintillate tattoo without a printed art layer decorates an existing permanent tattoo

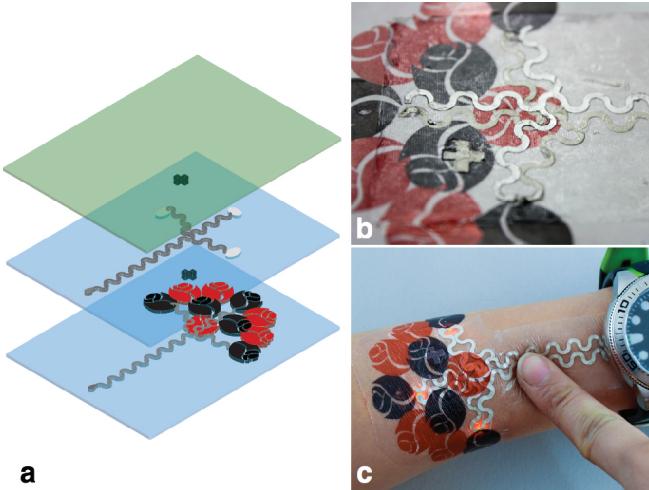


Figure 8. Multilayer Skintillate Display. a) A exploded illustration of the different layers: a bottom layer consists of the basic Skintillate art and conductive layer, a second conductive layer connected to the first layer through the vias, and the adhesive layer. b) a photograph of the two overlaying but insulated conductive layers, c) the multilayer display under operation while being compressed, showing that it maintains flexibility.

explored the aesthetic of electrical traces and power pads on the tattoo. The power pads, which are traditionally circular or square in shape in printed circuit boards, are designed to look like wings to fit with the aesthetic of the art layer of the tattoo. In Figure 7c, we investigated the potential of using Skintillates as a private wearable display for intimate bio-data. We downloaded two sets of publically available test electrocardiogram (ECG) signals from PhysioNet to simulate the heartbeats from two people. In real-life applications, the Skintillates bio-data display can interface with biomonitoring data from commercially available wearable devices. The LEDs are programmed to blink as the signal strength reaches a certain amplitude, mimicking two heartbeats. The user wore the Skintillate ECG display under a shirt so that he/she can lift and glance at the private display when desired. In Figure 7d, we explored the possibility of incorporating a Skintillate display with an existing tattoo. We omitted the art layer in this device and traced one of the tree branches on the silver ink conductive layer to power three LEDs to light up the tattoo flowers.

Multi-layer Display

Multilayer devices can be fabricated for higher visual or electronic complexity. In printed circuit board design, multiple layers are often needed to achieve desired form and function. Epidermal electronics have also explored using multilayer devices to support more complicated function. In arts practices, layers are often used as a means to create depth. In order to fully explore combining arts and electronics on a wearable device, the Skintillates fabrication process should be able to support electronic function and aesthetically attractive multi-layer devices. Figure 8a shows an exploded view of a multilayer Skintillates device. In this study, we created a second conductive layer, but the same procedure could be used for creating a second art layer. A second layer was screen printed on a separate temporary

tattoo substrate, and was released from the paper backing onto the first conductive layer. In order to electrically connect the first and second conductive layers, we created electrical vias, which are openings that allows for electrical connections, by cutting holes in the substrate at appropriate locations. Figure 8b shows a closed-up image of the dual-layer Skintillate device. The top layer traces are insulated from the bottom layer traces with a tattoo layer substrate, and vias are opened at the ends of the traces to allow the LED's to make contact with both sets of the traces. Although the multilayer Skintillates devices are thicker than the single layer devices, they remain reasonably flexible on skin. In figure8c, we show that the dual-layer Skintillates device remains operational even when the traces are being compressed into the skin.

Capacitive Sensing

Advanced sensing, including capacitive sensing, using epidermal devices is well-established [10, 18, 24]. In many research studies, various algorithms, data processing methods, and grounding schemes are utilized to overcome any technical difficulties usually associated with wearable sensing. Through careful material selections, we can achieve sensitivity suitable for common interactive applications. As mentioned in the Fabrication section, the silver screen printing ink used for Skintillates is very conductive ($0.5\Omega/\square$). The high conductivity is important in resistive switch design, where the touched surface needs to be conductive enough to close the switch; it is also pertinent in capacitor design, where increasing conductivity of the material increases the availability of charge, which directly affects the sensitivity of the capacitive button (Gauss law= $\frac{\sigma}{\epsilon}$). In the following sections, we will go through a few sensing examples using the Skintillates devices.

Capacitive sensing is ubiquitous in interaction design - from sensing gestures to sensing direct touch, the change in electric field carries rich information about the space around us. Skintillates can utilize this sensing mechanism to easily incorporate human interfaces that can be used as local input or as remote signals to control a mobile smartphone.

To ensure reliable performance of the capacitive sensor, both the electronic filtering and the physical device insulation have to be carefully designed. To reduce cost and simplify the design the raw data of the capacitive sensor is processed and filtered by a commercially available breakout board¹. To insulate the capacitive sensor against the skin where it is attached, we modify the fabrication steps slightly by adding insulative temporary tattoo substrates without any silver conductive ink on top of the conductive electrodes. This insulative layer prevents electric charges on the surface of the skin from interfering with the desired capacitive touch signal (Fig.9a).

In this study, we demonstrated using capacitive Skintillates buttons control various mobile smartphone applications (i.e. music, social media, etc) through a low power wireless bluetooth module². By placing the Skintillates on the inside of the users arm (Fig9b), he/she can control the mobile applications on an easily accessible body location (Fig9c).

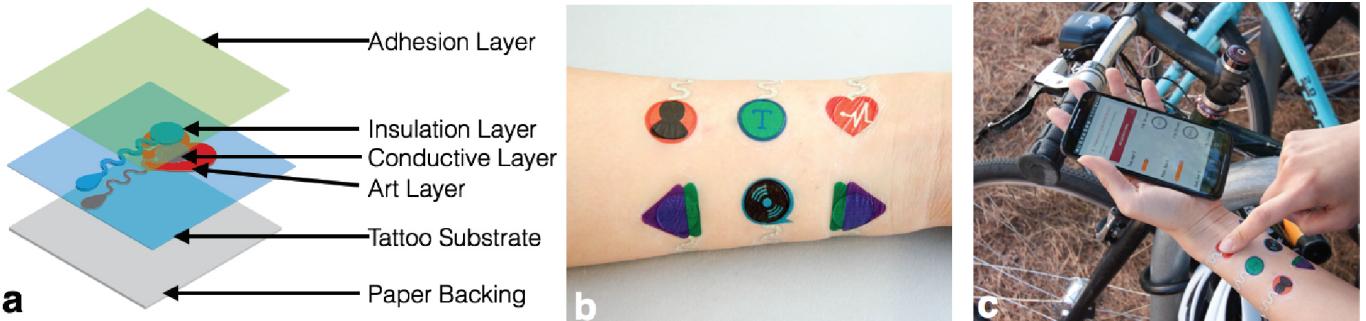


Figure 9. Skintillate Capacitive touch sensing. a) An exploded illustration of a Skintillate capacitive sensor showing one additional insulation layer on top of the conductive layer to prevent charges on skin to interfere with the capacitive touch signal, b) capacitive sensors can be applied on body locations convenient to the wearer, in this case, the inner arm, c) the Skintillate capacitive buttons were used to control a mobile device when the user was active and could not directly access the device screen.

The size and shape of the Skintillates buttons are highly customizable, enabling visual design freedom - such as creating buttons with shapes that represent the application being controlled. Skintillate capacitive sensors are also versatile in that they can be used as capacitive sliders and wheels in addition to simple buttons.

On-Skin Resistive Sensor



Figure 10. Skintillate Resistive Sensor. a) Two Skintillates resistive sensors shaped as kites are applied on user's arm. b) the Skintillates sensors are connected to the MakeyMakey to allow user to control the kites within the computer game.

Using the human body as a conductor to form a closed circuit to turn on a light is common science experiment, and this sensing method can also enable interesting interactions - such as turning bananas into switches - made popular by MakeyMakey. We demonstrated that Skintillates can be used as a resistor sensor that is compatible with MakeyMakey. The construction of the Skintillates resistor sensor is very similar to that of the capacitive sensor, with an insulative layer beneath the electrode to prevent electrically connection between the sensor and the skin that it is adhered to. Figure 10a shows two Skintillates resistive sensors shaped as kites, which are connected to the MakeyMakey to act as the left and right arrow of a computer keyboard. The custom buttons are then used as a controller to play a computer game of moving the kite up and down to avoid hitting objects in the sky (fig10b). A large open-source library and community support are available for prototyping with MakeyMakey, and the Skintillates resistive sensor can be used to enable a wide range of wearable interactions.

Strain Gauge

The subtle analog motions of the human body carry information that goes beyond the digital on/off button. The Skintillates strain gauge captures the fluid motion of the human body by translating the movement into a variable resistance. The strain gauge has a longer length in the direction of the wrist bending during typing. As the sensor stretches and contracts with the wrist flexure, the resistance increases and decreases. The change in resistance is detected through a Wheat stone bridge and amplified using an INA125P operational amplifier. Before amplification, the variation in the resistance ranges from 37Ω (when wrist is flat) to 54Ω (full wrist flexure). The amplified analog value is read using an Arduino Uno and transmitted to a mobile phone via Bluetooth, where the value is then displayed on the screen of the mobile phone. Appropriate warning messages are displayed as the users wrist posture change. Although the strain gauge is applied on the wrist in this example, similar application can also be used for back posture by placing the sensor on the neck (Figure 7c). In addition to posture detection, Skintillates strain gauges can serve as an always-available, non-intrusive sensor to detect different gestures for electronic interactions or be incorporated into performance art.

USER STUDY

While the functionality and signal quality of Skintillates is an important part of detailing its design, we were interested in how Skintillates would perform under every day, natural conditions with real users. We were also interested in users degree of comfort and reactions to the Skintillates aesthetics. To improve our understanding of these issues we conducted a series of user studies.

Study Participants

We recruited 10 participants (6 male and 4 female) through an office mailing list to be interviewed and wear a pre-designed Skintillate device. Our participants ranged in age from 25 to 42 years old with 29.7 being the mean. All of the participants were technically knowledgeable and had prior experience with electronics.

¹ Adafruit Capacitive Touch Sensor Breakout MPR121 connected to an Arduino Uno

² A low-power BLE module provided connectivity to the phone.



Figure 11. Strain gauge for body position sensing. **a)** The strain gauge reading indicates that the user's wrist is in a correct typing position. **b)** The strain gauge reading indicates that the user's wrist is not at a correct posture, which causes the mobile phone to send a warning message. **c)** The strain gauge can also be worn on other body positions, such as neck and back, to detect movement and posture.

Procedure

Each participant arrived and was met individually during the start of the workday. Three previously designed and fabricated Skintillates were presented to them along with an overview of the project and description of the individual elements of the Skintillate. The three Skintillates that were chosen in the study represented a broad range of sensing and display types. The three Skintillates were (1) a Skintillate display measuring 6.5 in x 1.0 in and connected to 3.3V coin cell batteries (Figure 12a-b), (2) a Skintillate resistive sensor measuring 1.3 in x 0.8 in and connected to a MakeyMakey (Figure 11c), and (3) two unaltered temporary tattoos without any conductive layer to be used as a control. Participants were invited to select a location to wear each Skintillates for the duration of a workday (ranging from 8-10

hours), and the researcher applied the devices on the chosen locations. Simple functionality tests turning on the LEDs on the Skintillate display and controlling computer keys with the Skintillate resistive sensor were performed immediately after the devices were applied on skin. The Skintillate displays were continuously powered and participants were asked to contact the researcher if the devices stop functioning. After the Skintillate devices were applied and tested, the participants returned to resume their normal daily work activities and to return at a predetermined time at the end of the workday. The work functions participants performed included office activities such as typing, writing, and manipulating light machinery (i.e. 3D printers, thermal oven).

At the end of the work day, participants returned and were interviewed about their qualitative experience of wearing Skintillates. We also conducted a survey to quantitatively measure comfort levels. Finally, the same functionality tests performed in the beginning of the study were performed on the Skintillate devices to assess their durability. Participants were free to choose whether they want to remove or continue wearing the Skintillate devices at the end of the interview. In both conditions, participants completed a follow-up survey the following day about the social aspects of Skintillates.



Figure 12. Representative Pictures of Skintillate Devices in User Study. Participants were free to apply the Skintillate tattoo on any body location, example applied body locations include **a)** neck, and **b)** arm. **c)** Skintillate resistive sensor used in the study worn on arm. **d)** Skintillate LED displays used in the study utilize small 0603 LED parts, which allows the Skintillate tattoo to retain its conformal profile.

Discussion and Findings

All ten participants chose to attach all of the Skintillates and control tattoos and completed the study. ****need to add a bit more here***. We analyzed our interview data using a thematic analysis to reveal patterns across data sets associated with specific research questions. These themes become the categories for analysis and are discussed in the subsections that follow.

Body Location Choices

The majority of the users chose to put the Skintillates devices on their arms, while one user placed the Skintillates display on the back of the neck. When asked about their decision of the placement of the Skintillates devices, users cited the shape of the Skintillates devices and their outfit of the day to be the main reason for their choice. All of the Skintillates displays were worn in publically visible location

- uncovered by the participants clothing. The wearing location of the Skintillate resistive sensors were based on participants preference on on-skin keyboard interactions. For example, R2 chose to put the resistive sensors on the inside of his/her forearm because he/she prefers using his/her thumb to control the on-skin keyboard while resting his/her palm on his/her arm.

Comfort and Social Acceptability

Participants were asked at the end of the 8-10 hour wearing period to rate the comfort of the Skintillate display on a 1-10 scale (with 10 being most comfortable). Users made this assessment with and without consideration of the battery connection (i.e. the copper tape connected to the battery). Since different body locations contain different nerve endings and degrees of sensitivity, it is difficult to generalize the results. However, we believe the quantitative results were valuable since they provide insights on the perceived comfort for the user-selected wearing locations. The average comfort of the control temporary tattoo was 9.2 (SD = 0.42). Without considering the battery connection, the comfort of the Skintillates display and resistive sensor was 8.2 (SD=0.67) and 8.8 (SD = 0.35) respectively. Most participants described Skintillates devices as something that they *don't even feel after a while and feels very similar to a normal temporary tattoo*, and the small 0.5mm-thick 0603 electronic LEDs were described as *little bumps* and did not appear to significantly affect any of the participants comfort assessment. None of the participants mentioned the electronic parts as an undesirable element of the design in terms of comfort. Not surprisingly, when considering the battery connection, the comfort level of the display decreased to 7.1 (SD = 0.53). Participants were most bothered by the battery connections and the hard coin cell batteries.

A exciting result was that even at the end of the formal wearable portion of the study, 8 of our 10 participants chose to continue wearing both Skintillates. In the follow up survey on the next day, participants were asked how long and why they continued to wear their Skintillates devices even after they were invited to remove them. All of the participants who had plans to interact with friends and family after the work day (8 out of 10) kept wearing the tattoo after the study so that they could show the Skintillates devices to their loved ones - I wanted to keep it because I thought my kids would think that this is the coolest thing ever. Two of the participates mentioned that although he/she did not have prior plans to go out after work that night, they decided to go to a public place (one to a restaurant for take-out, and one to a sports bar) to show off the Skintillates display. R7, who went to a sports bar to show off the tattoo, commenting *it seems to be a waste not to show this to someone*. Although all of the participants took off the Skintillates devices before showering or going to bed, all of them said that they took the devices off very carefully as to not damage them so that they could reuse them in the future.

Even more encouraging, all of our participants reported that they would like to wear the Skintillates device again, and

expressed a desire to design their own Skintillates displays and sensors.

Durability

During the study only one of the ten Skintillate displays was damaged. In one of the devices, the battery wire of the device was caught on the chair and was torn when the user stood up after wearing the device for approximately five hours. All the remaining nine displays functioned perfectly throughout the entire study. Within our lab group, we have found that Skintillate devices can remain functional for days after multiple removal and reapplying steps. We hope to perform longer term user study in the future to examine the limit of the durability of the different types of Skintillate devices.

Envisioned Applications

We asked participants after wearing Skintillates for the 8-10 hour day to describe imagined scenarios of usage with such devices. One class of applications were around creative interactions with nearby devices *"a henna tattoo that can control everything in my house"*, *"a tattoo buttons that make people massage my back when they need to turn on the light"*, or to *"control things with a Spiderman gesture"*. Another theme was more specific usage as a decorative body display *"put some evil red eyes on my [permanent] skull tattoo"*, *"burning man costume"*, *"a car tattoo with cycling LEDs on the wheels"*. We also found deep reflection on more functional designs – as *"turning signal for motorcyclists [mounted on the back of the neck]"* or *"a red/green light [to indicate if] I want to be bothered by people"*. *** Need some 2-3 sentences to wrap up user study section***

LIMITATIONS

While we have highlighted a number of benefits of the Skintillates design, there are several important limitations of the current technology. First, while the Skintillates device and its electrical traces are highly flexible, the external electrical interconnects to batteries for power are not. These are currently made with copper tape which does not have the same elastic properties as the Skintillates. This difference in material properties not only causes that electrical connection to be the mechanically weakest point of the device but also was a source of discomfort in our users. We believe this problem can be overcome by stabilizing the connection using a small piece of medical-grade tape - the tape relieves most of the stress exerted on the connection and prevents tearing of the connection. In future work, we would like to develop a flexible electrical connector that can move with the skin and provide an electrical interface with the Skintillate device.

Another limitation lies in the reusability of the Skintillates devices. In the research team's experience, the Skintillates devices can be reused at least four to five times if the devices contains finely traced (<2mm) circuits and many more times if the sensors consist of only large conductive patches. The reusability of the devices could potentially be improved with a thin (<10um) spray-on encapsulating layer. Further

studies can also be performed to optimize the electronic design for durability.

DISCUSSION AND FUTURE APPLICATIONS

The development of Skintillates has significant impact in customizable flexible and wearable electronics and their applications. The simple fabrication process of Skintillates provide an alternative to prototyping with 3D printing or polymer casting and curing. The design freedom, in terms of electrical, functionality, and visual aesthetic design, of Skintillates can support a diverse ecosystem of users from diverse backgrounds, including engineers, designers, and artists. We plan to continue to investigate the creation of more complex interactive electronics on Skintillate devices and studying how these devices can blend artfully and seamlessly into people's daily lives.

In order to support more complex interactions, we would like to develop flexible electronics to replace the Arduino and MakeyMakey that the Skintillates are currently interfacing. By using thin substrate and conductive polymeric electrical traces, we hope to create a multipurpose open-source development board specific for flexible wearable applications.

We would also like to expand upon the current aesthetic design of Skintillates by collaborating with artists, in particular tattoo artist and performance artists, to create Skintillates responsive and interactive tattoo designs. Since Skintillates sensors and programmable displays can be adhere on a diverse of body locations, we would like to explore some creative interaction and data display methods that are tailored to the human body instead of an electronic screen.

CONCLUSION

In this paper we presented a novel wearable on-skin technology - Skintillates. We demonstrated its wide range of capabilities from capacitive and resistive sensing input to point-light output, which are augmented with an easily inkjet-printable customizable full-color aesthetic design. We presented a range of functional designs across a set of application domains such as health and well-being, mobile device interaction, social connectedness, and personal fashion and lifestyle. We studied both in the lab and in the field via a user study how its thin (typically approximately 36 microns) and flexible material design easily conforms to the skin making it comfortable to wear for an extended period of time. We also measured its durability over time with a wide range of users, demonstrating how Skintillates performs well during everyday activities – remaining functional for hours or even days. Finally, we highlighted how our use of common design software, low-cost materials, and simplified fabrication techniques make Skintillates a truly accessible technology. We hope that this functional, comfortable, and accessible on-skin device will be enthusiastically adopted by other practitioners and inspire a range of novel applications and aesthetic designs for our future wearables.

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