SkinLink: On-body Construction and Prototyping of Reconfigurable Epidermal Interfaces

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Fig. 1. SkinLink democratizes the design and prototyping of on-skin interfaces through linking, adjusting, and deploying customizable circuitry directly on the body. We designed a construction toolkit that contains skin-conformable circuit components for building slim and stretchable interfaces; an on-skin fabrication workflow allows experimenting with versatile device expressions. SkinLink enables the on-body fabrication of a minimalist on-skin interface (a), an expressive face circuitry (b), a concealed digital prosthetic (c), an infused smart skin jewelry (d), and an integrated sports training system (e).

Applying customized epidermal electronics closely onto the human skin offers the potential for biometric sensing and unique, always-available on-skin interactions. However, iterating designs of an on-skin interface from schematics to physical circuit wiring can be time-consuming, even with tiny modifications; it is also challenging to preserve skin wearability after repeated alteration. We present SkinLink, a reconfigurable on-skin fabrication approach that allows users to intuitively explore and experiment with the circuitry adjustment on the body. We demonstrate SkinLink with a customized on-skin prototyping toolkit comprising tiny distributed circuit modules and a variety of streamlined trace modules that adapt to diverse body surfaces. To evaluate SkinLink's performance, we conducted a 14-participant usability study to compare and contrast the workflows with a benchmark on-skin construction toolkit. Four case studies targeting a film makeup artist, two beauty makeup artists, and a wearable computing designer further demonstrate different application scenarios and usages.

CCS Concepts: • **Human-centered computing** → *Ubiquitous and mobile computing systems and tools.*

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1 INTRODUCTION

Human skin is a soft, deformable, and topographically varying surface that allows sensing opportunities and subtle interactions within the user's reach. To address the versatile bodyscape, emerging technologies and construction-based toolkits have enabled the creation of flexible devices with a variety of fabrication methods, such as inkjet printing [59], screen-printing and water-transferring [32], lamination [34], tessellation [26], and free-hand painting [44]. While these techniques succeed in making sophisticated designs that fit a specific body location through software simulation or on-body preview, most of the devices are not modifiable once fabricated, impeding exploration and experimentation when prototyping. Even for approaches that allow circuit modification and reconstruction, limited material flexibility and stretchability hinder the interface from accommodating changes on the nonplanar and dynamic body surface. This work aims to develop novel tools that support re-configurable and adaptive on-skin prototyping, borrowing virtues from the special effects (SFX) makeup workflow.

SFX makeup artists use prosthetics to augment or change the facial or body structure. They often make prosthetics "out-of-kit" [46], which means the fabrication is done on-site and in real-time. The materials must be ready-to-use and flexible enough for most use cases, as personalized prosthetics can not be prefabricated. The need for subtle changes and a better fit on the specific wearer establishes the convention of using fast molding materials and paints to create prosthetics within a short period of time. The improvisation offers flexibility in the design and allows handy adjustments directly on the body, or "in-situ," during the application process. We found the process of SFX makeup inspiring, and the key concepts are applicable for prototyping on-skin interfaces. Since the overhead cost for on-skin prototyping comes from the device specificity that only serves one body location and one purpose, a toolkit approach that builds "out-of-kit" allows prototypes to be easily reconfigured for design explorations. When a prototype fails to fit the desired body location, enabling "in-situ" adjustments directly on the body would make the device adaptable without needing to repeat the prototyping process from scratch. Based on this idea, we present SkinLink, a toolkit fabrication approach that enables in-situ prototyping through an adaptive and adjustable wiring process for "out-of-kit" on-skin interface fabrication.

SkinLink consists of a customized construction-based toolkit and a workflow, inspired by SFX prosthetic makeup, for fabricating, applying, and blending the interface with the wearer's body for creating on-skin prototypes. To support the on-skin fabrication workflow, we leveraged a modular circuit design, where a SkinLink interface is built upon connecting multiple single-function flexible printed circuit boards (FPCBs). SkinLink modules are unique because they are engineered for comfortable skin-wearability and robust circuit connections on various body locations. Besides using flexible substrates, each circuit module is designed with ideal thickness and size to conform to the skin. Meanwhile, another design challenge is the occasional stretches to the circuit due to body movements. Here, we contribute a range of stretchable connectors specifically suitable for linking the on-skin circuitry and withstanding body movements. In this paper, we describe the detailed design of the toolkit, including the tiny flexible printed circuit boards (FPCBs) and stretchable slim trace modules. A technical performance evaluation of the four trace module types demonstrates the wiring options' adaptiveness that supports different applications.

To engage public interest and invite broader participation, we envision the toolkit as beneficial not only to experienced on-skin interface designers but provide easy-to-learn, feasible fabrication support to makers without an extensive technical background. To investigate how SkinLink can improve the on-skin prototyping experience, we conducted a 14-participant usability study to compare and contrast SkinLink with an existing on-skin construction kit by having participants prototype with both approaches. The result indicates that SkinLink enables a more flexible wiring process, unrestricted circuit arrangement, and less interfering wearability under a similar fabrication time to a baseline toolkit. A four-participant case study validates the feasibility of SkinLink in greater depth aesthetically and functionally.

We list the following contributions of the paper:

(1) We introduce SkinLink, an on-body fabrication approach for on-skin interfaces through an in-situ, "out-of-kit," and reconfigurable prototyping workflow.
(2) SkinLink comprises the on-skin fabrication process and a construction toolkit featuring flexible printed circuit board modules and trace modules optimized for on-skin wearing.
(3) We developed braiding techniques to make four types of modular traces to support flexible, stretchable, durable connections allowing body movement.
(4) We conducted a usability study and a case study to validate the design concept and highlight the aesthetic and functional customization opportunities.

2 RELATED WORK

SkinLink contributes tools and techniques toward on-skin fabrication and prototyping built on prior research in on-skin interfaces, wearable computing toolkits, and digital prosthetic makeup.

2.1 On-skin Interfaces and Fabrication Approaches

Cross-disciplinary research has been advancing technologies and materials to interface with the human skin. The material science field created epidermal electronic systems that are highly deformable by matching the skin tissue in similar mechanical properties, which enabled technical applications such as physiological sensing, near-field communication, and electro-tactile feedback [1, 25, 61]. HCI researchers extended this line of research and explored a wide range of input and output possibilities via the skin surface [29], from sensing touch or posture change [20, 30, 32, 34, 58, 59] to providing visual or haptic feedback [14, 59], and I/O integrated multi-functional devices [19, 34, 62]. Beyond interaction, other focuses in HCI include democratizing on-skin devices through exploring accessible materials and fabrication methods [20, 26], and fulfilling the aesthetic design potential of on-skin circuitry [20, 32, 34, 58].

To better conform to the skin surface, on-skin devices entail being flexible, stretchable, and lightweight. While a slimmer form factor is preferred, durability issues become trade-offs as the on-skin devices are required to work under skin deformations and body movements. These considerations result in the fabrication of fully-integrated circuitry off-body, where the device is built layer by layer on a 2D surface, including the substrate, electronics, adhesive, and the art layer that are produced separately and assembled before applying to the body. Manufacturing circuitry off-body allows a design space for more complicated device structures and insulated circuit layouts. A variety of fabricated techniques have been adopted, including 3d printing [11, 56], inkjet printing [32, 40], lamination [34], laser patterning [58–60], and weaving [49]. While these approaches yield slim, durable, and fully-integrated devices to stand alone on the skin, separating the fabrication and application steps makes previewing and iterating the designs difficult and time-consuming.

Alternatively, another trend of research exploits printing and painting conductive materials directly on-body to complete the on-skin circuitry. Instead of pursuing more accurate and finer details of the circuit layout, this line of research offers faster fabrication time [7], supports the creative free-hand design of the on-skin device [12, 44], or deforms devices to fit after fabrication [13]. While highly customizable and conform to the human bodyscape, these approaches are often hindered by the thicker and less conductive circuit traces, which leads to a more straightforward, single-functional design.

SkinLink aims to combine the advantages of both tracks of research. By breaking down complicated circuitry into swappable modules and adaptive slim traces, our approach enables extensible and impromptu circuit designs for quick fabrication and adjustment on the body.

2.2 Wearable Computing Construction Toolkit

Wearable technologies have become pervasive and broadly accessible, shifting public interest from *wearing* to *making* their own devices. Construction-based toolkits for wearables have encouraged and empowered individuals to create personalized designs [43]. Pioneering works such as the LilyPad Arduino [4] and EduWear [23] developed circuit parts by integrating electronics into textiles that can be sewn on clothes. Adding to the concept, later research [3, 18, 37, 38, 41, 42] and commercial products of textile-based toolkits such as the Flora[1] and fabrickit[2] further addressed crafting difficulties. Research that explored diverse materials and unique interactions further enriched the design space with modularized sensing and actuation options [2, 10, 27, 35, 51, 52].

Besides lowering the fabrication barrier, efforts were also made to simplify the programming of the devices. Customized software environments with visual aids help novices to learn and write code [23, 38, 47]. Built upon prior work in electronic and robot construction kits, MakerWear adopted a decentralized system model to decrease further the need for programming, where the pre-programmed circuit modules receive and pass the controlling signal in a linear order [24]. Combined with the plug-and-play tangible construction that leverages magnets for module attachment, the instant function response allows rapid design iteration. However, layout customization is limited by arranging modules in a particular order for the desired function combinations.

In addition to building circuitry on clothing, recent research explored other wearable forms, including smart jewelry [5] and on-skin interfaces [26]. To overcome challenges and *lower the floors* (to make it easier to begin) [45] for prototyping on the skin, SkinKit [26] transforms the rigid module parts and sockets into slim and flexible printed circuit boards and substrates in temporary tattoo forms. Following the decentralized architecture, the SkinKit circuit boards have pre-defined behavior and magnetically attach to a 2D pre-assembled circuit trace layout. While the approach is easy to learn even without a technical background, it limits the customizability of the module behavior. The linear sequence also confines every module to receive and react only to the preceding module's output signal.

Aiming for a toolkit that enables *higher ceilings* (possible for work on increasingly sophisticated projects) and *wider walls* (enabling a wide range of designs) [48], SkinLink brings back the one-microcontroller-to-many-peripherals model to allow more freedom in function and design customization.

2.3 Smart Prosthetics Makeup

Previous research has explored developing interactive beauty products and cosmetics for various body parts, including eyelashes [55], eyelid stickers [21, 33], fingernails [22], and hair [9, 54]. Targeting widely accepted cosmetic form factors creates a seamless integration of digital functions with the body, as people already wear and express personal aesthetics with these products in their daily lives. However, realizing such a small form factor either increases the need for circuit miniaturization or limits the capability of integrated circuitry.

Special effects (SFX) makeup provides the capacity for more complex customization and flexibility in embedding beauty technology. The process can be generally organized into three steps: (1) sculpting the effect, (2) applying the prosthetic on the body, and (3) concealing the prosthetic with makeup. Using prosthetic materials such as silicon and latex for sculpting, molding, and casting structures, SFX makeup can create advanced cosmetic effects with a realistic look [8]. Prior work applied special makeup on the face for sensing muscle movement as input [53] and enabling transformative makeup effects as output [57]. While human skin secrets oil and sweat

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[1] https://www.adafruit.com/product/659

[2] https://www.sparkfun.com/products/retired/10350

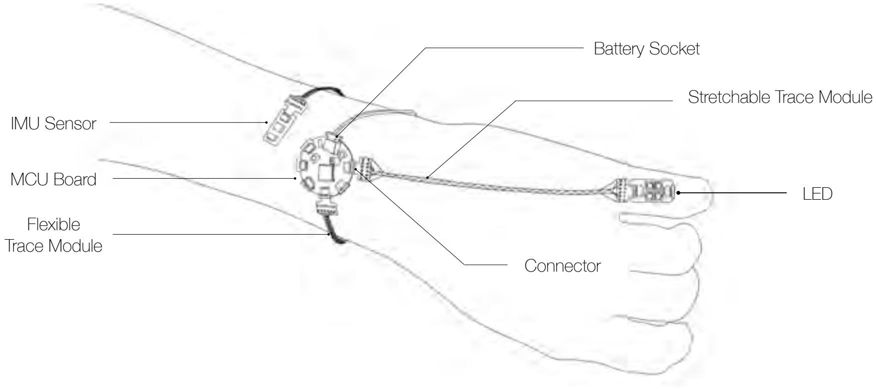

Fig. 2. Example diagram of a SkinLink device. The sensor and actuator modules connect to the microcontroller board via flexible and stretchable trace modules.

and is prone to detachment of devices, the well-established artistic technique has the advantage of durably augmenting designs on the skin surface [31]. The SkinLink workflow adopts SFX makeup techniques to improvise and manipulate circuitry adjustment during the application process while providing options for camouflaging the device conforming to the body surface.

3 SKINLINK

We designed a customized toolkit to demonstrate the SkinLink workflow's feasibility, which facilitates durable and flexible on-skin prototyping. This section describes the system in detail, including the design goals, circuit modules, adaptive connectors, and technical performance evaluation.

3.1 Design Goals

Learning from prior work in fabricating on-skin interfaces [11, 34, 44], existing gaps in wearable construction toolkits [18, 26, 47], and the affordances of the SFX makeup workflow [57], we lay out the following guidelines for SkinLink.

1. "Out of kit" and "in-situ" prototyping–Support modifiable circuit fabrication to allow adjustments during the application on the body. Users should directly see and modify their designs on the body.
2. Flexibility–Enable adaptive layout designs to address narrow or expansive, flat or uneven surfaces of the bodyscape. We explore on-skin prototyping on a wide range of body parts, including those requiring stretching (e.g., joints) and those with complex and intricate geometries (i.e., face).
3. Stretchability–Develop moldable and stretchable conductors with durable connections that endure body movements. SkinLink should provide various wiring options to support different use cases.
4. Extensibility–the SkinLink system is compatible with open-source electronics platforms like Arduino. New modules for additional sensing, actuation, computation, and communication functions can be added to the module library following the FPCB module designs.

The toolkit consists of (1) functional circuit modules made of flexible printed circuit boards (FPCB) and (2) flexible conductors of trace modules custom designed with distinctive properties. Following the design goals, we designed the circuit module to be miniaturized while extensible for adding new functions under the same system framework. Through experiments, we developed four types of trace modules that can conform to the skin on various body locations and for different usages, including a moldable trace, a flexible trace, a coated flexible trace, and a stretchable trace. A simple but robust connection mechanism provides critical adaptability for design adjustment on the body.

An example SkinLink circuit is shown in Figure 2. The circuit diagram consists of three flexible printed circuit board modules: a microcontroller (MCU), an inertial measurement unit (IMU), and an RGB LED. Based on the communication protocol, the IMU sensor and LED are connected to the I2C ports on the MCU module via two trace modules. The flexible trace module can conform to body curvatures, such as wrapping around the wrist. The stretchable trace modules provide elasticity and room for the wrist joints, where the circuit remains well attached to the back of the palm without hindering movement. Transparent prosthetic silicone is applied underneath and covering the device to facilitate adhesion to the skin.

3.2 Functional Circuit Modules

Our design is motivated by the concept of "PCB islands" [19, 34] that increase circuit wearability by dividing a bulky integrated circuit into smaller PCB islands that can be distributed throughout the body surface. SkinLink modules are categorized by functional purposes, including the main microcontroller, sensors, actuators, and data storage/transfer modules. We designed the microcontroller (MCU) module in a circular shape (20-mm diameter) and the rest of the peripheral modules in a rectangular shape (Figure 3). The microcontroller (MCU) module has multiple ports supporting communication protocols. There are three ports for I2C and two for SPI, all of which could be configured to UART, allowing the microcontroller to communicate with the chainable peripheral modules. To support linking more than one module to an MCU port that shares the same communication protocol, we designed most peripheral modules in a rectangular shape with one input port and one output port (marked by white arrows), all but except the microSD card and Bluetooth LE module. The rectangular shape of the peripheral modules supports easy chaining. A programming module allows users to implement code and program the MCU module from a laptop.

Figure 3 shows the 14 circuit modules developed for SkinLink with sensing, computing, actuation, and communication functions. To minimize weight and maximize skin conformability, all the modules are manufactured with a 2-layer flexible PCB (0.15mm total thickness, 35μm copper layers). SMD components with a small footprint and low power consumption are selected, whereas all the passive components (resistors and capacitors) have a 0402 package size. To minimize the resistance of circuit traces, 10-mil traces are used for power lines, while 8-mil traces are used for signals. Polyamide (0.1mm) and FR4 (0.2mm) stiffeners are applied behind larger IC components (e.g., MCU and sensors) and FPC connectors to reinforce the modules against bending on the body surface. For powering the system, the microcontroller board has a JST connector for connecting a 3.7V LiPo battery and a linear regulator that steps down the voltage to 3.3V.

SkinLink adopts a centralized architecture, shown in Figure 4, where a single circuit module with an MCU acts as a central hub. Based on the communication protocol, all the sensor and actuator modules are attached to the MCU as peripherals. Compared to its decentralized counterparts (*e.g.* [24, 26]), the centralized architecture enables more flexible connections between the modules. It allows more complex circuit designs, as the data flow is no longer restricted to be unidirectional. As a result, the modules on a bus sharing the same protocol can connect in any order. The users can program the microcontroller (ATSAMD21) by connecting the MCU board to the programming module, which will connect to a Seggar J-Link debug probe and the laptop. The software can then be programmed in an Arduino environment. We aim to make the toolkit accessible to any user with basic programming knowledge, *e.g.*, some exposure to prototyping platforms such as Arduino.

3.3 Adaptive Trace Modules

Finding a balance between the conductivity and stretchability of the conductor is a common challenge in choosing materials for soft on-skin devices [39]. At the same time, a moldable trace that allows hand manipulation, such as

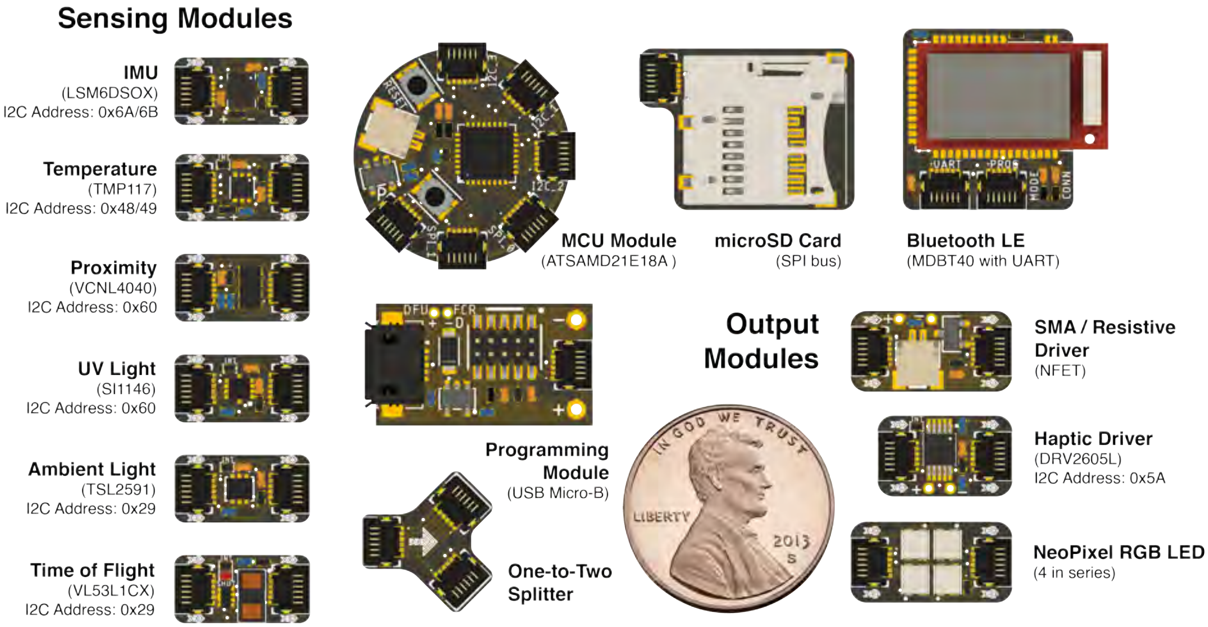

Fig. 3. 14 circuit modules with sensing, computing, actuation, and communication functions. A penny is shown for scale reference.

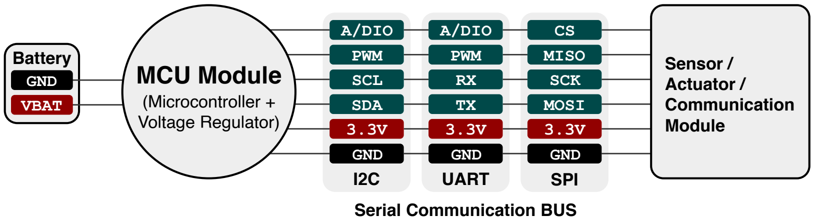

Fig. 4. SkinLink system architecture.

bending, twisting, and winding into a fixated shape, can be beneficial for designing the circuit layout. Therefore, besides exploring highly stretchable conductors, we aim to design SkinBoard trace modules with additional properties to conform to dynamic surfaces of the skin, including moldability, durability, and soft texture. To address different needs of the wire properties, we developed a multi-layer braided structure for altering the conductor characteristic as different combinations of braiding yarn and core material lead to a wide range of attributes. Through iterative experiments of material and fabrication methods, we developed four types of wires which serve different purposes, including (i) moldable braided wires, (ii) flexible braided wires, (iii) flexible braided wires with silicone coating, and (iv) stretchable bi-directional braided wires (Figure 6). The trace module serves the purpose of communication bridges and circuit layout extensions. Different lengths of the wire can combine or branch to one or more wires through the extender and 1-to-2 branch splitter boards.

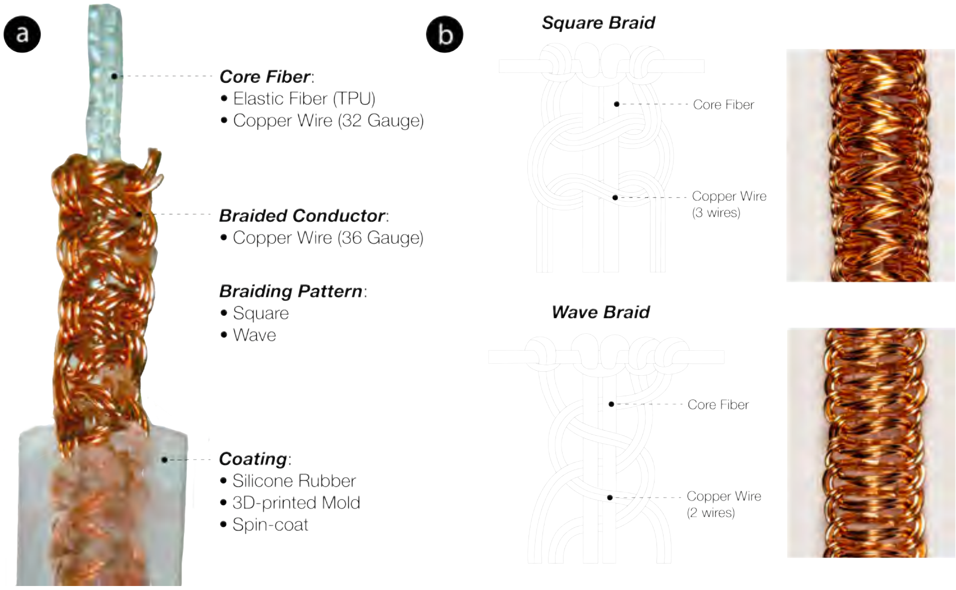

Fig. 5. (a) Design options for a SkinBoard adaptive trace module (b) braiding process of the two patterns

3.3.1 Trace Module Structure. The SkinLink trace modules are braided wires that consist of three main elements, including (1) the conductive material braided to the core fiber, (2) the core fiber, and (3) the coating layer covering the surface, as shown in Figure 5a. Below, we introduce each element along with its fabrication.

Braided Conductor. A braid is a string structure formed by interlacing two or more strands, where different braid techniques can result in different patterns and textures. Two braiding techniques: square knot macrame braid [3] and wave braid [4] were tested to fabricate the moldable and stretchable wires (Figure 5b) due to their thin but durable braid structure. Each braid consists of six enameled copper wires (36 gauge) braided on the core fiber for the six connections on the serial bus. To braid square knots, the core fiber is fixed on both ends, and the six copper wires are separated into two bunches of wire to perform a square knot, where a wave braid is tied with three wire bunches (Figure 5b). Both braiding methods can produce a tidy and compact pattern, where the square knot is denser and sturdier, and the wave braid possesses slightly better stretchability and is thinner in width. Though with similar mechanical properties, we chose the square knot in the current implementation because it is faster and easier to braid.

Core Fiber. Besides the braiding pattern, the mechanical characteristics of the wire are primarily influenced by the core fiber, i.e., the central cord that square knots are braided around. We tested different types of core fibers, including TPU nylon (0.5mm diameter), cotton yarn (Nm 10/2), linen yarn (Lea 30/1), and enameled copper wire (32 gauge), listed from the most elastic to the most rigid. Braiding with TPU nylon (Crystal Tec Korea) yields a soft and stretchable string, cotton and linen yarn lead to nonelastic but flexible braiding, and the copper wire core provides extra stiffness to hold the manipulated shape. We also experimented with braiding with different numbers of core fibers. We found that the single-core can be slippery, and we end up using a dual-core since it holds the braids in place better.

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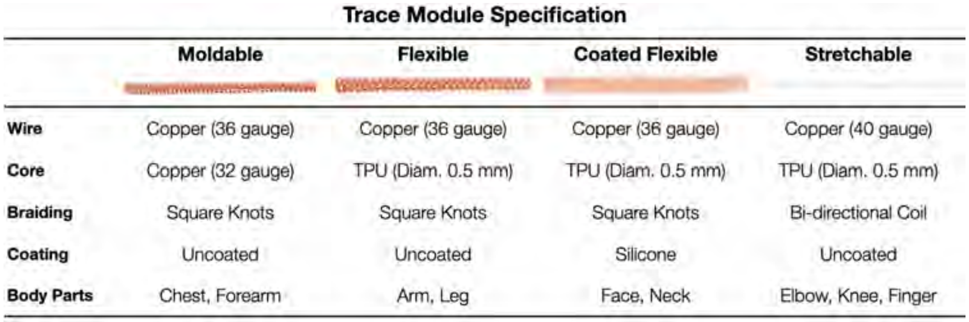
[3] https://www.instructables.com/How-to-Macrame-Square-Knots/

[4] http://www.free-macrame-patterns.com/wave-braid.html



Trace Module Specification

	Moldable	Flexible	Coated Flexible	Stretchable
Wire	Copper (36 gauge)	Copper (36 gauge)	Copper (36 gauge)	Copper (40 gauge)
Core	Copper (32 gauge)	TPU (Diam. 0.5 mm)	TPU (Diam. 0.5 mm)	TPU (Diam. 0.5 mm)
Braiding	Square Knots	Square Knots	Square Knots	Bi-directional Coil
Coating	Uncoated	Uncoated	Silicone	Uncoated
Body Parts	Chest, Forearm	Arm, Leg	Face, Neck	Elbow, Knee, Finger

Fig. 6. Specifications of the four trace modules: (i) moldable square braided trace, (ii) flexible square braided trace, (iii) flexible square braided trace with silicone coating, and (iv) stretchable bi-direction coil braided trace.

Coating. We coated the trace modules with silicone, which provides a smooth surface texture and protects end connectors but would increase 1mm thickness. Two coating methods were explored: (1) spin-coating with a servo motor and (2) molding and casting. The wire is rotated as the silicone is applied along the length of the wire and left to dry. This results in an even layer of silicone on the wire. For coating with a mold, rectangular molds were designed and 3D printed for the different lengths: 4cm, 8cm, and 12 cm. The coating process utilizing molds has three steps: (1) Make silicone. Mix part A and part B of Ecoflex 00-50 silicone rubber[5] with a ratio 1A:1B in a beaker. Depressurize silicone to -30 inHg in a pressure chamber for 10 minutes to remove bubbles in the mixture. (2) Coat braided wires with silicone. Fill rectangular molds with a thin layer of liquid silicone and place wires on top. To ensure even coating, press wires down to lie flat, then fill the mold to the top with silicone. (3) Remove wires from molds. After 3 hours, remove wires carefully from the molds. Clean up edges of silicone coating by cutting off additional silicone formed from overfilled mold. We mold the silicone as the final coating method to create a flat surface that better conforms to the skin.

3.3.2 Four Adaptive Trace Module Options. By tuning each element of the trace module described in the prior section, we can achieve four different trace options (Figure 6) suitable for specific use cases.

Moldable Trace Module: The first target design is a more rigid, non-stretchable trace module. Among the core materials, both cotton and linen resist stretching but are submissive to bending. For this design, the copper wire core has the desired properties holding rigidity and malleability that can retain the shape after manipulation. The moldable trace is suitable when it needs to align with the bone structure without joints, such as the chest and the forearm. It can also hold an intricate shape through bending and twisting.

Flexible Trace Module: The second design we selected is having conductors braided along a TPU nylon core, which allows for better flexibility to conform to the skin with a certain level of stretchability. We suggest using a flexible trace module when the trace requires certain flexibility to follow the body curve loosely, such as the arm and leg muscles.

Coated Flexible Trace Module: To add a smooth surface texture, we designed the third trace module by adding a coating layer to the TPU-core wires with silicone (Ecoflex 00-50), which makes them more comfortable to wear and provides more grip on the skin in exchange for a slightly larger footprint due to the coating layer. The coated wire provides a flat, smooth surface that is comfortable to wear and suitable for sensitive body parts such as the neck and the face.

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[5] https://www.smooth-on.com/products/ecoflex-00-50/

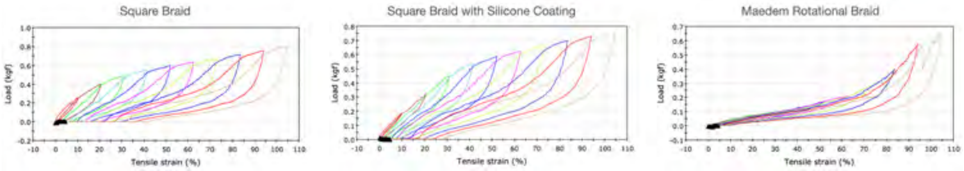

Fig. 7. Cyclic test loading to increasing strains for three types of trace modules.

Stretchable Trace Module: In addition to the three wires mentioned above created within our lab, we collaborated with a tinsel wire manufacturer, Maeden[6], to develop the most stretchable trace module. The wire is fabricated with a single TPU elastic fiber. Two sets of copper wires (two-wire inner layer and four-wire outer layer) are rotationally braided in clockwise and counter-clockwise directions. While the wire is more delicately braided with thinner elastic and conductive materials, it is well suited, especially for mobile body locations, because of its excellent stretchability. The stretchable trace module can be extended to two times its original length, preventing disconnection across a joint. Example body locations suitable for this wiring include the elbow, the knee, and the fingers.

3.3.3 Technical Evaluation. Amongst the four designs, three trace modules are stretchable, with the only exception of the moldable wire, which is not meant to be extensible in length. We characterize these stretchable trace modules under tensile loading to evaluate their conductivity, elasticity, and durability (Figure 7). Three 80 mm trace modules (Square Braid, Square Braid with Silicone Coating, and Maedem Rotational Braid) were loaded at a displacement rate of 80 mm/min and stretched to a maximum of 200% elongation. A source meter connects to both ends of the wires to measure resistance change, where the copper conductor yields a consistent conductivity (Square Braid: $\approx 1\Omega$, Maedem: $\approx 2\Omega$), and a less than 0.005% resistance change is observed for all three samples. We performed cyclic tests in 10 cycles to investigate the elasticity, increasing the target tensile strain from 10% to 100%. While the Maedem sample had a breakage when reaching 100% tensile strain, it has the most elastic modulus (0.8 MPa), whereas the square braid (w/wo coating) samples have a similar elastic modulus of (1.7 MPa). Though the traces have stable conductivity, we observed plastic deformations from the square braid samples, where the trace samples elongated 30% of length after undergoing 100% tensile strength. To investigate if repeated plastic deformations affect the trace connection, we conducted a follow-up tensile test on both square braid (w/wo coating) samples under 100% tensile strain for 1000 cycles, where the trace samples remained conductive after the test.

3.4 Connector Design

We designed and improved upon a slim and durable connection mechanism based on the design of a flexible printed circuit (FPC) connector from Huang *et al.* [16], which serves as the electrical interface between the trace modules and circuit modules. We chose 6-pin FPC connectors with 0.5mm pitch for connections between the stretchable traces and circuit modules. Six solder pads are extended from the electrodes to facilitate soldering (Figure 8a1 & b1). Two versions of the FPC electrodes were designed and tested. In the first version, shown in Figure 8a, the solder pads are arranged in two rows to minimize the overall width. To prevent the first-row pads from shorting the second row, a second version (Figure 8b) is designed, where all solder pads are placed in the same row, and two through holes are adopted for easier threading.

Each trace module has a connector soldered to each end of the braid. First, the six wires of a trace module are threaded into their respective pins on the connector (Figure 8a2 & b2). We gently sand the part of the wire

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[6] http://www.maeden.com.tw/

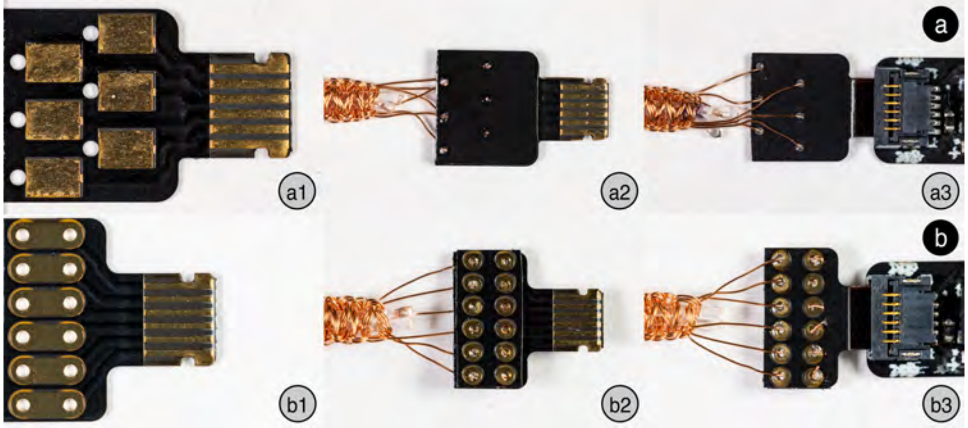

Fig. 8. FPC connectors and electrodes are used as the connection mechanism between the traces and circuit modules. Two versions are designed and tested with the six solder pads arranged in (a) two rows and (b) one row. Within each version: (1) FPC electrodes; (2) Electrodes with braided wires soldered; (3) Electrodes plugged into an FPCB module.

lying on the copper plates to expose copper from the coating. We then apply low-temperature soldering paste through a masking stencil to the sanded wires and melt the paste at 160 ° with a heat gun. At last, we place a protective top layer to sandwich the wires and use a heat gun to reflow the solder. The electrodes can then plug into a circuit module via the 6 Position FPC Connector Contact (8a3 & b3), which holds a maximum of 4.4 N of pulling before disconnecting.

3.5 Making with SkinLink

SkinLink aims to democratize making on-skin interfaces through the ready-to-use, accessible materials from the toolkit and a fabrication workflow that enables *in-situ on-body prototyping* and *real-time adjustment*. We optimized the following three-step workflow:

(1) Selecting circuit modules and adaptive traces: Depending on the desired functionality, the process starts with selecting and programming the circuit board and trace modules. The microcontroller (MCU) board module can be repeatedly programmed during this step to add/remove modules and fine-tune the circuit functions. When assembling a SkinBoard circuit, every peripheral function module must connect to the main microcontroller boards directly or via other modules that share the same communication protocol. For example, an I2C module can connect to another I2C module that chain links to the MCU with a different I2C address. Different lengths of the wire can combine or branched to one or more wires through the extender and 1-to-2 branch splitter boards. The goal of the first step is to find the initial prototype materials "out-of-kit," where the functionalities of the circuit boards can be programmed and tested before application.

(2) Temporary attachment and adjustment: After the prototype's components are decided, the circuitry can be applied to the desired body location with the help of a silicone modeling compound (3rd Degree[7]). Mixing the A/B part of the silicone, the mixture will first turn into a glue-like gel form, which is sticky enough to attach the circuit parts to the desired body location temporarily. Before silicone cures, the 5 to 10 minutes time span allows the user to make changes, such as relocating circuit boards, outlining the device layout, and linking different types of trace modules with the help of detachable and re-attachable connectors. After the silicone cures, it becomes firm and forms a durable bond between the circuit and the skin surface, and the design is then molded

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[7] https://alconemakeup.com/shop/details/silicone_products/3rd_degree/PM3DEG/

and secured on the body. The critical "in-situ" adjustment process is done during the second step. The temporary attachment allows the user to preview, explore, and modify the design directly on the body.

(3) Aesthetic customization: The last step to finalize the design is to customize the device outlook in various ways to express personal aesthetics. The circuit traces and boards can be exposed on the skin as a bold statement or hidden for further decoration. One example implementation is to "camouflage" the circuit parts with extra prosthetic silicone, where a thin layer of prosthetic silicone is applied on top of the circuitry. This top layer of prosthetic silicone provides an insulation cover to protect the circuitry. Also, it works as an art layer for applying skin-tone dyes or makeup products that go on to both the skin and the prosthetic.

4 USABILITY COMPARISON STUDY

To validate the fabrication feasibility of the concept, we utilized A/B comparisons working with a different toolkit as the baseline [28]. The evaluation method is often used to suggest improvement over a prior approach that supports similar tasks previously adopted by UI toolkit research, such as the MAUI toolkit [15]. Regarded as the most relevant toolkit for comparison, we chose and replicated the fabrication of SkinKit by Ku et al. [26], a construction-based prototyping toolkit for on-skin interfaces. We chose SkinKit because, to the best of our knowledge, it is the only modular toolkit for on-skin interface prototyping available in the field currently.

Through the comparison study tasks, we aim to collect both quantitative measurements and qualitative feedback from the participants about their experience making with both toolkits. To understand the challenges users might encounter when learning to make with the SkinLink toolkit without specific technical or design backgrounds, we recruited study participants with limited or no experience prototyping wearable devices. We designed the usability study to have participants evaluate the two toolkits under the same condition without specifying SkinLink as the proposed approach. By doing so, we hope to collect a more objective evaluation of SkinLink than testing alone. Meanwhile, we hope to shed light on the improvements that the SkinLink approach enables by comparing and contrasting the fabrication workflows, device form factor, and overall prototyping experiences.

Introducing SkinKit, the comparison toolkit. SkinKit [26] is the first construction toolkit for prototyping on-skin interfaces consisting of two components: (1) skin-conformable base substrates and (2) reusable Flexible Printed Circuit Boards (FPCB). An example circuit is demonstrated in Figure 9b. The skin substrate (or skin cloth) is made of a thin silicone layer on top of a PVA sheet, which is cut into square pieces with notches for tessellation. Three traces of conductive fabric tape representing Power, Ground, and Signal connect the skin cloth module and the FPCB modules and help construct the circuitry, where magnet pairs form a stable electronic connection between two connection parts. The FPCB modules adopt the decentralized architecture and are categorized by functions, including power, sensor, actuator, and modifier. As the signal transmits in a daisy chain format, the FPCB modules must be connected in a particular sequence (*e.g.*, power → sensor → actuator) to work.

4.1 Method

The study had three parts, including a 5-min study introduction, a 60-min making session, and a 25-min post-study survey and semi-structured interview session. The researcher first introduced the concept of on-skin prototyping and the circuit components to the participant. During the making session, a researcher guides the participant to fabricate two circuits with the same functionality using modules from both toolkits. Participants build two circuits (one from each toolkit) and wear them on their desired body locations. To eliminate biases while gathering insights from each participant, we designed within-subject study tasks with counterbalanced order of the two toolkits. A semi-structured interview was performed at the end of the study, where the researcher asked questions regarding the circuit fabrication and application, wearability, aesthetic customization, and potential improvements. Figure

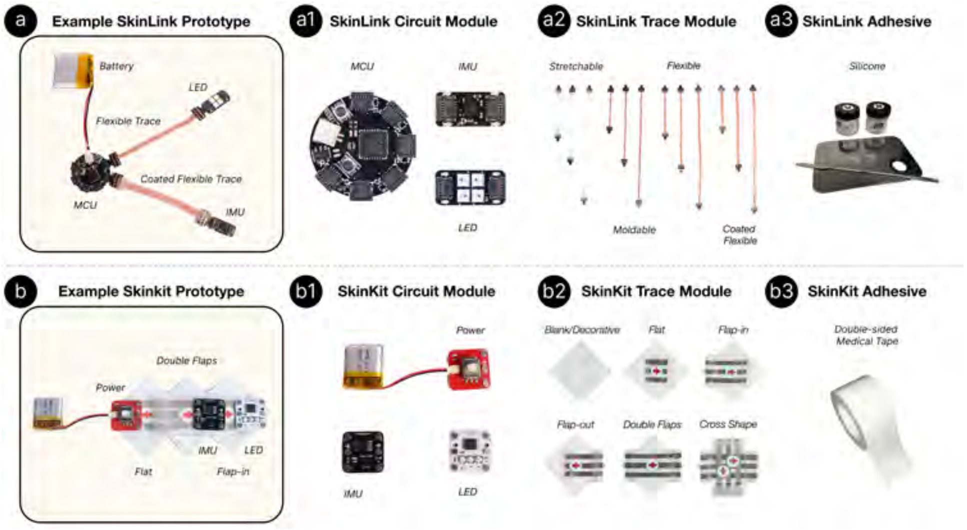

Fig. 9. A/B Usability Study Materials for (a) SkinLink and (b) SkinKit.

10 shows the 90-min study structure, where two researchers facilitated the study and recorded the entire study process in video and audio.

4.1.1 Apparatus. We prepared materials for making circuits of the same function for both toolkits, which involved an IMU sensor and a 4-series LED module (Figure 9). For SkinLink, a microcontroller (MCU) and all four kinds of trace modules (Moldable, Flexible, Coated Flexible, and Stretchable traces) in three different lengths: 4cm, 8cm, and 12cm were prepared (Figure 9a2). Extender modules were also provided to combine multiple trace modules into a longer piece. We prepared prosthetic silicone (3rd Degree) for participants to adhere to and mold the SkinLink prototype onto the skin (Figure 9a3). On the other hand, SkinKit consists of two main components, including single-functional PCB circuit modules and trace modules comprised of thin silicone sheets and three traces (power, ground, and signal) made of conductive fabric tape. While the initial version of SkinKit doesn't include an IMU sensor or 4-series LED, we followed the layout and customized the boards using the same microcontroller (ATtiny 85) with the same module dimension. We provided three SkinKit-style circuit modules, including the power module, IMU sensor, and the 4-series LED actuator (Figure 9b1). Besides the circuit modules, we fabricated the skin cloth substrate in five types of wire modules except for the blank/decorative design for the participants to create customized circuit layouts (Figure 9b2). A medical-grade double-sided tape was used for attaching the SkinKit device to the skin (Figure 9b3).

4.1.2 Participants. Fourteen participants participated in the study: ten females and four males, aged between 19-28 (Md=21.5, SD=3.25). A pre-study survey was used to collect participants' demographic data and past experiences with programming, electronics, arts and crafts. 11 out of 14 participants have a STEM background (e.g., Information Science, Electrical/Mechanical Engineering), and three participants have a design background (e.g., Fashion/Product Design).

4.1.3 Tasks. The researcher instructed the fabrication workflow for each making session and had the participant practice the construction techniques in the first 10 minutes. The design goal of each making session was to combine the IMU sensor and the 4-series LED actuator into a circuit layout that displays LED lights based on the

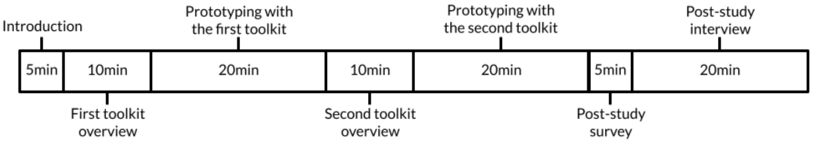

Fig. 10. Usability study structure

sensor orientation. When the sensor is tilted, the LED will light up gradually to signal the change in the tilting angle. The participant first decided on the body locations for placing the sensor and the actuator before making the first circuit. The exact body locations will be reused in the second session for comparison. After fabricating the circuit, the researcher helped the participant apply the circuit, and the participant wore the device for five minutes. The device was removed before the participant started the next session.

4.1.4 Analysis. For quantitative data, we measured the number of wire/trace modules used in each circuit design, the time spent fabricating each circuit, and the covered surface area on the skin. We aim to compare the fabrication cost and effort in terms of time spent, the complexity of the circuit by the number of modules used, and the surface occupancy on the skin when wearing the prototypes. Ratings from the 7-point Likert scale post-study survey with questions regarding fabrication feasibility and device wearability were also analyzed using the Wilcoxon signed-rank test. However, we only report on results with significance. All qualitative data in the semi-structured interviews were transcribed and iterative coded by three researchers independently to identify common themes with a reasonable degree of agreement.

4.2 Result and Findings

We summarized the study result by reporting quantitative measurements and describing interview analysis of common patterns and themes.

Figure 11 displays the circuit made by the participants using (a) SkinLink (left) and (b) SkinKit (right), respectively. Regarding body location, seven participants chose the wrist and palm for placing their prototypes, four participants chose the forearm, two placed the circuitry on the thigh, and one put their designs on the shoulder. Given the same set of circuit modules, participants created different circuit layouts. Based on the location of circuit modules, the participants experimented with different types of trace modules for the SkinLink prototype. Similarly, different SkinKit wire modules were combined for the customized layout.

Analyzed from the post study interview, Table 1 shows the coding result sorted by frequency (number of participants who mentioned this theme) under four main themes: (a) form factor, (b) fabrication, (c) wearing, and (d) aesthetics.

4.2.1 Quantitative Measurements. Figure 12 shows the comparison between the SkinLink and SkinKit fabrication approaches in terms of time, number of modules, and the coverage of skin surface area. All 14 participants were able to design and fabricate the on-skin prototypes successfully after learning the SkinLink and SkinKit workflows. On average, participants spent less than 13 minutes fabricating the prototypes (Figure 12-1), which was drastically faster than the previous on-skin interfaces' fabrication, which took time ranging from 3.5 hours to 11 hours [17, 19, 59]. We observed that participants spent a longer time at the adhering step for SkinLink, where a fixed period of 3 to 5 minutes is required for the silicone to solidify.

Despite the extra waiting time in the skin adhering stage, our study shows SkinLink has a similar fabrication time to SkinKit, as participants used fewer wire modules to build the circuit layout with SkinLink (2.14 on

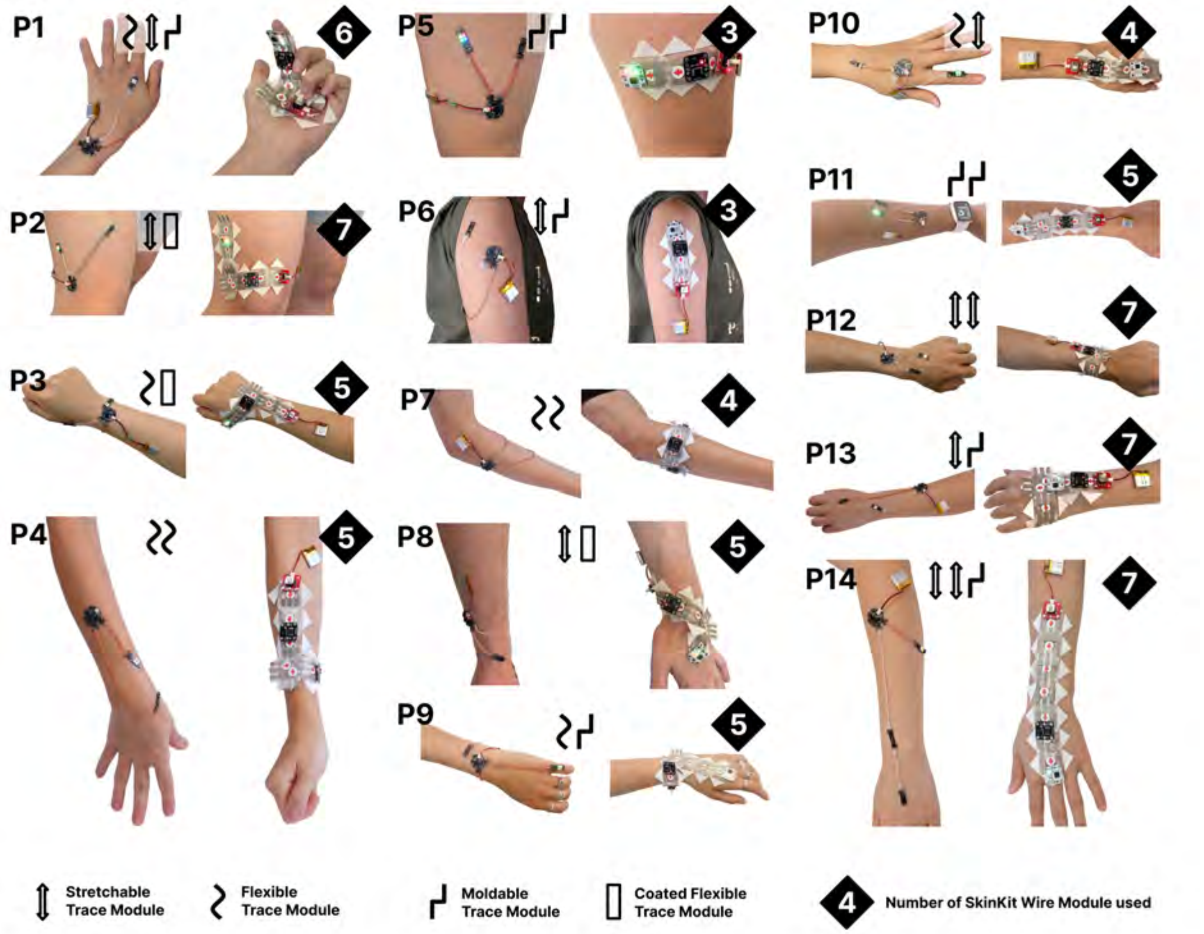

Fig. 11. 14 participants created on-skin prototypes using SkinLink(left), and SkinKit(right). Symbols on the top right corner represent the type and amount of trace modules used in the SkinLink prototype, and the number in the diamond shape symbol denotes the amount of SkinKit wire modules used.

average) than Skinkit (5.21 on average) (Figure 12-2). We observed that for the same device placement on the body, SkinLink trace modules allow a more efficient and adaptive routing and linking process for the circuit boards.

Each SkinLink trace module has a width ranging from 2.5mm (uncoated) to 3.5 mm (coated) and a length of 4, 8, or 12cm, which covers a surface area of less than 5 cm square. In contrast, each SkinKit wire module is uniformly 16cm square. By summing the area of trace modules, PCB modules, and connection parts, we estimate the total skin surface area each on-skin prototype requires. The SkinLink prototypes from the 14 participants took 11.53 cm square on average, while the SkinKit prototypes took 65.71 cm square on average (Figure 12-3). The result shows that for a similar device placement on the body, SkinLink trace modules allow a more efficient and adaptive routing, and the traces for linking circuit boards take up less total skin area.

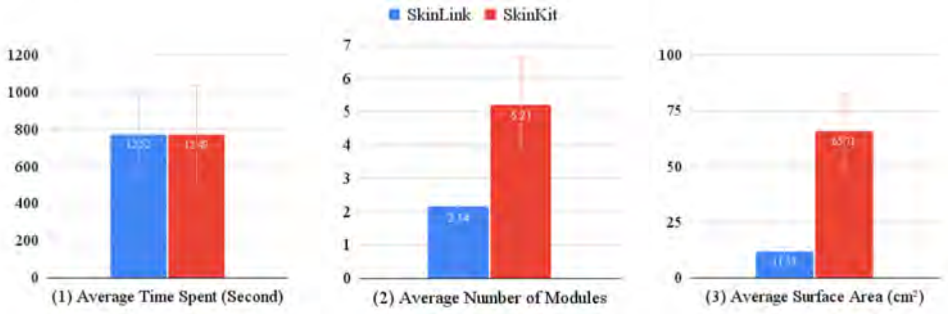

Fig. 12. SkinLink and SkinKit: (1) time spent on fabrication, (2) number of trace/wire modules used, and (3) covered surface area.

4.2.2 Form Factor and Footprint (Table 1a). SkinLink circuit modules take up a smaller surface area due to a minimized connector design and fewer microcontrollers required in the centralized system structure. Participants commented that the stretchability and flexibility of the SkinLink trace modules provide more freedom in design and align well with the bone structure of most body parts (n=11). While some participants appreciate the lightweight footprint of SkinLink modules (n=4), others felt nervous about the tiny connectors and regarded the fabrication as a delicate task. On the contrary, nine participants reflected on the larger surface area covered by the SkinKit modules that are bulkier than SkinLink, which they think is only suitable for planar body locations with larger surface areas. For delicate body parts such as fingers, the SkinKit modules failed to fit and conform to the narrow structure (n=6). Another limitation of SkinKit designs comes from the right-angle layout (n=8). As a comparison, SkinLink supports freeform designs, such as a curve or an acute/obtuse angle shape.

4.2.3 Ease of Fabrication (Table 1b). SkinLink aims to support a "high-ceiling" and "wide-wall" [48] on-skin prototyping workflow and allow free-form circuit layout application and adjustment on the body. Participants described both circuit fabrication processes as easy, intuitive, and fun but also reported several differences between the toolkits based on their prototyping experiences. They commented that SkinLink was inspiring for the creative process, especially because the in-situ on-body adjustment during application allows for experimentation with different layout designs (n=3). Participants also praised the connection jackets between the trace and PCB modules for being consistent and durable (n=6). On the other hand, four participants described that building SkinKit prototypes reminded them of building Legos. The upright, straight-angle layout of the SkinKit wire modules made it challenging to change the circuit direction (n=1) on the curvy body surface and required an additional step of tessellation (n=7). During the post-study survey, the participants rated SkinLink to be easy to prototype (Median (M)=6 on the Likert scale; 1=strongly disagree, 7=strongly agree.) The Wilcoxon signed-rank test result showed a significant difference compared with SkinKit (M=5) (p<.05.) While both SkinLink and SkinKit are easy to design and plan the circuit layout, SkinLink enables participants to directly construct and build the circuit on the body, with the advantage of adaptive and durable wiring options.

4.2.4 Seamless Wearability (Table 1c). Regarding wearing the SkinLink and SkinKit devices, most participants considered attaching to skin the circuitry made with both toolkits to be comfortable. Many participants reported they eventually "neglected" the existence of the SkinLink device as they got used to the soft silicone prosthetic layer, which is almost unnoticeable (n=5). The silicone prosthetic could perfectly fill the gap between the modules and skin, leading to slim and skin-conformable wearability (n=6). Oppositely, for SkinKit, participants reported that they could feel the medical tape on the skin since it covered a larger surface area and became less

Table 1. The code frequency (number of participants) for SkinLink and SkinKit from the post-study interview.

SkinLink			SkinKit		
Theme	**Sub-theme**	**Frequency**	**Theme**	**Sub-theme**	**Frequency**
(a) Form Factor	Stretchable & Flexible	13	(a) Form Factor	Cover Larger Area	9
	Delicate	7		Only Right Angles	8
	Lightweight	4		Unfitting	6
(b) Fabrication	Easy & Intuitive	8	(b) Fabrication	Easy & Intuitive	7
	Fun	7		Tessellation Effort	7
	Durable Connection	6		Fun	6
	On-body Adjustment	3		Lego	4
(c) Wearing	Comfortable	9	(c) Wearing	Comfortable	6
	Conform to the Skin	6		Tape Noticeable	6
	Silicone Unnoticeable	5		Magnet Detach	5
(d) Aesthetic	Different Colors	10		Hindering Movements	5
	Conceal the Device	7		Uncomfortable	4
	Socially Acceptable	6	(d) Aesthetic	Conceal the Device	6
	Jewelry	5		Uniform Design	5
	Futuristic	5		Socially Acceptable	4

air/water permeable over time (n=6). Four participants complained about the removal of SkinKit devices being uncomfortable due to the tape sticking to body hair. The magnetic connection of SkinKit raised concerns of detachment (n=5), and the limited stretchability of SkinKit wire modules could hinder body movement, especially on the joints (n=5). SkinLink offers ideal wearability with the soft, slim module form factor and the comfortable prosthetic silicone application process.

4.2.5 Aesthetics (Table 1d). When asked about the modules' appearance, some participants wished the SkinLink modules could have a more uniform shape like the SkinKit design (n=5). Many participants suggested color-coding the boards and traces to help with prototyping (n=10). Still, other participants appreciate the metallic style of the braided wire, which resembles jewelry and affords a futuristic, sci-fi look (n=5). While we designed the trace modules to have a minimal footprint, a participant (p5) suggested we include different widths of the traces as one of the design choices for different aesthetic needs. Regarding social acceptance, 6 and 4 participants, respectively, were open to wearing the SkinLink and SkinKit device in public if they provide practical functions. A consensus of customization for both SkinLink (n=7) and SkinKit (n=6) prototypes is concealing the device by adding a thin covering layer or camouflaging it into a skin-tone prosthetic.

4.2.6 Summary. All 14 participants were able to design and fabricate the on-skin prototypes successfully in under 13 minutes after learning the SkinLink and SkinKit workflows. The study results suggest that SkinLink enables a more flexible wiring process, unrestricted circuit arrangement, and less interfering wearability when designing an on-skin prototype. Compared to the SkinKit, the SkinLink interface has a much smaller footprint, better stretchability, easier fabricating, and more seamless wear under a similar fabrication time.

5 CO-DESIGN CASE STUDY

We invited four on-body design experts to learn, fabricate, and incorporate SkinLink into a project of their choice to understand the expressiveness of the toolkit in depth. We chose the participatory design process as the study methodology, demonstrated in previous toolkit research [36, 47]. We define on-body design expertise as extensive experience with either analog forms of body craft (makeup, body art, FX makeup) or digital on-body technology (e-textiles, wearable technology). Through the case studies, we aim to (1) gauge the feasibility of SkinLink in greater depth aesthetically and functionally, (2) understand what participants design and build for themselves, and (3) analyze how on-body design experts progress in their understanding of the use of SkinLink.

5.1 Participants

Our participants (anonymized by pseudonyms) include Victoria, a film makeup artist with four years of makeup experience in face painting, film makeup, and beauty makeup; Madison, a part-time fashion makeup artist who practiced makeup for over a decade and has done makeup service for a fashion magazine; Ivy, a part-time makeup and body art artist with two years of experience who has done makeup and body art for runway fashion shows; Riley, a wearable interface researcher who has six-year software programming experience and two and half year of experience designing novel wearable interfaces. Participants were recruited through snowball sampling and extensive social media advertising. We provided a USD 50 gift card as gratuity for participation.

5.2 Method

We performed the study in two sessions. The participants first attended a 1-hour briefing and brainstorming session, in which we introduced them to SkinLink, demonstrated interactive examples, and explained the prototyping process. Participants then brainstormed ideas for an on-body interface design of their choice. During the brainstorming session, we would discuss with participants the SkinBoard circuit modules required to realize their idea, suitable adaptable trace options, the body location for deployment, and the desired aesthetic customization they wished to achieve. In the second session, participants came to the lab for a 3-hour time block to realize their project with SkinLink. In addition to the materials we provided on our end, such as silicone, silicone dye, and wires, the participants were allowed to bring their own cosmetic and body art supplies to decorate the devices. Participants then applied their designs to a model provided by our research lab. During the three-hour session, we demonstrated how to use the toolkit, assisted the participants in tasks unrelated to the design process (*i.e.*, testing circuit functions), and observed the users' prototyping process. After device construction and testing, we interviewed each participant for approximately thirty minutes to gauge their feedback and experience. We present the case study by transcribing the session video recordings and interviews based on the grounded theory approach [6]. We describe the participants' projects, the body craft techniques they incorporated with the SkinLink workflow, and the semi-structured interview results below.

5.3 Victoria's Project: A Heartbeat on the Cheek Figure 13a)

Victoria, a film makeup artist, described her practice as experimentation in creating abstract designs on the face. Unless there was a particular character need, she preferred creating interesting patterns that would retain the visibility of the skin and not obscure the face. Also experienced with prosthetic makeup, she often adds textures to the makeup layer by layering prosthetic silicone pieces in her practice. Her makeup practice follows color theory design principles, with the design fitting to the contour and anatomy of the face.

In her project, Victoria aimed to create intricate free-form curls and curved patterns on the face. She integrated a ***time-of-flight sensor*** and a ***haptic driver*** into her design. She placed the sensor on the forehead, the actuator on the cheek, and the MCU at the temple. Between the boards, she used two ***moldable trace modules*** to realize the detailed winding pattern of meandering vines. Inspired by the social distancing regulations during the

Fig. 13. (a) Victoria's project created a heartbeat on the cheek. She winded moldable trace modules to create intricate patterns paired with silicone prosthetics. The circuit consists of a time-of-flight sensor and a haptic driver. (b) Madison's project hid a proximity alarm on the forearm. She used a skin-tone foundation to camouflage the circuit with a thin layer of prosthetic skin. Four LED modules will light up gradually when the proximity sensor detects an object getting closer.

pandemic, she designed an interface that provides a vibration pulse feedback on the cheek when someone stands within two feet of the wearer. To decorate the interface with different colors and textures, she fabricated purple silicone strings and membranes to enhance the design visually. The silicone string intersected and contrasted with the metallic moldable trace module; the semi-transparent membrane covered the vibration motor, swelling and shrinking with the pulse. She aimed to create a "heartbeat on the cheek" (Figure 13a).

5.4 Madison's Project: On-Skin Proximity Alarm (Figure 13b)

Madison, a part-time makeup artist, values aesthetic harmony and realism in her practice. Instead of exposing any part of the circuitry, she was determined to conceal the entire device under a thin layer of prosthetic skin. With cosmetic products that matched the model's skin tone, she camouflaged the device to be nearly invisible on the arm by shaping prosthetic silicone and applying a liquid foundation to blend the circuitry with the skin.

The device consisted of four ***LED modules*** and one ***proximity sensor***. The sensor was situated between the thumb and index finger, the MCU was on the wrist, and four LEDs were spread across the forearm. She leveraged the ***stretchable trace module*** to connect the MCU and sensor, which allowed the wrist joint to bend freely. To connect the LED modules, she selected four ***flexible trace modules*** that conform to the forearm curvature with a minimum length for easy concealing. Madison designed the interface to represent her response to physical touch, which she described as pins and needles moving along her arm. The four LEDs lighted up sequentially from the point of contact toward her heart. Depending on the proximity, the LEDs displayed a color gradient that conveyed different warning levels (Figure 13b).

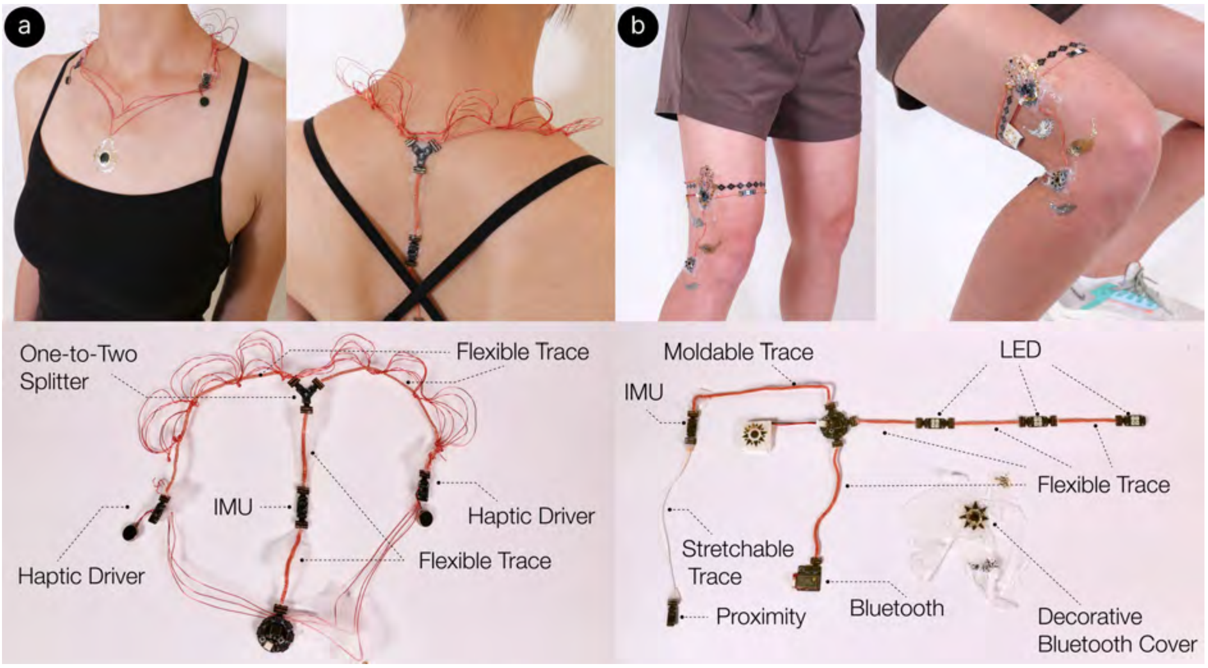

Fig. 14. (a) Ivy's project integrated on-skin circuitry into a hybrid form of filigree-like jewelry shaped with copper wire. The device can monitor the user's posture with an IMU sensor, which creates vibration feedback from the two haptic drivers when the user slouches. (b) Riley's project built a strength training posture trainer comprising a Bluetooth module, an IMU sensor, a proximity sensor, and three LEDs on the thigh.

5.5 Ivy's Project: Filigree On-Skin Jewelry for Posture Detection (Figure 14a)

Ivy, a part-time makeup and body painting artist, used bold lines to generate an expansive design spanning different body locales. She was particularly interested in the metallic aesthetic of the adaptable traces, which reminded her of filigree jewelry she had worked with before. In her project, she aimed to explore a hybrid form of on-skin circuitry paired with decorative filigree-like line jewelry. Using copper wire, she made a SkinLink circuitry decorated with a 3D line-form neckpiece. This was finally accented with a temporary tattoo at the collarbone (Figure 14a).

The device comprised one ***IMU sensor*** and two ***haptic drivers***. Ivy placed the IMU sensors and the MCU board module on the back, connecting them along the spine in a straight line. The IMU was also connected to a one-to-two splitter module that branches the circuit to two haptic driver modules on each side of the upper chest. The circuit function works as a posture-reminding device, vibrating when the user slouches. Ivy only used ***flexible trace modules***, which aligned with the anatomy of the chest and curvature of the collarbone. She hand-manipulated additional copper wires that linked the two vibration motors and shaped abstract, organic designs of thin metal loops around the neck.

5.6 Riley's Project: Strength Training Posture Trainer (Figure 14b)

Riley designs body-centric interactions based on e-textiles. In addition to her experience in software programming, she is also well-versed in creating customized wearable interfaces, from designing circuit boards to soldering electronic components. Riley designed a practical application of the SkinLink interface with multiple sensing and actuating functions and customized the circuit behavior by programming the MCU module. Although she had less professional experience in makeup, Riley chose to decorate the prototype with metallic temporary tattoos.

The circuit included a ***Bluetooth module***, an ***IMU sensor***, a ***proximity sensor***, and three ***LEDs***. Riley designed the device for monitoring strength training postures such as squatting (Figure 14b). The IMU sensor measures the tilting angle on the back of the thigh, while the proximity sensor on the leg keeps track of the distance between the thigh and the leg. After performing a cycle of squatting with the correct posture, the LEDs will light up, and the Bluetooth module will update the counts onto the smartphone. Riley used a ***moldable trace module*** to form a right-angle bend and a ***stretchable trace*** to connect the two sensors across the knee. She used ***flexible traces*** for the remaining connections between the LEDs.

5.7 Observations

5.7.1 Functional and Aesthetic Expressiveness. All participants were able to integrate electronics into their practice of makeup or body painting, ranging from silicone prosthetics, makeup foundation to copper wire art and temporary tattoos. The slim, skin-conformable form factor provided smooth circuit integration to different body locations, including challenging face, collarbone, chest, and thigh areas. Victoria commented on the small size of the circuit boards, which paired with the curved lines and face prosthesis of her design. Madison appreciated the flexibility of the circuitry, which conforms to the curved geometry of various body parts. It simplified her plan of concealing the circuitry with a natural look. Riley was able to integrate a complex on-skin circuitry of 6 circuit modules and six wire modules on her right thigh. She was amazed by the diverse functionalities of the circuit modules, which saved her from designing an integrated on-skin system from scratch.

5.7.2 Disclose or Disguise the On-skin Circuitry. Interestingly, participants held different perspectives towards aesthetic expression with the SkinLink interfaces. Victoria regarded the adaptive trace itself to have a futuristic aesthetic, so she wasn't interested in concealing or fighting the look of the board and trace modules. Instead, she exposed the whole circuit on the face and utilized soft silicone pieces to contrast with the tiny metallic circuit traces. On the other hand, Madison wanted to camouflage the entire circuit by blending it in with the skin. She left only the actuation module (LEDs) exposed to display visual effects when triggered. Ivy preferred blending in the circuit boards and traces with decorative elements of a similar material: copper wire. She wove extra copper wires in a filigree-like fashion into the SkinLink circuitry to complete her design. While their different attitudes toward the on-skin circuitry greatly affected the customization process after attaching the circuitry, all the participants appreciated the SkinLink workflow that enabled a wide range of possibilities for varying body crafting techniques.

5.7.3 Adaptive Wiring for Diverse Bodyscapes. All the participants considered the on-body adjustment during the application process critical in their prototyping process. Victoria described her process of adjusting the design after seeing the circuit applied to the face. "It's impossible to reach the ideal design with the first attempt; seeing the modifications on the body gives me direct feedback for adjustments." The on-body adjustment saved her significant effort from repeatedly detaching and reapplying the prototypes. Madison appreciated the ease of modification—when applying even the same design to different individuals, it is still necessary to make minor adjustments. Riley iterated the design multiple times on the body to optimize the choice of board locations and trace types. She mentioned that the on-body fabrication allowed her to go through a trial and error process so that she could complete the design on the go, even with little body art experience.

6 DISCUSSION

Comparing On-body Fabrication Assistance. SkinLink supports on-body prototyping through the replaceable modular circuit construction. To highlight the design concept, we can visualize the comparison with previous

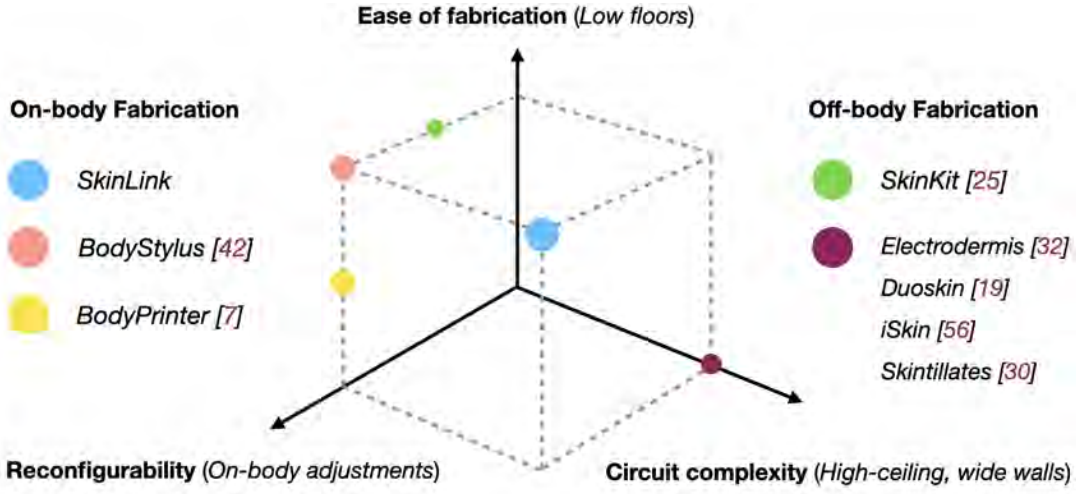

Fig. 15. 3-dimensional graph differentiating SkinLink from relevant approaches. SkinLink aims to support reconfigurability and circuit complexity while providing accessible tools (low floors) for a wide range of users.

work in a 3-dimensional vector space, as shown in Figure 15. Compared with other on-skin interface research, we see two directions of building on-skin interfaces: directly construct circuits on the body or prefabricate the circuit off-body. While on-body fabrication approaches often come with accessible building tools and allow fast re-constructions (reconfigurability), the circuit complexity is often limited. Building circuits off-body is the opposite direction that exchanges ease of fabrication with better circuit complexity. Our design aimed to combine the advantages of both approaches and assist users in the three goals–ease of fabrication, reconfigurability, and circuit complexity. By prefabricating the circuit parts and traces into modules, SkinLink does not require users' expertise in software/hardware skills such as circuit board design or soldering and still keeps the capability for designing complicated prototypes. In addition, the workflow inspired by SFX makeup provides critical experimentation opportunities to explore and iterate designs. As a result, SkinLink is currently the only on-skin interface fabrication method that assists the most complete prototyping process with the three aspects we identified and learned from relevant research.

SkinLink Designed for Whom? The motivation for the SkinLink project originates from our research team's nearly one decade of first-hand experience fabricating fitting yet adaptive on-skin interfaces. The original idea was to support experienced on-skin interface designers with suitable prototyping tools. However, the usability study showed positive learnability results, where participants without extensive prototyping experience could replicate a simple design. With the potential to be accessible for novice users, there are still gaps to fill to guide the process in detail, from constructing and programming the circuit to applying more complicated circuitry on the skin. On the other hand, we also learned from the case studies collaborating with more expert study participants with either design or technical experiences. As they all built their own practices of body arts or wearables, each modified and added to the instructed workflow to achieve their design. From the perspective of enabling "high-ceiling" (enabling increasingly sophisticated projects) and "wide-walls" (supporting a wide range of designs) for creative on-skin prototyping [26, 48], our goal is for SkinLink to serve as an extensible framework encompassing advanced implementations where experienced creators (e.g., designers, engineers, researchers) can repeatedly utilize the toolkit for rounds of iterative prototyping towards a more comprehensive design and also to support the generation of diverse applications.

Scalable Manufacture. To fabricate the PCB modules, our researchers designed the boards, soldered components, and programmed the software in-house. All the trace modules were also manufactured (except for the stretchable wire) and soldered with the connectors within the lab. While in this paper, we were able to evaluate and demonstrate the toolkit by manually fabricating all the materials, scalable manufacture of PCB and trace modules is desired to introduce and distribute SkinLink to broader communities at scale, as demonstrated by the impact of the precedent toolkit research such as the LilyPad Arduino [4]. While PCB manufacturers provide printing and assembling services, braiding and soldering the trace modules are the bottleneck for large-scale fabrication. One possibility is to leverage a customized braiding machine that performs braiding patterns or to engage in collaborative manufacturing with conductive wires or yarn manufacturers. Another possible way to replace the soldering process is to design a crimping connector that grips the braided copper wires by pressure.

Practical Wearability Issues. SkinLink aims to offer an enabling toolkit for rapid on-skin interface design iterations rather than fabricating interfaces for long-term usage. However, the fabrication workflow that leverages prosthetic makeup techniques can potentially address wearability concerns around waterproofing and robustness against wear and tear. During the study, participants applied prosthetic silicone onto the circuit traces and board modules. The silicone formed a protection layer, which did not interfere with the circuit function and helped all the circuits become waterproof and remain well-attached throughout the study process. Nevertheless, conducting a longitudinal usability study can help characterize the circuit's robustness, waterproofing, and power consumption. Currently, the power supply relies on the Lithium Ion thin film battery, which can last up to three hours for a typical circuit with less than four peripheral modules. To address the need for changing batteries, we plan to integrate remote charging circuitry in future work.

Extending the ToolKit. We designed the Microcontroller Board (MCU) to support multiple communication protocols, including I2C, SPI, UART, and GPIO. Users with knowledge of circuit design can extend the module library with personalized sensors and actuators. We've explored different braiding materials and techniques to implement the four trace modules. However, additional design variations are possible through different core materials or alternative stretchable conductors such as liquid metal [50] or serpentine trace patterns [25]. In this work, we relied on an extender module to connect two trace modules for longer circuitry, as each trace module currently has fixed lengths of 4cm, 8cm, and 12cm. For future improvement, we plan to develop fabrication methods to make traces with arbitrary lengths from rolls of braided wires.

7 CONCLUSION

We present SkinLink, an on-body fabrication approach for prototyping on-skin interfaces by leveraging prosthetic makeup techniques. To support the workflow, we developed a customized construction kit that comprises adaptive traces and tiny flexible printed circuit board modules with different sensing and actuating functions. Inspired by SFX makeup techniques, SkinLink enables fabricating, applying, and blending the on-skin circuitry with the wearer's body as a slim prosthetic. Benefiting from the prosthetic silicone's plasticity, the circuitry is adjustable during the application process, where the designer can fine-tune the prototype's shape, structure, and location. Aesthetic customization can go on the surface without interfering with circuit functions. We described the design, fabrication, and technical evaluation of the toolkit. A 14 participants usability study compared with a baseline on-skin construction kit, SkinKit, shows the advantages of the SkinLink approach in design flexibility, ease of modification, and module size. Three case studies with makeup artists demonstrate the design extensibility of SkinLink by incorporating elements of their existing makeup, body art, and prosthesis art practices. One case study with a wearable interface designer demonstrates the toolkit's potential to integrate multiple sensing and actuating units to address a more complex application scenario. SkinLink provides methods for "high-ceiling" and "wide-wall" prototyping and expressive customization [48], which enriches the field of UbiComp and HCI by broadening the participation of makers, artists, and crafting communities in hybrid on-skin designs.

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