# DuoSkin: Rapidly Prototyping On-Skin User Interfaces Using Skin-Friendly Materials

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**Figure 1: DuoSkin is a rapid prototyping and fabrication process using the skin-friendly material gold leaf to create wearable on-skin user interfaces, such as (a) sensing touch input, (b) displaying the user's mood using a thermochromic tattoo, and (c) communicating and sharing data with other devices through NFC—all while maintaining body decoration aesthetics.**

## ABSTRACT

Miniature devices have become wearable beyond the form factor of watches or rings—functional devices can now directly affix to the user's skin, unlocking a much wider canvas for electronics. However, building such small and skin-friendly devices currently requires expensive materials and equipment that is mostly found in the medical domain. We present *DuoSkin*, a fabrication process that affords rapidly prototyping functional devices directly on the user's skin using gold leaf as the key material, a commodity material that is *skin-friendly*, *robust* for everyday wear, and user-friendly in fabrication. We demonstrate how gold leaf enables three types of interaction modalities on DuoSkin devices: sensing touch input, displaying output, and communicating wirelessly with other devices. Importantly, DuoSkin incorporates aesthetic customizations found on body decoration, giving *form* to exposed interfaces that so far have mostly been concealed by covers. Our technical evaluation confirmed that gold leaf was more durable and preferable when affixed to skin than current commodity materials during everyday wear. This makes gold leaf a viable material for users to build functional and compelling on-skin devices. In our workshop evaluation, participants were able to customize their own on-skin music controllers that reflected personal aesthetics.

### Author Keywords

Electronic skin; Temporary tattoo; Gold leaf; Fabrication; Craft.

### ACM Classification Keywords

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

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## INTRODUCTION

Everyday devices have now become so small that they can be embedded into fabrics [10], worn as accessories [20], or be attached directly to the user's body on skin. Particularly such epidermal electronics are promising [15,34], as they are always available and expand the sensing modalities of current mobile and wearable devices by sitting directly on skin, which facilitates direct access to users' biomedical signals.

However, the manufacturing of epidermal electronics is expensive and requires materials and fabrication processes that are limited to the medical domain and material sciences. Indeed, applications commonly monitor vital signals [15], glucose levels [1], and skin conditions [16], but so far have not extended beyond health, activity, and wellness.

Researchers have sought to expand such on-skin devices from medical purposes to everyday user interaction. For example, iSkin is a flexible, visually customizable overlay that appropriates the skin for input [31]. Although promising, iSkin (700µm) is significantly thicker than existing epidermal electronics (0.8µm) [15] and still requires expert grade materials (silicone elastomer and carbon particles).

In this paper, we aim to make durable and skin-friendly *on-skin user interfaces* available to the wider community, using commodity materials, electronic components, and fabrication processes. We appropriate gold leaf as the key material to fabricate such wearable interactive devices, a type of metal leaf that appears golden. More than wearable around the body, the devices we showcase and their thin user interfaces attach directly to skin, bringing the benefits of epidermal electronics to low-cost interactive prototypes, which we call *DuoSkin* devices. The devices shown in Figure 1 sense input, display output, and communicate wirelessly with proximate devices. We created these devices exclusively using DuoSkin, whose process is outlined in Figure 2.

DuoSkin thus closes the gap of prior work on fabricating body interfaces [31] by repurposing accessible materials (e.g., gold leaf, thin tattoo paper) and tools (craft electronic

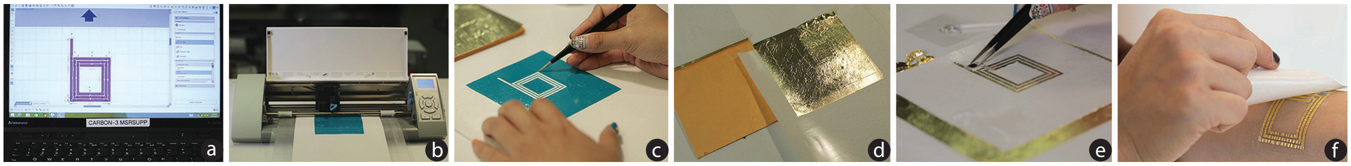

**Figure 2: DuoSkin's three-step workflow. Step 1: (a) Sketching skin circuitry with graphic design software. Step 2: (b) Fabrication, which includes (c) creating stencils of the circuitry, (d) applying gold leaf as the conductive material, and (e) mounting electronics. Step 3: (f) After completing the circuitry, we apply the DuoSkin device to the user's skin through water-transfer.**

cutter) for rapidly prototyping *on-skin user interfaces*. We demonstrate input sensing, thermochromic displays, NFC tags, and multi-layer circuitry to show DuoSkin's potential.

Complementary to their technical functionalities, DuoSkin devices accommodate *decorative aesthetics* and thus allow users to combine on-skin electronics with body decoration. Our evaluation shows that it is the gold leaf material that enables this complementation, as traditional non-rigid circuit prototyping materials, such as copper tape and conductive thread do not enable such comfort, durability, and aesthetics on the skin. In a workshop study, we observed how participants easily created skin music controllers that reflected their personal aesthetics using DuoSkin.

## CONTRIBUTIONS

Our paper makes the following five specific contributions:

1. Our main contribution is *DuoSkin*, a rapid fabrication process for prototyping on-skin user interfaces.
2. The key material that enables DuoSkin is gold leaf, which is skin-friendly and user friendly for fabrication. Importantly, we appropriate gold leaf as a conductor for three *different* modalities: *sensing* touch input, *heating* thermochromic displays, *communicating* wirelessly with other devices using induction (NFC).
3. We demonstrate *functional* devices made with DuoSkin, all of which are interactive, affix to the user's skin directly, and are robust and durable during long-term use.
4. A technical evaluation on the durability and conductive properties of gold leaf and modalities of DuoSkin devices, showing DuoSkin's viability for device prototyping.
5. DuoSkin brings form to function in on-skin user interfaces, allowing users to add their sense of aesthetics to the creation of functional and decorative on-skin devices.

## RELATED WORK

DuoSkin relates to main areas of research: on-body devices and miniature technology, fabrication and materials, as well as body art and jewelry for aesthetic inspiration.

### On-Body Devices and Miniature Technology

On-body devices appropriate the user's body as an always-available surface for input, output, and communication. To sense input, related projects have used bio-acoustic [11], capacitive [14,31], and magnetic signals [4]. Empirical studies have found that users prefer their forearm for on-body input [32]. To display output, related projects have mounted small projectors [11] or displays [28] onto the body. The Vivalnk tattoo is a commercially available NFC sticker [30], but without the ultra-thin qualities of tattoos. Researchers have also evaluated the quality of sensing input and displaying output *through* skin using interactive implants [12].

In the materials sciences, epidermal electronics are integrated electronics with soft, stretchable forms with skin-like properties [15]. Targeted for medical applications, their use includes electrocardiograms, electromyograms, and temperature and UV sensing [16]. On the flip side, these capabilities entail challenges in manufacturing, federal regulation and cost [13,33], which restricts wider access by the community.

### Fabrication and Materials

Several related projects have presented fabrication processes for devices on or close to the skin. For example, iSkin is a flexible silicone-based skin overlay for sensing touch input [31]. iSkin requires mixing material-science grade materials (PDMS with carbon) and its sticker-like thickness of 700µm is more than 800 times that of epidermal electronics (0.8µm). With DuoSkin, we attempt to produce *seamless* skin interfaces using commodity components. Skintillates prints conductive silver ink on temporary tattoo paper to create 36µm thick on-skin devices [19], which comes closer to our goal. It remains unclear, however, how robust silver ink circuitry is under practical circumstances over the course of a user's day. Our evaluation of gold leaf as DuoSkin's key material shows the robustness of gold leaf during motions and users' regular activities with 2µm-thick interfaces.

The Maker community has repurposed craft materials to create flexible circuitry and devices. For example, A-Kit-of-No-Parts are fabric-based circuits [23] and Paper Electronics are circuitries made with copper tape [24]. Midas creates custom capacitive touch sensors on objects with copper tape [26]. PrintScreen creates flexible displays with thin-film electroluminescence [22]. Building on the commodity approach of all these toolkits, DuoSkin brings rapid prototyping to the skin, overcoming wearability and material factors.

Finally, our key material gold leaf is traditionally used in the craft and art domain as a workable material for gliding statues and picture frames, paper and yarn [8] to create metallic aesthetics. Except for one project that repurposed gold leaf for paper-based circuitry [25], we could not find a use for prototyping. Epidermal electronics [5,34] have leveraged a similar material, i.e., thin layers of pure gold (Au) for on-skin circuitry, yet the materials processes are expensive and require expert facilities. Gold leaf, in contrast, is cheap ($0.50 per 15x15 cm$^2$) and purchasable at every craft store.

### Body Art and Jewelry

Body art is the aesthetic modification of the body, including tattooing, piercings, to makeup [3]. DuoSkin draws from a trend in body art around metallic jewelry-like tattoos [9], which are temporary tattoos printed with non-conductive metallic ink. Artistic explorations have integrated technology into body painting and makeup, but remain conceptual [7] or limited to individual LEDs [18,29]. Jewelry-like wearables (e.g., Intel MICA [20]) are decorative objects close to the body that integrate technical functionality.

Unlike projects in the related work, DuoSkin leverages readily-accessible materials and processes that enable users to create and customize on-skin circuitry. This accessibility expands on-skin electronics beyond medical applications while considering the aesthetics of body art.

## DUOSKIN: FABRICATING ON-SKIN USER INTERFACES

We now introduce gold leaf as DuoSkin's key material, describe our fabrication process, and demonstrate functional example devices and applications of DuoSkin.

### Gold leaf: A Skin-friendly and Conductive Material

For DuoSkin, we repurpose gold leaf as our key fabrication material, because it is conductive, skin-safe, easy to attach to and remove from skin, and clean. Gold leaf is also robust to movements and skin deformations during motion. Finally, gold leaf is both, workable and aesthetic in appearance, resembling the look of jewelry, making it our prime choice.

### DuoSkin: The 3 Steps of our Fabrication Process

*1. Sketching:* We start with a paper prototyping process, common in tattooing, where paper stencils are placed on the body to decide the location and size of user interfaces. Users then design the actual skin circuitry in 2D design tools, such as a graphical editor (e.g., Illustrator as shown in Figure 2a).

*2. Fabrication:* DuoSkin user gold leaf as the conductive material and thin tattoo paper silicone as the flexible substrate that adheres to skin. Overall, our process comprises three parts, which users can execute manually or automate with custom machinery.

*2.1. Create stencil:* We create a stencil for the circuitry by applying a layer of vinyl film (Clear Covering Self-Adhesive, $6/roll) on thin tattoo paper (Silhouette Temporary Tattoo Paper, $8/pack) and cut the film layer with a low-cost electronic cutter (Silhouette Cameo, $230). A stencil on tattoo paper results from the positives of the cut film-layer (Figure 2b&c). The tattoo paper is an off-the-shelf commodity material available in any craft store for creating tattoos.

*2.2. Apply conductive material:* After creating the stencil, we layer gold leaf on top to create conductive traces by applying spray adhesive (Speedball Metal Leaf Adhesive, $8) onto tattoo paper and stacking multiple layers of gold leaf (Speedball Gold Leaf, $10/pack). Afterwards, we remove the remaining negatives of the film-layer, which leaves the conductive gold leaf traces as shown in Figure 2d & e.

*2.3. Incorporate electronics:* We now attach surface-mount electronics to the gold leaf traces by cutting a small hole in the tattoo paper, fixating all electronics in place through the holes (Figure 2e), and securing them to the metal leaf traces with a small piece of conductive fabric tape (LessEMF, $15/roll). We add a layer of thin tattoo paper adhesive for adhering to skin. The total cost of creating a 3x4 cm$^2$ NFC tag is less than $2.50.

*3. Application on skin:* Finally, we apply the fabricated components to the skin though water transfer (Figure 2f), similar to applying temporary tattoos.

### DuoSkin Devices

DuoSkin allows users to create three types of user interfaces: 1) *input* on skin through capacitive touch sensing, 2) *output* on skin through thermochromic resistive heating circuitry, and 3) wireless *communication* through NFC.

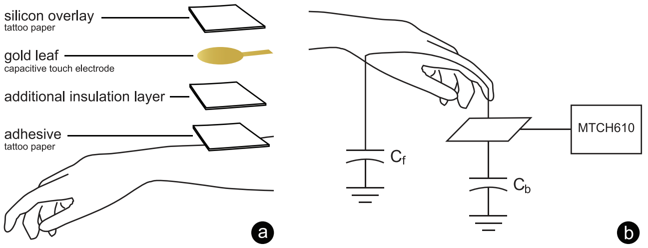

**Figure 3: Layers and schematics of DuoSkin's capacitive touch electrode ($C_b$ = baseline capacitance, $C_f$ = finger capacitance).**

#### *1) Input on skin using capacitive touch sensing*

Using DuoSkin, we created on-skin input elements that resemble traditional user interfaces, such as buttons, sliders, and 2D trackpads. Figure 3 shows a typical capacitive touch electrode composition. An additional insulation layer of silicone (tattoo paper) insulates the electrode from skin. This prevents electric charges on the skin surface from interfering with the capacitive touch signals. The touch electrodes are connected to a capacitive touch controller (MTCH6102), which filters all raw data. From our fabrication experience, a (1.9 cm)$^2$ gold leaf electrode was reliable for a finger to tap on and provided stable sensing performance.

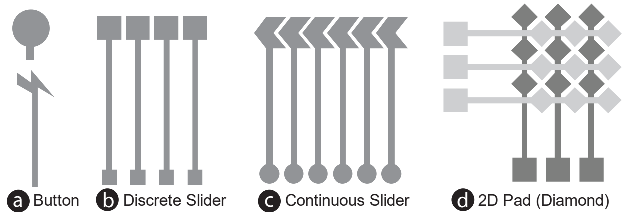
ⓐ Button ⓑ Discrete Slider ⓒ Continuous Slider ⓓ 2D Pad (Diamond)

**Figure 4: The four designs of input elements we explored with DuoSkin. All sense capacitive touch input on the user's skin.**

We created the four types of touch sensors shown in Figure 4: a) discrete buttons, b) discrete sliders, c) continuous sliders, d) 2D touchpads. While the discrete and continuous sliders appear similar, the latter uses interdigitated electrodes [2] for truly continuous sliding; the tapered shapes cause the measured capacitance of a touch for each electrode to be proportional to the contact area. While the discrete slider is easier to fabricate since the electrodes are independent, the continuous slider provides greater granularity for input.

Figure 4b shows our 2D touchpad, which uses row-column scanning in a two-layer construction that isolates horizontal traces from vertical traces. We fabricate the two layers separately and then apply and overlay them onto skin.

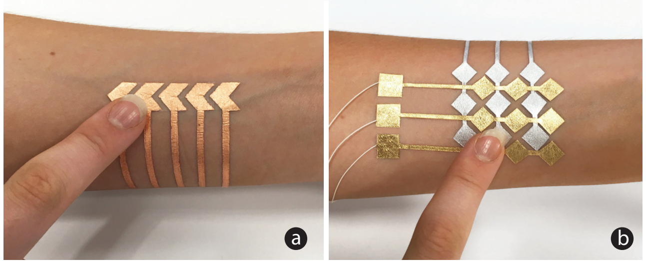

**Figure 5: Input on (a) a continuous slider and (b) 2D touchpad.**

As an example, we built a skin bracelet that controls music on the skin (Figure 1a). Each butterfly is a capacitive touch button and touch events are forwarded to the music app on a smartphone. The prototype bracelet connects to an Arduino under the sleeve, which detects touches and wirelessly communicates with the phone, acting as a Bluetooth remote.

### *2) Output: Skin as a Display using Thermochromics*

DuoSkin brings *soft* displays onto the skin, enabled through the ink-like qualities of thermochromic pigments. These displays have two different states and color change is triggered when heated beyond body temperature. Displays can also be separated into designated parts. To activate color changes on our displays, we fabricate resistive heating elements underneath the thermochromic layer. Figure 6a shows a typical DuoSkin display composition. The thermochromic layer comprises thermochromic pigments (colorchange.com.tw) mixed 1:1 with a silicone base and overlaid on top of the gold leaf. The pigments change color above body temperature. We selected pigments certified for food grade packaging and toys, and encapsulated them in the silicone base for safety.

Unlike LED arrays, DuoSkin displays resemble body art, sacrificing output resolution and dynamic range for appearance. We argue that this better fulfills users' desires, since studies have shown their preference for textile output with naturalistic aesthetics over displays directly on clothing [6].

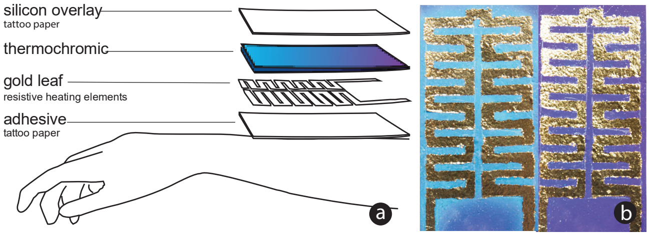

**Figure 6: (a) Layers of DuoSkin displays. Resistive heating activates color changes in the thermochromics. (b) Space-filling heating pattern, left is default color, right is heated up.**

We generate the resistive heating elements with a space-filling meandering pattern [27], which dissipates heat over the entire surface of the display as shown in Figure 6b. We fabricate these traces onto the thermochromic layer with gold leaf. For fabrication traces in general, we found the minimum trace width for reliable fabrication to be 2 mm.

Heating elements of various density and distribution lead to different color dissipation patterns. Thermochromics can be configured to be individually addressable, similar to individually addressable pixels in LED arrays by segregating resistive heating traces to contours, and activating them individually as shown in Figure 7.

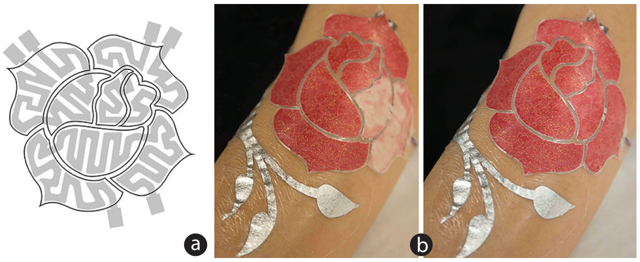

**Figure 7: (a) Display with three cells. (b) A cell (right petal) is activated and turns white; when deactivated, it returns to red.**

As an example, we built 'Couple Harmony', an app for couples to visualize each other's current mood. One person wears a thermochromic fire tattoo (Figure 1b) that shows white when the other person indicates that they are angry by pressing a capacitive touch "mood button" on their forearm.

Figure 7 shows our second example, a rose tattoo with individually addressable pads that reflect temperature changes by switching from red to white. A thermistor circuit in the silver rose vine thereby detects the temperature and the rose petals turn white when the temperature exceeds the thermochromic pigment's color change threshold.

### *3) Wireless communication through on-skin user interfaces*

To exchange data across on-skin interfaces, communication needs to be wireless. DuoSkin devices communicate using NFC, whose tags comprise a chip that connects to a coil. We fabricate this coil using gold leaf, customized to various shapes and sizes (Figure 8). An NXP MF1S5030X DA4 IC attaches to the coil with conductive fabric to form a tag.

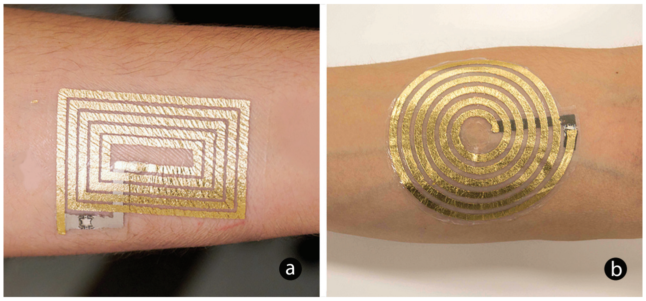

**Figure 8: (a) Square & (b) round NFC antenna using gold leaf.**

The design of such coil antennas faces two challenges to achieve good radiation efficiency. First, the conductivity of the traces limits the radiation efficiency; a lower resistance will increase the efficiency of the tag, for example by applying additional layers of gold leaf. Second, the size of the antenna dictates the relative aperture to harvest power from the reader; a smaller coil, while blending more seamlessly onto one's body, harvests less power, which limits range.

We built an example NFC armlet (Figure 1c). Our phone app allows the wearer to update their "skin status," which others read by touching their phones to the wearer's armlet.

### *Microcontroller platform of DuoSkin devices*

While our NFC tags are passively powered and possess no processor in addition to their IC, all other DuoSkin devices connected to a microcontroller, which processes sensor data, provides power, and connects other devices over Bluetooth. Many microcontrollers are suitable for this purpose; we used an Arduino Mini and a small LiPo battery.

## DUOSKIN AESTHETICS: CUSTOMIZING APPEARANCES

We now outline options for users to aesthetically customize the DuoSkin devices they create using our process.

*Color customization:* Users can fabricate DuoSkin devices using gold, silver, copper, or variegated leaf. Our process extends to any color by layering pigments and inks onto thin tattoo paper before applying the metal leaf. The leaf thereby serves as the conductive material, while the colored inks provide the decorative elements of the device.

*Juxtaposing functional and decorative components:* DuoSkin metal leaf traces serve both, decorative and functional purposes. Figure 9 shows an example of jewelry-like routing made with DuoSkin. Our process also supports creating purely decorative (i.e., non-conductive) elements with pigments and inks, which can be printed with inkjet printers for intricate designs. We layer the decorative elements atop the functional elements or apply them as independent tattoos.

**Figure 9: Aesthetic customization: LED skin necklace. The color is customized with variegated leaf, and the traces are decorative while serving as functional circuitry**

## EVALUATION

We conducted two evaluations: a technical evaluation and a workshop study. In our technical evaluation, we first compared durability, ease of application and removal, aesthetics, and comfort of wearing gold leaf against traditional non-rigid prototyping materials, i.e. copper tape and conductive thread, demonstrating why gold leaf is a preferable material for on-skin prototyping. Second, we assessed the durability of DuoSkin traces of varying widths when exposed to every day wear. Third, we evaluated the performance of DuoSkin devices, including capacitive touch sensor, NFC tag, and display. Fourth, we observed first-time users of DuoSkin fabricating NFC tags to assess the ease of working with gold leaf. In a workshop, we evaluated aesthetic customization where participants created a music controller with DuoSkin.

### 1.1) Copper Tape vs. Conductive Thread vs. Gold Leaf

Copper tape and conductive thread are standard non-rigid prototyping materials for circuitry and serve as our baseline in this evaluation. We used 4.5 mm wide copper tape, 2-ply, 0.2 mm diameter conductive thread attached with eyelash glue, and a 4.5 mm wide gold leaf trace attached with water transfer. The length of each material was 75 mm. We did not take advantage of the tattoo paper adhesive to adhere the copper tape or conductive thread to skin, because it was too weak and did not attach to these materials; instead, we utilized the existing adhesive on the copper tape and eyelash glue (for conductive thread) since they were much stronger adhesives. Table 1 shows the basic properties of these materials, including thicknesses and resistances per unit length. We excluded conductive silver inks from this evaluation, because they are not skin safe to the best of our knowledge.

*Participants:* We recruited ten participants (five female) from a university, ages 19–30 years (M = 24.8 years).

*Procedure:* Participants arrived at our lab to apply all three materials onto their left forearm. Participants applied each material themselves to experience ease of application, after which we verified that it properly adhered. Afterwards, they resumed their regular activities and returned 8 hours later for our evaluation. We tested the continuity of each material with a multimeter and recorded if it still adhered to skin. Participants then removed all materials themselves to assess ease of removal. We concluded with a Likert scale questionnaire on ease of application, comfort, aesthetics, and ease of removal (1=most negative, 5=most positive). Participants also ranked the three materials in order of preference.

| | Copper tape | Conductive thread | Gold Leaf |
|---|---|---|---|
| **Thickness** | 6.3μm | 20μm | 2μm |
| **Resistance** | 0.01 Ω/cm | 0.52 Ω/cm | 0.26 to 0.65 Ω/cm<br>(M = 0.45 Ω/cm) |

**Table 1: Material properties for copper tape (width=4.5mm), conductive thread (2-ply, 316L stainless), and DuoSkin trace.**

*Results:* After eight hours, the conductive thread had detached from two participants and the copper tape had detached from five. The copper tape on the remaining five participants was bent and partially detached. In contrast, no gold leaf trace detached from any participant. One trace lost continuity, because the participant had spent the majority of their day in a machine shop, which also caused the conductive thread and copper tape to fully detach from his skin.

Testing the questionnaire results, a three-way ANOVA found a significant main effect of material on aesthetics ratings ($F_{2,18}$=19.509, $p < .001$). Bonferroni-corrected post-hoc t-tests showed that gold leaf was rated significantly more aesthetically pleasing (M = 4.3) than thread (M = 2.3) and copper tape (M = 2.6), all $p < .05$. While we found no significant differences in comfortability and ease of application, participants suggested that conductive thread and copper tape caused issues; three participants said that conductive thread was painful to remove, two told us that conductive thread collected lint and hair. Copper tape caused a rash on one participant. Finally, nine of the ten participants ranked gold leaf as the most preferable material.

### 1.2) Gold Leaf Durability

In this evaluation, we determined the optimal width of gold leaf for reliable fabrication and wear throughout the day.

*Procedure:* We fabricated ten 75 mm long rectangular traces with widths ranging from 0.5 to 5 mm and adhered them to a 7.5x5 $cm^2$ square of silicone with 2 mm height, which replicated skin for our experiments [12]. We placed the silicone onto a linear actuator setup for repeated stretching by 10%. After each stretch, we checked the electrical continuity with a multimeter and recorded the stretch count after which a trace broke. We repeated this process 5 times.

*Results:* Traces wider than 4.5 mm remained fully functional even after stretching them more than 2000 times. Narrower traces exhibited less reliability.

### 1.3) Performance of DuoSkin-created components

#### *Capacitive Touch Accuracy*

*Participants:* We recruited eight right-handed participants (five female), ages between 20–35 years (M = 26.5).

*Procedure:* We attached a $(1.9\ cm)^2$ electrode on each participant's left wrist, which was connected to a capacitive touch controller (MTCH6102). A laptop processed all data. Since capacitive baselines differ across users, we initially calibrated a detection threshold between the two centroids of capacitive values for no-touch and touch events.

*Task:* Participants repeatedly touched the sensitive area as accurately as possible in one-second intervals, guided by a metronome. Participants received visual feedback on a monitor upon touch. Participants practiced until they were comfortable with the task. We logged all touch events on a computer. Overall, each participant provided 110 touches during a session of approximately 15 minutes.

*Results:* We determined the accuracy of our recognition from the percentage of correctly recognized touch contacts out of all 110. On average, the detection accuracy was 98% (SD=2). Our detection missed a total of 15 taps among five participants, and accidentally double triggered once for a single participant. These results show that DuoSkin's capacitive touch sensors function reliably with little training.

#### *NFC Tag Performance*

We now evaluate the design of an DuoSkin NFC coil. We chose 7x9 $cm^2$ as the coil dimension based on the Mifare Coil Design Guide [21], which suggests a mean coil area larger than 4x7 $cm^2$. We evaluated the reliability of the NFC tag by range through scanning it at various distances with laser-cut spacers using a Microsoft Lumia 735. Overall, the phone reliably scanned the chosen NFC tag up to a distance of 1.4 cm, in range of the typical 2–4 cm [17].

For electrical analysis, we used a Keysight E4990A Impedance Analyzer to measure the coil's resistance (23Ω), inductance (2.3 μH), and quality factor (8). Additionally, the resonant frequency of the coil was beyond the range of the impedance analyzer (20 MHz), which indicates that the coil acts as an inductor at the operating frequency of the IC (13.56 MHz). The datasheet of the NXP MF1S5030XDA4 recommends that coils have a resistance of 6.07Ω, an inductance of 3.6 μH, and a quality factor of 30. While our current coil does not meet these values, changing the tag shape or adding layers of gold leaf would improve them.

#### *Thermochromic Resistive Heating Circuit Response Time*

To evaluate the latency of a DuoSkin display, we fabricated a 5x3.5 $cm^2$ rectangular thermochromic tattoo with 30μ thickness. The resistive heating trace was 2.5 mm thick at 11Ω resistance. We measured 10 times and averaged results.

After applying 5V [illegible]

median of 2. Gold leaf, though delicate, was rated with a median of 2 on "ease to work with". Participants rated the process as fun and enjoyable (median 4) and reported no discomfort when applying or wearing the tattoos.

### *2. Are users able to create a personalized DuoSkin device?*

The goal of this study was to gauge the user friendliness of DuoSkin to create personalized designs.

*Participants:* We recruited five participants (four female) from the accessibility study, who therefore had experienced the fabrication process. Participants received a $20 gratuity.

*Procedure:* Participants first filled out a survey on their use of body art (makeup, piercings, tattoos, etc.) and then learned about their task: create a fully functional skin music controller using DuoSkin. Although defined, the task left room for functional customization (Figure 4). Participants then sketched and created paper stencils and placed the stencils on their bodies to decide the optimal size and location. We thereby provided feedback on circuitry routing. Participants then digitized their sketches using a vector app of their choice and fabricated the design with an electronic cutter and gold leaf. Afterwards, participants applied their creations onto their skin. We assisted participants in connecting their tattoos to the capacitive touch controller to complete their functional DuoSkin device. Participants then interacted with the phone we provided by using their skin music controller. Finally, we elicited feedback through a 15-minute interview. Each participant completed the study in 2.5 hours.

*Results:* All created music controllers fully worked and all participants chose to design for their forearm, stating it was a most suitable location for music control (echoing [32]). We observed *functional* customization through the use of buttons (Figure 10c&d), discrete sliders (Figure 10a), continuous sliders (Figure 10b), and *aesthetic* customization though various colored metal leafs, and the segregation of decorative versus functional elements (Figure 10c&d).

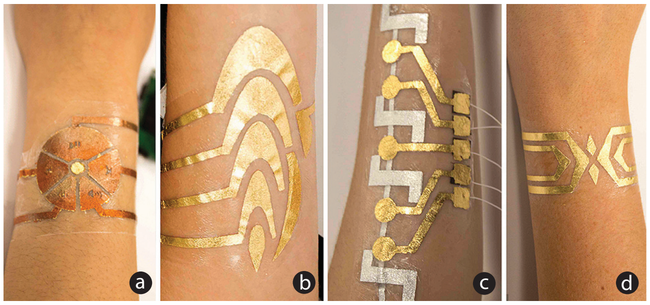

**Figure 10: Four music controllers that participants designed.**

Participants expressed their personal style and identity though the devices they designed. P3 designed geometric tribal patterns (Figure 10d), because *"I dress boho [bohemian] style, but I love the symmetry and logic in math."*, while P2 designed Figure 10b in *"an amour shape"* to reflect a *"unisex, tomboyish"* dress style. From the survey, most (4) participants decorated their bodies on a daily basis (makeup, etc.) These participants mentioned a resemblance of DuoSkin to body decoration processes, noting the ability to customize and apply the device *themselves* made it intimate and something they would like to wear. The accessibility of the process was also noted, P5 said *"it's good I can design my own thing so I know how it works, it's not a huge mystery to me [...] it satisfies my curiosity."* We did, however, see a need for further automation to decrease manual effort and increase precision to support more intricate DuoSkin designs.

## CONCLUSION

We presented DuoSkin, a rapid fabrication process for creating on-skin user interfaces. The key element of DuoSkin is gold leaf, a skin-friendly and conductive material that we appropriate for three purposes in DuoSkin devices: sensing input, powering displays for output, and near-field communication, all of which we demonstrated in a series of DuoSkin devices that we fabricated using gold leaf.

Our evaluation showed that participants preferred gold leaf for on-skin electronics compared to copper tape and thread. Gold leaf is a skin safe and aesthetic material that attracted users and at the same time exhibited robust durability, making DuoSkin devices viable for interactive purposes during everyday use over a longer period of time.

Following from our observations, we conclude that on-skin user interfaces have the potential to evolve beyond their so-far primary realm: the medical field—a domain that can afford the expensive and elaborate machinery process necessary to build epidermal electronics today. To bring more expressive forms of skin art to such on-skin devices, wearers *themselves* must gain aesthetic control over the fabrication process to easily implement their desired functionality.

DuoSkin work fuses the traditional practices of skin art with those found in digital fabrication to create a *hybrid body decoration* process, allowing users *themselves* to sketch, fabricate, and apply functional devices with *their* personally-desired purpose onto their own body. With the development in materials and automatization, we expect to see such devices and user interfaces to reach even broader adoption.

Finally, we believe that skin serves as the bridge between the physical and digital realms, enabling users to leverage the personal aesthetic principle that is often missing in today's wearable tech. It is our vision that future on-skin electronics will no longer be black-boxed and mystified; but they will converge towards the user friendliness, extensibility, and aesthetics of body decorations, forming a *DuoSkin* integrated to an extent it has seemingly *disappeared*.

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