Weaving a Second Skin: Exploring Opportunities for Crafting On-Skin Interfaces Through Weaving

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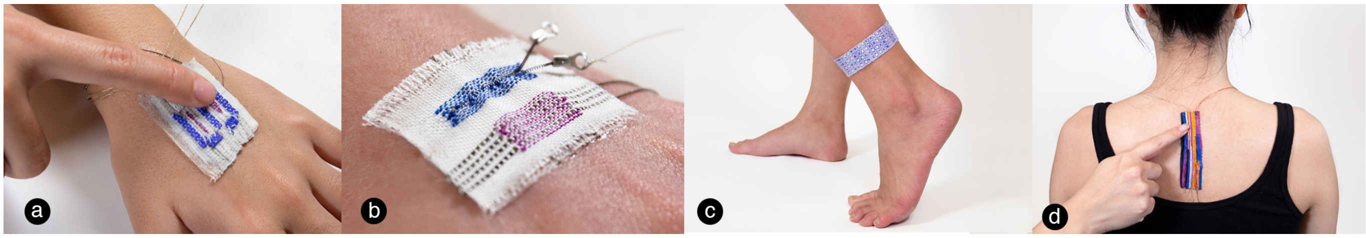

Figure 1. We explore adapting the woven craft to expand the expressiveness of on-skin interfaces. Adopting a research-through-design approach, we contribute a design space and a series of case studies that extend the *functional* dimensions of on-skin interfaces through weaving’s capability for 3-dimensional circuitry, multi-functional designs (a)(b), and ability to integrate novel materials. We also extend the *asethetic* dimensions of on-skin interfaces through the variety of patterns (c), textures and materiality afforded by weaving. We conducted a workshop study in which textile practitioners crafted their own woven on-skin interfaces (d), as well as a user study confirming wearability.

ABSTRACT

Weaving as a craft possesses the structural, textural, aesthetic, and cultural expressiveness for creating a diversity of soft, wearable forms that are capable of technological integration. In this paper, we extend the woven practice for crafting on-skin interfaces, exploring the potential to "weave a second skin." Weaving incorporates circuitry in the textile structure, which, when extended to on-skin interface fabrication, allows for electrical connections between layers while maintaining a slim form. Weaving also supports multi-materials integration in the structure itself, offering richer materiality for on-skin devices. We present the results of extensive design experiments that form a design space for adapting weaving for on-skin interface fabrication. We introduce a fabrication approach leveraging the skin-friendly material of PVA, which enables on-skin adherence, and a series of case studies illustrating the functional and design potential of the approach. To understand the feasibility of on-skin wear, we conducted a user study on device wearability. To understand the expressiveness of the design space, we conducted a workshop study in which textiles practitioners created woven on-skin interfaces. We draw insights from this to understand the potential of adapting weaving for crafting on-skin interfaces.

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CCS Concepts
•Human-centered computing → Human computer interaction (HCI);

INTRODUCTION

Weaving is one of the oldest forms of making, a practice that, from its conception, merges technique, tool development, and artistic expression [26]. Weaving possesses the structural, textural, aesthetic, and cultural expressiveness for creating a diversity of soft, wearable forms that are capable of technological integration. Research in woven smart textiles [46, 12, 6, 16, 15] builds on the structural capabilities of weaving to incorporate interaction, bringing forth *soft* wearable computers. Indeed, in recent years, wearable computers have drastically progressed beyond traditional forms, with extremely thin interfaces that can sit directly on the skin surface. These *on-skin interfaces* [56, 31, 40, 41, 55] enabled the skin as a new surface for *designing interactions*.

Current on-skin interfaces are usually created through digital fabrication approaches spanning laser-cutting [56], lamination [41], and inkjet printing [44], or through simple craft techniques of screen-printing [40, 57] and stenciling [31]. While function affording, their expressive and material qualities are largely limited to color and graphic customization. Weaving expands the design potential for on-skin interfaces through its two- and three-dimensional [1, 24] structural capabilities for easy integration of more complex circuit typology, its broad inclusiveness of materials [3], and its diverse textures [11].

In this work, we explore adapting the woven craft to expand the expressiveness of on-skin interfaces. We adopt a research through design [65] approach to explore the emergent materialities of woven on-skin design. Specifically, we present a series of case studies that also serve as an *annotated portfolio* [19] of our design investigations, which, underscored by Gaver, can be a means for theory production in research through design.

By bridging craft and emergent technology on the skin surface, this work supports a broader range of *functional* and *aesthetic* customization opportunities for on-skin interfaces. Based on a holistic five-dimensional view outlining opportunities for adapting the woven craft for on-skin interfaces, we present the following main contributions:

- We present a fabrication method called *WovenSkin*, which adapts weaving for fabricating on-skin interfaces. The method supports a broad range of material and structural richness for on-skin design.
- We identify polyvinyl alcohol (PVA) film as the main material for enabling a skin conformable form factor for the woven fabrication approach.
- The weaving-derived approach can support more complex circuit topologies under-explored by previous on-skin fabrication techniques. This includes *electrical connections (e.g., vias)* between layers and *multi-component* interfaces, and easy integration of *novel functional materials.*
- The platform offers rich aesthetic customization opportunities under-explored by current on-skin interfaces, spanning textures, patterns, unusual materials to blank space.
- We conduct a user study to uncover wearability factors and a workshop study where textile artists created their own WovenSkin devices to understand the expressiveness of the fabrication approach.

BACKGROUND AND RELATED WORK

Fabrication Methods of On-Skin Interfaces

On-skin devices render the user's body as an always-available surface for sensing and interaction. Early works stemmed from the material sciences in which *epidermal electronics* [34] with skin-like properties monitor a range of physiological signals. However, they often entail high manufacturing costs. The HCI and wearable communities have developed inexpensive fabrication approaches, developing interfaces for sensing touch input [56, 31, 44, 40, 57], displaying output [57, 55, 31], providing haptic feedback [60, 23], and texture-change output [29]. Other works have sought to create fully integrated systems that sit on the skin [30, 41].

The fabrication processes of these on-skin interfaces in HCI often involve the adoption of existing digital fabrication processes to take in thin materials. Methods include laser patterning [56, 57, 60], inkjet printing [40, 44], lamination [41], embedding [23], and molding and casting [29]. Other approaches adopt simple craft techniques including screen printing [40, 57, 44], stenciling [31], and sew-and-transfer [30]. As an emerging fabrication realm, the interfaces focus on affording the functions mentioned above. While some bring in aesthetic expressiveness into the discussion [56, 40, 31], they are often limited to choices in color and graphic customization.

Inspired by the richness of weaving [3, 11], we adapt this craft for the creation of more expressive on-skin interfaces. Specifically, weaving's wealth of options and material versatility expands the possibilities for unique aesthetic and textural qualities. Paired with the capability to create multi-layered structures, this approach enables complex and varied circuitry.

Fabrication Methods of Smart Textiles

The HCI and wearable communities have investigated the integration of input sensing [48, 49, 38, 64, 33, 45, 52, 9] and output actuation [59, 37, 21] into fabric form factors. Processes for smart textiles fabrication include *surface level integration* of interactive elements through embroidery [46, 64, 22], stitching [50, 7], machine sewing [43], felting [4, 25], silkscreening, [35] and inkjet printing [62]. While ideal for rapidly augmenting a textile, these methods change the textile solely in an extrinsic manner. Our research focuses on the fabrication of a textile structure itself so we can fine-tune its properties for on-skin application.

Weaving [6, 16, 51, 12, 18] and knitting [58, 47, 21, 2] afford *structural level integration* of interactive elements into textiles. Weaving involves intersecting two sets of yarns in perpendicular directions held under fixed tension on a loom. This structure allows for fine control of tension to incorporate delicate electronic components and thin materials, which are more likely to break under the higher tensions of knitting's continuous loop-to-loop structure. Weaving can also create stacked layers, ideal for complex circuits. The most common technique for structurally integrated smart textiles, weaving has been used to create integrated electrical circuits [6, 16, 15], touch surfaces [51, 49, 66], shape-changing interfaces [53], to color-changing [13, 12] and optical fiber displays [5]. Weaving's ideal structural qualities and its lack of restrictions for the materials that can be used make it a uniquely favorable method for the exploration and optimization of materials in the first on-skin textile interface, WovenSkin.

Weaving Process Overview

Woven fabric is formed by interlacing warp (vertical) yarns and weft (horizontal) yarns, which run in perpendicular directions. The warp yarns are held under tension on a loom, while weft yarns pass between warp yarns that are raised in specific sequences to create structures and patterns. While warp yarns must be able to withstand sufficient tension, there are no requirements for materials used in the weft. A method called *supplementary warp* can also integrate a wide range of materials in the warp. For a comprehensive description of our weaving process, please refer to our supplementary document.

DESIGN SPACE FOR WOVEN ON-SKIN INTERFACES

In this section, we identify opportunities for adapting the unique characteristics of weaving for on-skin interface fabrication. We synthesize this 5-dimensional design space (Figure 2) through the research team's one-year extensive weaving experiences, bi-weekly consultations with professional weaving experts, and literature review of woven textiles [3, 10, 46, 12, 13], as well as on-skin interfaces [31, 57, 57].

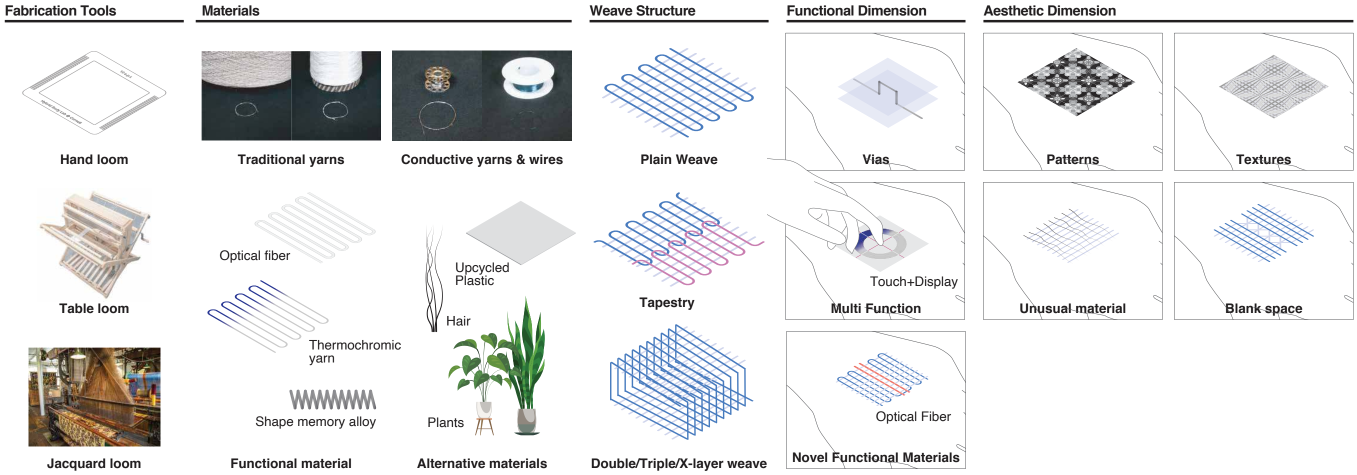

Figure 2. Design space for woven on-skin interfaces.

Method	Materials	Adhesion (Hours)	Observations
Layer on top of device	PVA sheet + Adhesive	16	Comfortable, likely to partially detach
Layer on top of device	Silicone sheet + Adhesive	12	Comfortable, likely to partially detach, thicker
Strips woven in device	PVA strips (0.5 cm wide)	13	Slower to make, thicker and more rigid
Layer between device and skin	PVA sheet + adhesive	22+	Firm adhesion even at the edges, clean appearance

Table 1. WovenSkin on-skin fabrication approach comparison.

Fabrication Tools. We can weave on-skin interfaces with different loom types, which enable a wide range of fabrication experiences as well as end-user communities. Inexpensive handlooms can be used by maker communities for rapid prototyping, while floor looms, which can afford more complex structures and patterns, can be adopted by those with textile backgrounds. Jacquard looms can enable industrial-scale manufacturing of woven on-skin interfaces for scalability.

Materials. For an on-skin form factor, interwoven materials should be as thin as possible while being durable for on-body wear. The warp yarns must also withstand the tension applied during weaving. These materials include traditional (non-conductive) textile materials, electronic textile conductive materials, non-conductive functional materials (e.g., optical fibers) and alternative materials (e.g., hair, grass) that are thin, conformable, and bio-compatible. This extends the materiality of current on-skin interfaces beyond a focus on *inks* and *silicone-based materials* to unexplored textures.

Structure. All weaving structures can translate into the fabrication of woven on-skin interfaces. The most basic structure is plain weave, in which each weft yarn goes over one warp yarn and under the next. In tapestry weaving, weft yarns can be incorporated in specific locations through hand manipulation to create free-form designs on textiles. Double weave creates two layers of plain weave simultaneously, generating a two-layer structure. The process for double weaving can be extended to create triple layers and beyond.

Functional Dimension. Woven on-skin interfaces afford versatile 2- and 3-dimensional integration of circuitry into the textile structure itself. The fabrication approach supports electrical *vertical interconnect access structure* (vias) while maintaining a slim form. While vias present a challenge for printed and laminated approaches due to alignment and material constraints, multi-layer weave structures can easily incorporate conductive yarns that traverse two layers. Weaving can readily integrate *multiple functions* in a weave structure, for instance, incorporating both input (e.g., capacitive touch or pressure sensing) and output elements (e.g., thermochromic display or haptic feedback) in one interface. *Novel functional materials* can also be interwoven in the design for advanced functions.

Aesthetic Design Dimension. Woven on-skin interfaces can support unique aesthetic properties not afforded by printed or laminated approaches. This includes providing *unusual textures* through rich materiality of integrated elements. Woven on-skin interfaces also introduces the richness of *pattern design* of the woven art form [10] for on-skin design. *Unusual materials*, such as plastic bags or leaves, can be woven into a textile structure for expressive effect. Weaving for on-skin interfaces involves unique considerations for the textile designs that are appropriate for and complement the skin, such as the technique to form *blankspace* in the design which reveals the underlying skin and skin landmarks [57] for aesthetic design.

WOVENSKIN FABRICATION APPROACH

PVA as Key Material for Woven On-Skin Interfaces

For an on-skin form, it is necessary to find a material that can adhere thin woven materials to the skin while being conformable. For our systematic exploration, we investigated materials successfully used in previous on-skin interface research [34, 31, 40, 44]: temporary tattoo sheets (Silhouette Temporary Tattoo Paper), which include a silicone layer and adhesive layer, and polyvinyl alcohol (PVA) film (Sulky Solvy Water Soluble Stabilizer), a thin, biocompatible, and water-soluble sheet which becomes adhesive when dissolved. We experimented with various methods for using these materials, including adding a layer on top of the device, weaving strips into the device, and adding a layer between the device and skin. Our comparison encompassed a total of 13 method and material combinations, and we also varied parameters such as PVA brand and thickness of woven strips. We eliminated approaches that did not adhere for 8 hours, were overly complicated to fabricate, or disrupted the device appearance. Four viable approaches are shown in Table 1. The approach that was superior in terms of adhesion time, comfort, and aesthetics, was adding a layer of PVA and adhesive between the device and the skin, which we adopt for fabrication.

Other Materials: Yarns and Conductive Traces

Thin, durable yarn is desirable for the base structure of a woven on-skin interface. We compared various yarns, spun from plant, animal, and synthetic fibers, and identified a silk yarn (60/2, HASEGAWA Co., Ltd, $25/spool, 100g) for its strength, lustrous appearance, and smooth and soft texture. WovenSkin’s functionality is enabled through extremely thin, yet robust and durable insulated copper wires (38 AWG, Remington Industries Magnet wire, $7/spool, 600 meters) and stainless steel conductive threads (2 ply, Adafruit Stainless Thin Conductive Thread, $7/spool, 23 meters, 1.3 Ω/in).

WovenSkin: The 3-Steps of our Fabrication Process

Step 1: Preparation

To *weave* an on-skin interface, the initial step involves a preparation of sketching and planning, hybridized from weaving [10] and on-skin interface [31, 30] fabrication practices. Weave design software tools [18, 24] can support this endeavor.

- *Sketching Weave Size Based on Body Placement.* We start with a paper prototyping process, typical in body art, where paper stencils are placed on the body to articulate the location and size of the user interface.
- *Drafting the Woven Interface.* Based on the interactive function of the device, we decide on the weave structure (e.g., plain weave, tapestry weave, or double weave.) We calculate and draft the length, width, and ends per inch (EPI) of the WovenSkin device. We describe the drafting process in detail in the supplementary document.
- *Preparing Materials & Setting up Loom.* Based on the draft, we prepare corresponding conductive and non-conductive materials for weaving. The loom is then set up accordingly with the materials. We use the Baby Wolf Loom with 8-shafts and 10 treadles (Schacht, $2,535) to allow for complex designs and structures not afforded by hand looms. We describe loom setup details in the supplementary document.

Step 2: Fabrication

With the loom setup according to the draft, we can now weave the device on the loom. The device is fabricated by repeatedly passing the weft yarn under raised warp yarns. On the floor loom, this is accomplished by manually passing a boat-like shuttle containing the weft yarn from one hand to the other as the feet press the treadles to control the lifting of warp threads. Each woven structure and pattern has a unique sequence in which the warp yarns are raised. This process is further detailed in the supplementary document.

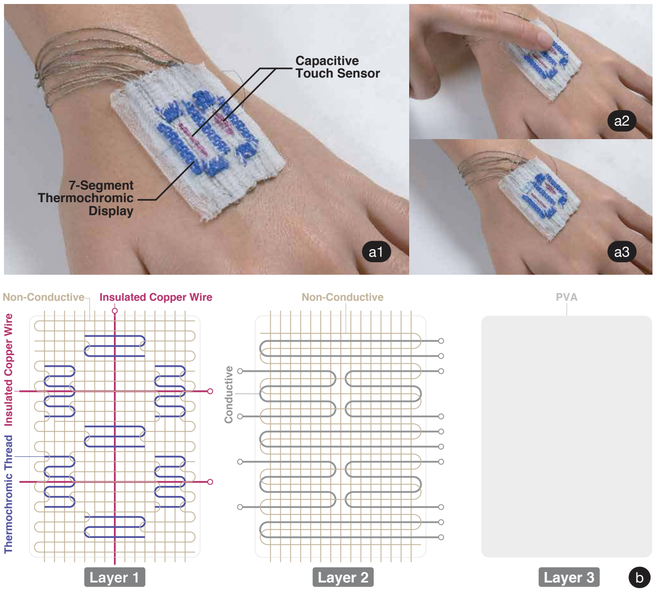

Figure 3. Multi-functional interface with output display through thermochromic yarns and input through capacitive touch sensing. (a1) 7-segment display displaying number "8," (a2) pressing capacitive touch "+" icon, (a3) display increases to number "9." (b) weave structure of on-skin interface.

Step 3: Apply on Skin

To prepare the PVA layer, cut a piece of PVA film and temporary tattoo adhesive layer to the size of the WovenSkin device, and transfer the adhesive layer to the PVA film using a filling spatula. Remove the adhesive layer backing to stick the PVA layer to the under side of the WovenSkin device. To apply on the skin, place the WovenSkin device on the desired skin location and dissolve the PVA with water using a spray bottle. The PVA film becomes a liquid gel form, adhering the woven device to skin.

CASE STUDIES: FUNCTIONAL DIMENSION

We present a total of 8 case studies generated through our research through design [19, 65] methodology, which also form an *annotated portfolio* [19] to explore design opportunities for woven on-skin interfaces. In this section, we present 4 case studies on the functional dimensions of the design space. In the next section, we present 4 more studies, shifting focus to aesthetics. Here for the functional dimension, we first examine 3 case studies on complex circuit typologies enabled through the 2- and 3-dimensionality of weaving, and 1 case study investigating novel functional materials.

Multi-functional On-Skin Interface. Building on the capability of weaving to incorporate multiple functions in a structure, we present a case study to integrate input and output functions in an on-skin interface. Here we present an example which combines touch input and visual output to compose a

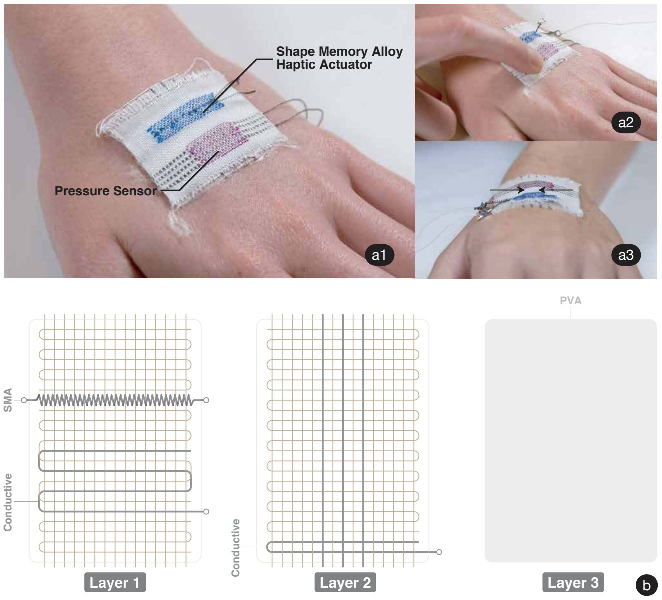

Figure 4. (a1) Multi-functional interface with haptic feedback through SMA and input through pressure sensing. (a2) When a firm press is detected on the pressure sensor (a2), a timer is set, and the (a3) SMA actuator will contract to provide haptic feedback when time is up. (b) weave structure of on-skin interface.

touch display. To illustrate this, we implemented a capacitive touch-enabled display (Figure 3). It consists of a 7-segment thermochromic display (shown in blue) [32, 55], whose value can be increased or decreased by two capacitive touch points (the purple "+" and "-" icons inside the 7-segment display).

Structure wise, this is implemented through a double weave, with the thermochromic yarns on layer 1 for visibility, and the conductive yarns for resistive heating in layer 2 to be hidden from view. The two capacitive touch electrodes are implemented on the first layer with insulated copper wires forming two distinct intersection points between warp and weft. The design of the 7-segment display is woven with tapestry weave to integrate freeform designs.

Multi-functional On-Skin Interface II. In this case study we present another example of two functions integrated in a textile. We were specifically interested in an output not limited to displays but with an ability to provide haptic sensations on the skin surface. This example combines input through pressure sensing and output through shape memory alloy (SMA) haptic feedback [23]. We imagine a discreet on-skin alarm system (Figure 4). Due to the pressure sensing characteristics, this alarm system registers light touch and firm touch, providing two input modes, potentially with the light touch serving as a snooze button for the haptic feedback alarm.

Our pressure sensor is based on piezoresistive sensing, which involves two electrodes separated by a piezoresistor, whose resistance varies linearly with applied force. For the WovenSkin pressure sensor (Figure 4), we apply double weave to create two layers with conductive yarns, and completely enclose a piezoresistive layer of velostat (Pressure-Sensitive Conductive Sheet (Velostat/Linqstat)) in between [42]. The SMA actuator is woven on the top layer as an supplementary weft in the plain weave. We tested with several SMA wires, with .15 mm wire diameter SMA springs (Toki BioMetalHelix BMX150) providing the best effect in our woven structure.

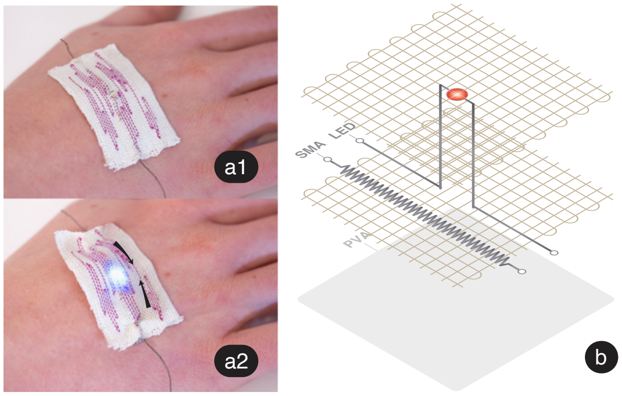

Figure 5. (a1) 3-dimensional electrical connection between layers established by inserting the electrical traces from layer 1 into layer 2. (a2) SMA haptic feedback and LED output activated using a single voltage source. (b) weave structure of on-skin interface

3-Dimensional Electrical Connection Between Layers. Here we present an example which can afford electrical connection between layers (vias). We demonstrate a two-tier output through a single voltage source, which, as an example application, can provide two types of notifications: the first tier (e.g. SMA haptic feedback only) for non-urgent notifications and the 2nd tier (e.g. SMA haptic feedback and LED output) for urgent notifications. We use vias in a double weave to electrically connect an LED on the top layer and an SMA spring on the bottom layer in parallel (Figure 5). Copper wires are soldered to the two ends of the LED and woven partially into the top layer, then inserted and woven into the bottom layer in the same weft as the SMA spring. The stable interlocked structure of weaving secures the connection points between the LED and SMA spring. Using vias, both the LED and the SMA can be controlled with a single voltage source. The SMA is activated at a voltage of 2.75 V and the LED is activated at 4.0 V.

Novel Functional Materials. In this case study we explore the feasibilty to easily weave in novel functional materials in an on-skin form factor. We integrate a stretchable optical

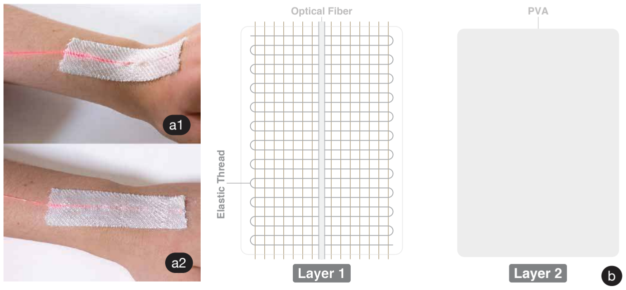

Figure 6. (a1) Integrating novel functional material of stretchable optical fibers, (a2) changes in light intensity when joint bends and straightens. (b) Weave structure of on-skin interface.

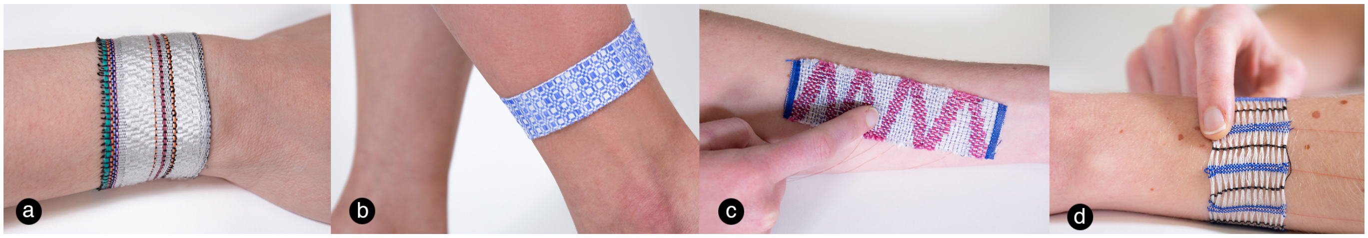

Figure 7. Aesthetic Dimension Case Studies. Thermochromic displays with explorations in (a) texture and (b) patterns. Capacitive touch input explorations with (c) unusual materials (up-cycled plastic bags) and (d) open space design which shows underlying skinmarks.

fiber [61] with extensible elastane filament to create a stretch sensor. When placed along a joint that can bend and straighten, the optical fiber extends or contracts based on the wearer's movements, changing the intensity of the light that travels through the optical fiber. This example is woven with a 2x2 balanced twill with a supplemental 0.5mm diameter optical fiber weft. The twill weave has fewer intersections than plain weave, which allows the elastane and optical fiber wefts to stretch while maintaining structural stability.

CASE STUDIES: AESTHETICS DIMENSIONS

Texture. The woven fabrication process can incorporate different materials in different weave structures, resulting in a variety of possible textures. Our sample shows an improvised twill pattern alternated with a plain weave (Figure 7a). The twill is woven with white silk, where the repetition creates a textured surface, and is interspersed with plain weave that uses thermochromic pigmented cotton (orange to white transition at 37°C), resulting in a subtly textured conformable skin.

Patterns. Weaving allows for the fabrication of a myriad of patterns in a vast design space. Using a silk yarn with thermochromic pigment (white to blue transition at 37°C) applied to it, we show a monk's belt pattern [17] as an example, with the pattern appearing in blue when heat is applied (Figure 7b). Monk's belt has a modern aesthetic but dates to pre-Christianity, and is typically used as a border treatment. It is a blocked pattern that can create complex orthogonal geometries but only requires 4 shafts to weave.

Unusual Materials. Many unconventional materials can be incorporated into a woven structure, allowing for WovenSkin devices to have a sustainable capacity by designing with organic or upcycled materials. Plastic bags were cut into thin strips and used in the weft of a woven structure to give a second life to a single-use plastic item. Any colours or designs on the upcycled plastic can be strategically incorporated into the design of a new WovenSkin device. We present a 2x2 balanced twill alternating the weft between 0.5cm thick strips of plastic bag and blue silk with supplemental insulated copper wire, shown in Figure 7c. The copper wire was woven continuously to create a capacitive touch trackpad for the forearm.

Blankspace. Blankspace is formed with a hand manipulation technique to gather warp yarns and expose gaps in the woven structure, revealing the skin underneath. This provides the wearer an opportunity to feature their birthmarks, scars, freckles or vitiligo, incorporating their own body into the design process. In our example, an adapted version of brooks bouquet lace, four warp yarns are gathered at a time by a clove-hitch knot [17] across a row. Then six rows of plain weave and a supplemental copper wire are woven to space out the gathered warp yarns before knotting another row of clove-hitch knots. The conductive wire adds a slider capability to the WovenSkin device, which can be worn around the wrist.

Microcontroller platform of WovenSkin devices. All WovenSkin devices presented in the case studies are connected to a micro-controller circuitry that processes data, provides power, and connects other devices over Bluetooth. Many micro-controllers are suitable for this purpose; we used an Arduino Mini and a small LiPo Battery. A capacitive touch controller (MTCH6120) supports capacitive touch sensing.

EVALUATION

Exploratory Workshop Study

We conducted a workshop study with three textile practitioners to (1) gauge the feasibility to create personalized designs with the fabrication process, and (2) probe textile expert perceptions towards "weaving" an alternative form factor of on-skin interfaces. Although we deployed this workshop for textile artists, who created original designs to display the aesthetic potential of the WovenSkin devices, this fabrication approach, as well as the insights gathered from the study, can be generalized for everyday designers and makers.

The participants first came in the lab for a 1-hour briefing, where we introduced them to the fabrication process, demonstrated the interactive devices, and introduced the functional materials and structures used to create each project. Participants were then given one day to individually plan their project, where they could ask us questions regarding interactive functional components. They were then asked to come into the lab for a 4-hour time block to weave their project. We conducted a 45 min post-study semi-structured interview to elicit participant reactions. Our participants (anonymized by pseudonyms) include: Skylar, a textiles artist with 15 years of weaving experience who runs her own weaving studio; Quinn, a textiles studio assistant with 3 years of weaving experience; and Avery, a university textile art instructor with 14 years of professional experience. We present each of the participant's projects, the techniques they used, and their workflow. This is followed by results from semi-structured interviews. We provided a $50USD gift card as gratuity.

Skylar's WovenSkin: Touch Sensor for the Heart. Skylar expressed an interest in bridging emotive and spirituality qualities into her woven projects. For the workshop, she came up

Figure 8. Skylar's WovenSkin device: A capacitive touch slider for "touching one's own heart" woven with overshot patterns.

with an idea to create a touch sensor that could be worn near the chest such that she could "touch her own heart." She was especially interested in an *overshot pattern*, which involves weaving 2 wefts at once (1 ground cloth and 1 pattern "overshot" over it), since she found it be especially expressive. With the overshot pattern, Skylar came up with the idea of weaving conductive wires in the "overshot" layer which would enable it to both be an aesthetic pattern as well as functional touch element (Figure 8). In the weaving process, Skylar mentioned initially feeling challenged by weaving with such thin yarns. It was also her first time working extensively with thin copper wire. She mentioned the importance of "getting to know" the copper wires by being able to manipulate them by hand, from which she later developed a method to make straight edges with the wires so that they could successfully move between the weft.

Quinn's WovenSkin: Drawing Interface for the Back. Quinn described their textile art practice as using yarns to draw. To this end, they enjoyed the free-form nature of tapestry weaving. For the workshop, Quinn built on the childhood game of drawing on someone's back and having them guess what was written. They wanted to develop a touch interface which could be worn on someone's back. When someone touches the interface, it could display different colors while projecting the touch input on a phone or laptop screen so the wearer could see it (Figure 9). Driven by their practice, Quinn applied tapestry weaving to create this design. They created a free-form pattern which integrated many sections of insulated conductive copper wires of various colors. Thermochromic yarns were also woven into their design. Quinn mentioned being unused to the scale and granularity of the project at first and how they underestimated the time it would take to fabricate the device. They mentioned that gaining tactile experience of working with the thin form was critical to speeding up their work process.

Avery's WovenSkin: On-Skin Safety Pendent. Avery was interested in the sculptural qualities of textiles and creating different textures. For the workshop, Avery drew on the metaphor of creating a "safety blanket" for the skin with touch capabilities that a wearer could rub when they felt unsafe or distressed. She was interested in a tactile quality that would be soothing and unique. Avery mentions that she likes to take an improvised approach to her textile practice where she experiments with and learns about the materials. To this end, she attempted various textures with different structural qualities, starting with improvised twill and satin weave, which created reliefs for the touch sensors. However, she found the designs to not be as slim as she liked. This led her to do an open space design with exposed warps, where she wove in stand-alone shapes with tapestry weave, revealing the skin underneath . This achieved the relief structures that she was looking for, while realizing a slim form. She decided to leave fringes at the end of her WovenSkin device since it would be soothing to touch and suited her "blanket" metaphor (Figure 10).

Figure 9. Quinn's WovenSkin device: A drawing interface for social interaction. When someone touches the interface, it changes color while projecting the touch input on a phone or laptop screen so the wearer could see it.

Figure 10. Avery's WovenSkin device: An on-skin safety button with unique textures and fringes that one can touch when feeling unsafe or distressed.

Observations from Post-Study Interview. We observed several emerging themes in our post-study interviews:

Weaving for Thin Form versus Yardage. Participants found the fabrication process similar to their existing textile practice, yet also different in aspects mostly due to the smaller scale and thin form. Skylar mentioned that she usually "weaves in yardages," and this was her first experience thinking about achieving thin forms as an end goal. Quinn compared the process to weaving "a tiny swatch." They mentioned that while swatch weaving is typically a "quick and dirty" early-stage process for testing weave designs, their swatched-sized WovenSkin project required intense focus to achieve the intricate tapestry design. Avery started her experimentation with thicker yarns and then progressed towards thinner yarns. She described it as weaving an "extreme textile." We observed participants feeling both challenged and intrigued by the design constraint of achieving a thin form for on-skin wear.

Bringing Textural and Tactile Qualities onto Skin. Participants were excited about extending textile qualities, especially textures, as a new dimension for on-skin design. Avery mentioned that for a textile designer, the "feel" of textile is central to the end product, and achieving a certain textural quality for the skin drove her design process. She described a wide variety of materials that could be woven in to add texture to the skin. Quinn described this as "body art that feels like textiles," and how they would consider getting a "permanent textile tattoo" due to its textural qualities. Skylar talked at length about the rich cultural histories of textile art, its means for expressing one's status and identity, and how body art also serves these functions. She described how merging the two can blend the intimacy of body art with textile and material qualities. Interestingly, all participants choose to incorporate capacitive touch sensing into their designs. Avery explained how touch input relates to the tactile qualities of textiles, which are central to her weaving process. Quinn and Skylar both reflected on the intimacy of textiles to the body, and the increased "closeness" when placed directly on the skin and coupled with touch interactions.

New, Hybrid Form Factor. Participants compared and contrasted the woven on-skin interfaces with exiting form factors. Avery described it as woven bandages that are aesthetically designed or body ornamentation that "has functionality integrated within." Skylar compared it to very thin textiles such as hosiery, but attached to the skin. Quinn described the form as a body modification by integrating textiles into, rather than onto, the body. Participant reactions suggest WovenSkin devices straddle body art and textiles, providing a new hybrid form factor, and an emerging hybrid aesthetic [54, 28] for on-body design.

Wearability Study

In this study, we aim to uncover wearability factors towards wearing a woven skin patch. We focus on understanding initial user reactions towards wearing the woven on-skin traces developed from our fabrication approach, not including rigid microcontroller units, which are a limitation of all current on-skin interfaces. Building on research guidelines for evaluating the wearability of wearable and on-skin interfaces [39, 36, 63, 20, 30], we synthesize the following aspects for evaluation:

- Mechanical Durability: How well does the interface remain *mechanically adhered* to the skin under everyday wear?
- Electrical Functionality: How well can the interface maintain *electrical continuity* when worn on the skin?

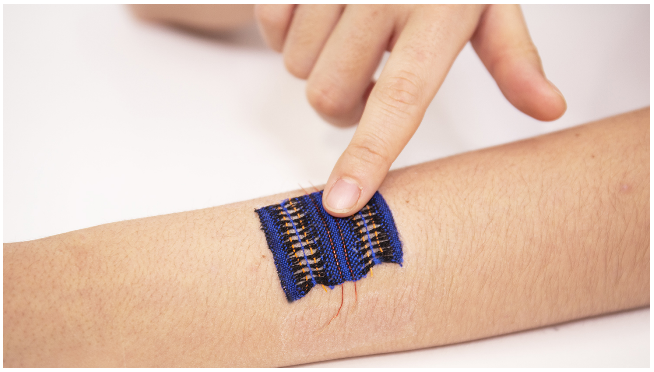

Figure 11. Wearability study patch: on skin testing of durability, comfort, and functionality of test swatch using OpenSpace design.

- Comfort: How does wearing the device affect the wearer or how the wearer may feel?
- Perception: Socially, how does the wearer feel about being seen by others when wearing the device? Personally, is the device something the wearer would find desirable to wear?

This study design focuses on ecological validity by testing them in the context of everyday wear, in contrast to controlled bench tests used in previous works [31], which are repeatable but are not clear that they capture daily stresses.

Apparatus. We fabricated 1.5×1.5 inch woven patches with 60/2 silk as a base, interwoven with 2 conductive copper wires and 4 orange thermochromic pigmented silk yarns in the weft. The samples followed the OpenSpace design, with blue silk knots in the weft gathering black silk warp yarns. These patches serve as simplified swatches of WovenSkin devices and its interactive materials are examples of the design capabilities of WovenSkin.

Procedure. We recruited 10 participants (8 female), ages between 20-30 years ($M = 22.7 \pm 3.1$). Participants did not overlap with those in the workshop study. We met with participants at the start of their workday to apply the woven patches on the outside of their non-dominant forearm. Participants wore the devices for 24 hours as they carried on with their daily activities as usual. For each hour (excluding sleeping), participants photographed the device and measured the conductive traces with a multi-meter. After 24 hours, participants removed their woven patches. Finally, they reported on their qualitative experience in an post-study interview.

Results

Mechanical Durability. 7 of 10 devices remained attached on participants' body for 24 hours. The remaining three lasted for 8, 14, and 19 hours. Some devices peeled off slightly on the edges. Participants agreed that the device remained well-attached on the body throughout the day, with a median of 6 on the Likert scale (1=strongly disagree, 7=strongly agree). They reported that activities that caused the device to peel off included putting on a jacket or backpack, and showering.

Electrical Functionality. The conductive wires maintained electrical connection throughout the day for all devices. Showering did not affect trace connection upon drying off.

Comfort. On the Likert Scale (1=very uncomfortable, 7=very comfortable), participants rated the attachment process a median score of 6. They described the device as "very light," "overall comfortable," and said they "couldn't really feel it", reporting a median of 6 (1=strongly disagree, 7=strongly agree) for becoming accustomed to having the device on the body over time. While all participants described the device as being comfortable overall, some experienced discomfort during larger movements such as extreme wrist flexion as the adhered device pulled at their arm hairs. Participants did not have to change their daily routines due to wearing the device, rating this aspect 6 on the Likert scale (1=changed routine all the time, 7=did not change routine at all). These results suggest that WovenSkin traces can be integrated for daily wear.

Social Perception and Aesthetics. Participants rated wearing the device in social settings 5.5 on the Likert scale (1=very awkward, 7=not awkward at all). Some participants were "excited to explain it to [their] friends" or "showed it to people" because it was "cool." For others, the topic did not arise unless they were asked about the device. All participants reported that they did not mind explaining the purpose of the device.

Participants gave positive responses about whether the device was aesthetically pleasing to wear, reporting a median of 6 (1=strongly disagree, 7=strongly agree). While some participants felt that the device design was aligned with their individual sense of style, others expressed a preference for black and white, dark or neutral colors, or geometric designs. Just like the variety of textiles available in our clothing, in the future, a variety of WovenSkin colors, patterns, and designs can be customized for the user.

DISCUSSIONS, LIMITATIONS, AND FUTURE WORK

Opportunities for Co-Production of On-Skin Interfaces

In our workshop study, weavers expressed an adjustment period in working with thin materials and the smaller form. However, they also mentioned the importance of working with the materials by hand for engaging with tactile qualities of the end product (a form of *co-production* [14, 18], described by Devendorf and Rosner, between the maker, tools, machine, and materials). The rich tactile and textural qualities of woven on-skin interfaces were highlighted in our expert workshop study as a unique distinction from ink-based body art (e.g., tattoos), pointing to the potential to further elaborate on "textured" interfaces as a new dimension for on-skin design. To enable more creative, improvised experimentation to explore this design space and to streamline the process for both expert and novice weavers, we can introduce on-skin specific hand tools for weaving such as magnifying glass loom extensions and tapestry-needle like shuttles.

Weaving, in comparison to other on-skin interface fabrication approaches where production is off-loaded to the machine, offers ample opportunity for placing the wearer/maker at an "equal footing" [18] with the materials, tools, and machine to *co-produce* [14, 18] and *craft* [8] on-skin interfaces. Interestingly, this interconnection between the wearer/maker, raw material, and tools is also common in analog body arts (e.g., the personalized ritual of applying makeup can be seen as an intimate co-production between the makeup pigments, brushes, and the wearer.) As such, weaving presents an opportunity for extended forms of *hybrid body crafting* [28] for on-skin interfaces, enabling wearers *themselves* to gain control over the fabrication process to sketch, craft, and apply functional devices with *their* personally-desired purpose and aesthetics onto their own body.

Scalability

As designated in our design space, woven on-skin interfaces can also be fabricated through digital Jacquard looms for scalability and speed. Thus, we observe a uniqueness of the woven approach: at one end of the spectrum, it affords creative experimentation by hand, while at the other end of the spectrum, it also affords scalable manufacturing. For future work, we can explore the potential for fabricating woven on-skin interfaces at scale, which is a challenge with other silicone-based on-skin interface fabrication approaches. To this end, it would be fruitful to expand on existing *front-end software tools* [18, 24] in a specific version for on-skin woven interfaces, which would streamline the preparation steps of deciding body placement and planning the weaving draft.

Free-Form Woven Designs

Due to the grid-like nature of weaving, end products are often rectangular. However, body art often comes in free form shapes. While a straightforward solution is to cut out a shape from a textile (and glue or sew edges to prevent fraying), for future work, we can explore efficient ways of weaving free-form silhouettes while maintaining the textile's structural integrity. One possibility is Issey Miyake's "A Piece of Cloth" (A-POC) [27] fabrication method, which weaves seams into a clothing structure that can then be cut into any shape.

Towards Fully-integrated and Durable On-Skin Interfaces

While WovenSkin traces are skin conformable, the connector and micro-controller still need to be realized with rigid components, which is a current limitation of on-skin interface research [30]. In the future, we can explore distributing electronic components into individual circuit islands that can be more seamlessly woven into the textile structure, and build upon thin-film electronics research for further miniaturization. Our current PVA approach provides a durable and conformable attachment to the skin. Yet, we have not evaluated its stretchability when worn along joints with extensive flexing. We could investigate stretchy medical-grade adhesives for improved flexibility and device reuse, where cost would be a trade-off.

CONCLUSION

In this paper, we explore the design possibilities of fabricating on-skin interfaces through weaving. Through a series of case studies adopting a research-through-design methodology [65, 19], we developed a fabrication process to explore the design space of weaving on-skin interfaces. Due to its unique versatility in textural and structural qualities, we observe how weaving can support the construction of multiple functions in a single structure, the capacity to easily bridge functional elements across layers, and the integration of novel functional materials. Weaving also expands the aesthetic richness of on-skin interfaces with dynamic patterns and unusual textures not enabled by other fabrication approaches. In our workshop study, textile practitioners successfully adopted the fabrication process to create personalized designs, while also reflecting on the rich materialities for a hybrid form factor that sits between textiles and body art. Our wearability study demonstrates the comfort of the woven traces for continuous wear. In the discussion, we highlight the versatility of the woven fabrication approach. On one end of the spectrum, it supports hand experimentation for the *co-production* and *hybrid body crafting* of on-skin interfaces, while on the other end of the spectrum, it presents the opportunity for scalable manufacturing. Through our design explorations and reflections, we shed light on the opportunities for expanding the tactile materiality, functionally-integrated structural complexity, and human/machine production capacity of on-skin interfaces by adapting the woven craft.

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