SkinKit: Construction Kit for On-Skin Interface Prototyping

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The emergence of on-skin interfaces has created an opportunity for seamless, always-available on-body interactions. However, developing a new fabrication process for on-skin interfaces can be time-consuming, challenging to incorporate new features, and not available for quick form-factor preview through prototyping. We introduce SkinKit, the first construction toolkit for on-skin interfaces, which enables fast, low-fidelity prototyping with a slim form factor directly applicable to the skin. SkinKit comprises modules consisting of skin-conformable base substrates and reusable Flexible Printed Circuits Board (FPCB) blocks. They are easy to attach and remove under tangible plug-and-play construction but still offer robust conductive connections in a slim form. Further, SkinKit aims to lower the barrier to entry in building on-skin interfaces without demanding technical expertise. It leverages a variety of preprogrammed modules connected in unique sequences to achieve various function customizations. We describe our iterative design and development process of SkinKit, comparing materials, connection mechanisms, and modules reflecting on its capability. We report results from single- and multi- session workshops with 34 maker participants spanning STEM and design backgrounds. Our findings reveal *how* diverse maker populations engage in on-skin interface design, *what* types of applications they choose to build, and *what* challenges they faced.

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

Additional Key Words and Phrases: On-skin interfaces, wearable computing, soft circuitry, construction kits

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1 INTRODUCTION

On-skin interfaces, which often come in the form of smart tattoos [35, 44, 77] or bandages [45], are an emerging form of wearable computing. They expand the sensing capabilities of current mobile and wearable devices by

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Fig. 1. We introduce SkinKit, a new construction toolkit for on-skin interface prototyping. (a) The modules are made of slim, skin-conformable tessellated base substrates, with Flexible PCB blocks which would be worn on diverse body locations. (b) The SkinKit system. Three wire module connection types provide flexibility for different body locations. An exploded diagram shows the components mounted onto the PCB and in the wire module. Different types of PCB modules can be distinguished by the color codes.

facilitating direct access to signals that represent people's physiology. Their slim and conformable form factor holds great promise in realizing Mark Weiser's vision of a truly *invisible computer* [78] for pervasive healthcare [14], elderly assisted living [9], and the future of work [8].

While prior on-skin interfaces have suggested benefits to society, the difficulty of prototyping on-skin interfaces is limiting progress in this nascent yet potentially transformative field. Sitting between physical and digital realms, the field of on-skin interfaces has attracted makers of all stripes—ranging from STEM researchers [35], artists and craftspeople [70], to elementary school students [4]—to make their own on-skin devices. However, the high bar in realizing a skin conformable form factor—including achieving needed softness, slimness, and flexibility—has limited wider access to this field. Even for experienced research teams, quick prototyping in the exploratory stages of the design process remains a challenge. These challenges include a generally-long fabrication time for a single device (3.5—11 hours [27, 34, 77]), fixed circuit layout after fabrication, and not supporting quick form-factor preview on different body locations. To overcome the aforementioned challenges, we adopt a plug-and-play approach from the rich history of tangible-digital physical toolkits [12, 13, 38, 52]. By encapsulating the prototyping process into modualar connection of "smart tattoo blocks", we develop a re-configurable, reusable, and extensible prototyping toolkit for on-skin interfaces.

Nonetheless, realizing a modular kit for on-skin interfaces demands breakthroughs regarding the form factor and connection mechanisms. While existing electronic connection techniques (*e.g.*, pin headers or snaps) are fast and straightforward, they are often rigid and bulky [3, 30, 64]. On the other hand, making a slim and flexible connection with methods such as sewing with conductive thread is time-consuming, and not adjustable for trying different circuit layouts [1, 18, 37]. To fill this missing yet critical gap, we extensively tested different connection methods as well as module materials, and came up with a system structure that separates the circuit construction into two two main components: (1) single-function modules made of pre-programmed slim, flexible printed circuit board (FPCBs), and (2) slim, flexible, and skin-conformable substrate pieces made of silicon-based tattoo paper that serve as the infrastructure connecting the functional modules, and a base that conforms and adheres to human skin. The PCB modules were made to be reusable, reconfigurable, and easy to attach/detach, enabling extensible circuit function customization. The flexible wire modules help overcome challenging body locations and provide stable power transmission and signal communication between the PCB modules.

SkinKit aims to lower the barrier for creating on-skin interface prototypes that can be tested on the human body directly and serve as a unique platform to explore the integration of electronics with soft materials. Two user studies were conducted to evaluate SkinKit's usability. We first conducted a single-session workshop to gain insights for design improvement. Nine participants with backgrounds spanning design and engineering joined the study, providing us feedback in multiple aspects including form factor, functionalities, and aesthetics, leading us to an improved version of the SkinKit. After finalizing the design of SkinKit, a final, multi-session user study with 25 participants was performed to evaluate SkinKit through a complete on-skin device prototyping process from ideation, implementation, to wearing on skin. The final study enables us to conduct novel assessments of how diverse maker populations build on-skin interfaces, including how they approach the process, the type of applications they want to build, and how they envision the technologies integrated in everyday life. Our findings show that makers from diverse backgrounds can easily and successfully prototype a fully-functional on-skin device from scratch in less than 23 minutes on average. A broad range of personally meaningful applications were developed, with aesthetic customization using various materials. The prototypes can also be worn on challenging body locations not afforded by existing wearable devices.

We list the following contributions of this paper:

- SkinKit, the first modular on-skin interface prototyping toolkit which includes tangible plug-and-play Flexible PCB modules and custom on-skin substrate design for slim, flexible, and quick circuitry routing on the skin, drastically lowering barriers to on-skin interface prototyping.
- Findings from the single- and multi-session evaluative workshops with 34 maker participants, revealing *how* diverse maker populations engage in on-skin interface design, *what* types of applications they choose to build, and *what* challenges they face.

2 BACKGROUND AND RELATED WORK

2.1 Wearable Computing and the Rise of On-Skin Interfaces.

Since the advent of wearable computers nearly three decades ago [61, 68, 69], they have taken the dominant form of body-mounted devices (watches, accessories or "pod"-like devices) [7, 40, 59, 67, 84], or clothing (garment-integrated computing) [57, 75]. Body-mounted devices tend to protrude from the body (limiting wearability), require users to remember and don the device daily, and generally confine the technology to one body location. Garments do not suffer from these challenges, yet launderability and the anthropometric challenges of precise fit for effective sensor placement have hindered widespread use. A new form factor, *on-skin interfaces*, has emerged only in the past decade mostly because of the recent extreme miniaturization of sensor devices and breakthroughs in soft, biocompatible materials. They have rapidly gained traction as the next generation of wearable computers [14] because they generally do not suffer from the aforementioned drawbacks of body-mounted devices and clothing, are seamless to wear, and directly contact the skin for precise and always-available biomonitoring to realize pervasive healthcare.

Early work in on-skin interfaces stemmed from the material sciences in which *epidermal electronics* [11, 41, 83] were used to monitor various physiological signals. However, they often entail expensive clean-room facilities and manufacturing costs [5, 80]. Since 2015, the HCI and wearable and ubiquitous computing communities have developed inexpensive fabrication approaches that can be performed outside of clean-room settings, developing interfaces for sensing touch input [24, 35, 44, 50, 71, 76, 77], displaying output [32, 35, 74, 77], providing haptic feedback [25, 79], and texture-change [33]. The fabrication processes of these on-skin interfaces in HCI often adapt existing digital fabrication techniques to accommodate thin materials. Methods include laser patterning [76, 77, 79], inkjet printing [44, 49, 50], ink deposition [20, 58], lamination [45], embedding [25], molding and casting [33]. These novel techniques aimed to achieve fast and low-cost fabrication of on-skin interfaces for an arranged set of functions but did not support function-wised customization.

As an emerging fabrication realm, on-skin interfaces focus on affording technical function and often require specialized materials, engineering expertise, and access to digital fabrication tools. This limits nontechnical makers who seek to prototype on-skin interfaces; they cannot begin due to a lack of *low floors* (easy to begin)[60]. *This project aims to bridge this gap by developing easy-to-access tools and processes that enable people to easily begin.*

Table 1. Comparison between SkinKit and previous e-textile/wearable construction toolkits. Properties of SkinKit include skin conformability, free-form layout for different on-body placements, reconfigurable components to support an iterative design process, and exploiting a decentralized programming logic for the modularized system structure.

Property	**LilyPad**	**TeeBoard**	**EduWear**	**i*CATch**	**Flora**	**MakerWear**	**Brookdale[64]**	**Snowflakes**	***SkinKit***
Skin-conformable	X	X	X	X	X	X	X	X	O
Free-form layout	O	X	O	X	O	X	O	O	O
Reconfigurable	X	O	X	O	O	O	O	O	O
Decentralized	X	X	X	X	X	O	X	X	O
Modularized	X	O	O	O	X	O	O	O	O

2.2 Wearable Computing and E-Textile Construction Toolkits.

We aim to *lower the floors* [60] for making personally meaningful on-skin interfaces through building construction toolkits [65, 66]. The use of kits is grounded in the education philosophy of Papert's constructionism [51], which underscores the compelling learning experiences of building things by hand. By providing a set of sewable, Arduino-compatible microcontrollers and electronics, wearable toolkits such as the LilyPad Arduino [17, 18] and Flora [1] have emerged as a powerful media for engaging diverse populations in computing [23, 29, 37, 46, 48, 63]. However, they require programming, knowledge of electronics and circuits, and manual skills such as sewing/soldering, resulting in high-barrier to entry for some users. Besides, sewing conductive thread makes permanent connections. From the perspective of prototyping, this limits the reconfigurability of changing circuit parts. Other electronic textile (e-textile) toolkits including TeeBoard [46], i*Catch[47, 48], EduWear [37], and fabrickit [3] have sought to increase accessibility through platforms that preclude sewing [6, 10, 16, 21, 43, 46–48, 54, 55, 72], and/or by adopting modular architectures [12, 42, 46, 48, 64, 73] and visual programming aids [37, 48, 64]. Besides prototyping smart clothing, SnowFlakes developed a modular toolkit that helped designers explore computational jewelry designs that satisfied form qualities of non-smart jewelry [19]. Indeed, the kits above attempt to simplify aspects of building wearables, but they all adopt a traditional embedded systems module of a centralized processing hub to many peripherals approach that requires interfacing with a computer to write, compile and download code. MakerWear [38] is a significant move towards a *tangible* approach of programming wearable design through plug-and-play. MakerWear builds upon prior tangible digital-physical toolkits designed primarily for robotics, such as Cubelets [2], littleBits [13], and Electronic Blocks [81, 82] where behaviors are 'programmed' by connecting simple, single-function electronic blocks in unique sequences (*e.g.*, sensor blocks to action blocks). MakerWear makes a move into the realms of wearable computing and has a demonstrated effect in further decreasing barriers for diverse end-users. We aim to adopt a similar plug-and-play approach for our on-skin kit. However, creating a skin-conformable modular toolkit would require breakthroughs in multiple aspects. The form factor of fabricated devices needs to be sufficiently slim for on-skin wear, and the connection methods between modules need to be robust against various body locations and movements. An implementation of reconfigurable circuit construction is also necessary to support iterative prototyping. Moreover, e-textiles kits mentioned above cannot be adopted for on-skin wear, due to their connection methods of either sewing into packaged Printed Circuit Board (PCB) through-holes [1, 18, 31, 37], or the use of snaps [3, 30, 46–48]. Even though they are suitable for prototyping textiles, typical PCB or snap-integrated fabric components are too thick for on-skin wear. They are also not designed for attachment to the skin. Above all, the biggest challenge for an on-skin prototyping toolkit lies within the trade-off between a suitable form factor and a fast, detachable connection method. To this end, on-skin interface kits require a new examination of the suitable materials and methods. Table 1 shows the comparison of SkinKit and other construction toolkits. We consider the five properties listed in the table as the essential qualities that contribute to a low-floor on-skin prototyping toolkit, which previous work has not met. Posch [56] also highlighted the need for kits that can support the creative exploration of alternative slim materials (*e.g.*, silicone) beyond textiles and paper; this project directly contributes to such exploration. *This project aims to expand the form factors of construction kits beyond e-textiles and robotics to the emerging field of on-skin interfaces, broadening the material library for construction kits.*

3 SKINKIT

The implementation of SkinKit involves material, mechanical, and hardware design. We highlight the design considerations for an on-skin prototyping toolkit as following:

(1) Suitable form factor for attaching to the skin.
(2) Robust yet slim connection mechanisms between the modules.
(3) Reconfigurability of the circuit components for extensible prototyping.
(4) Fast and flexible device prototyping that allows iterative design process and quick on-body preview.

A typical SkinKit circuit is composed of two kinds of modules: PCB modules and wire modules, and requires three traces connecting each module, including the power, ground, and signal line. Each PCB module works contingently with the received signal and generates the output signal for the next module. The wire modules serve a primary function as the power and communication infrastructure of the PCB modules. They consist of three traces made with conductive fabric tape (Gennel conductive cloth fabric adhesive tape) adhering to the slim and flexible skin cloths.

As shown in Figure 1 (b), the main structure of a SkinKit circuit involves a flexible printed circuit board (FPCB) connecting to traces on two wire modules with the help of small magnets (Deryun mini magnets; 2mm in diameter, 1mm thickness). The top layer, FPCB, comes with six magnets in two rows with opposite polarity, sitting on both ends of the board. The magnets were adhered to the FPCB, and a protective layer of nail polish was applied to secure the magnets. Following the FPCB, we have two pairs of three conductive traces aligned with the magnet position adhering to the wire modules, which helps to connect the power, ground and signal lines between FPCB modules. Another set of six magnets are located underneath the traces on the surface of each wire module. As we designed the magnet pairs to hold opposite polarities, the board and the traces are sandwiched between the two magnet sets by the magnetic attraction, thus form stable electric connections [26]. Below we present the details of each part of the implementation.

3.1 Material Design

To achieve an on-skin form factor, extensive prototyping iterations were devoted to making a slim but durable skin substrate that is skin-safe and comfortable to be worn on skin. Based on the testing results amongst different materials such as cotton, silk, and silicone, we ended up with a fabrication process that creates a multi-layer thin

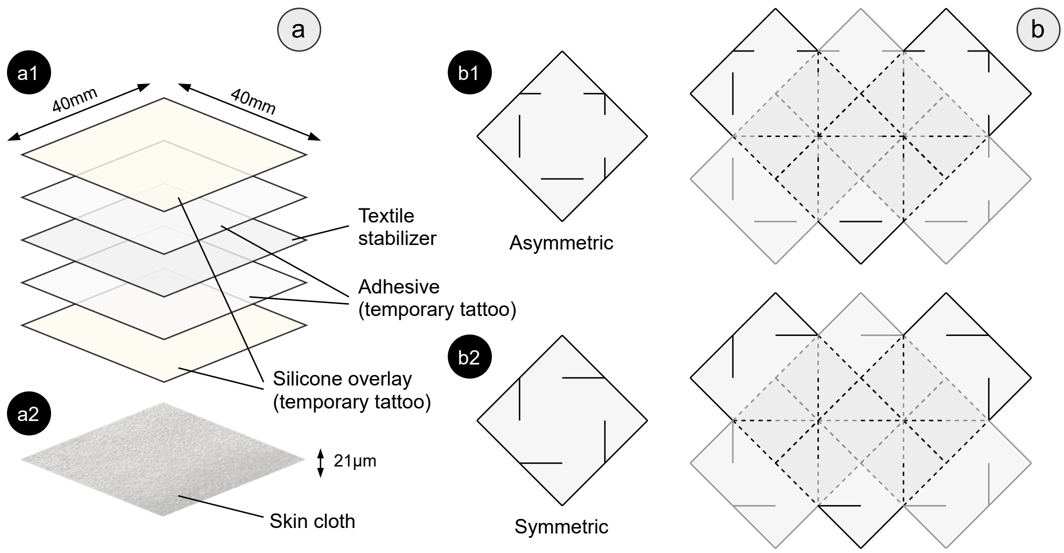

Fig. 2. Skin cloth (a1) design exploded diagram, (a2) photo, and two tessellation designs: (b1) asymmetric and (b2) symmetric.

film structure to meet our requirements. We named the skin substrate as *"skin cloth"* since it has a slim form factor that is conformable to skin, and compatible with hand sewing or embroidery techniques. The skin cloth is made of tattoo paper (Silhouette temporary tattoo paper) and textile stabilizer (Sulky water soluble stabilizer). The fabrication process of the skin cloth is detailed below:

(1) Attach adhesive to two pieces of the tattoo paper. Apply the double-sided adhesive included in the temporary tattoo paper package to two pieces of tattoo paper on the side of the silicone layer.

(2) Sandwich the textile stabilizer between tattoo papers. Cut a piece of textile stabilizer in the same size as the tattoo paper, and adhere the tattoo papers on both sides of the stabilizer. Press and remove bubbles between the layers to ensure good adhesion.

(3) Shape and cut the processed material into skin cloths. Apply water on both sides of the material. The paper backings can be lifted up easily when they're wet. Wait until dry, then cut the material into specific dimensions with the electronic cutting machine.

The structure of the custom fabricated skin cloth consists of two silicone layers, two adhesive layers, and one layer of textile stabilizer in the middle (Figure 2 (a)). To allow users to tinker and customize the outlook of a device with more expressive layouts, we referred to *tessellation* techniques [28, 30] to combine small pieces of skin cloth into different shapes. Tessellations [28] adopt the concept of "minimum inventory and maximum diversity" and are embraced in design fields for benefits of standardization along with customizability for personalization. We designed the diamond shape of each skin cloth with a 4cm side length. The male/female cutting lines can be used to tessellate multiple skin cloth pieces into one seamless panel. We evaluated two tessellation designs, asymmetric and symmetric, in the pilot and final study, accordingly. We observed that participants spent less time tessellating with the symmetric design. Besides the fact that the symmetric design doesn't require orientation alignment, most of the participants also reported that it is easier to work with the symmetric skin clothes. Figure 2 (b) shows the two designs of tessellation.

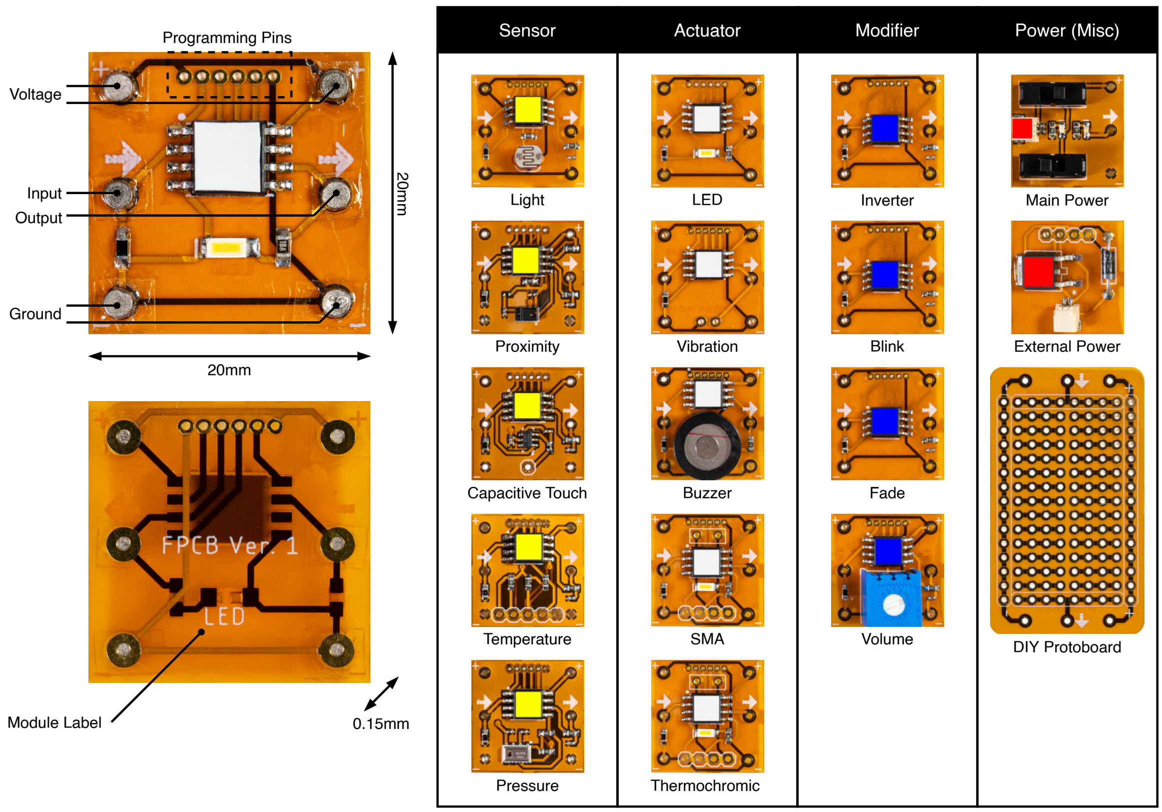

Fig. 3. FPCB dimensions and current module list.

3.2 Hardware Design

SkinKit enables users to create on-skin prototypes by manipulating tangible plug-and-play modules. We scaffolded identified sensors and actuators into individual modules. We extend the approaches of tangible digital-physical toolkits [2, 13, 38, 62, 81, 82], which are "programmed" by connecting simple, single-function electronic blocks in unique sequences (*e.g.*, sensor blocks to action blocks). Programming experience (from user input to output) is tangible, without the need for a computer. Creations work instantly as the modules are connected, allowing for improved tinkering [15].

The current platform consists of single-function, tangible programming modules that, when attached, create elaborate, interactive behaviors. Drawing from our iterative prototyping observations and related work in functions afforded by existing toolkits [2, 13, 38] and on-skin interactions [34, 35, 45, 76], our hardware design includes 16 types of FPCB modules (Figure 3), distinguished by different colors: (1) *sensor* modules (yellow) that sense input and generate data (*e.g.*, light levels, skin temperature, barometric pressure); (2) *actuators* (white) that consume data and react accordingly (*e.g.*, displays, haptic feedback); (3) *modifiers* (blue) that transform input signals to other output signals (*e.g.*, blinkers, inverters) (4) *power and miscellaneous* modules (red), in which miscellaneous includes a DIY electronic module for building with raw electronic components. The dimension of the board is 2cm in width and length and 0.1mm in thickness. We designed the circuit to have all components soldered on the front side to reduce thickness and conform to the skin better. Each sensor/actuator/modifier module contains a pre-programmed microcontroller (ATtiny85). Software customization is also available via the programming pins on top of each module. Six metal pads at the bottom surface align with the power, ground, and signal lines. As shown in Figure 3, two silk screen printed arrows on the front sides show the direction from input to output, which helps the user identify the orientation of the module and construct the circuit sequence.

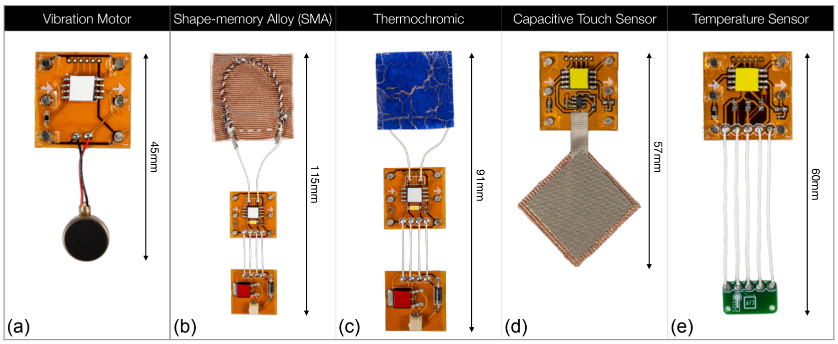

Fig. 4. (a) The vibration motor is extended from the board to contact the skin directly. (b) The SMA module contains a coil extension that contracts with heat. (c) The thermochromic extension is created using thermochromic pigments that change color with heat [36]. (d) The capacitive touch sensor contains an extended touch surface covered by conductive fabric tape. (e) The temperature sensor is extended away from the main circuit board for contacting the skin directly.

Fig. 5. The stretchable module is made of stretchable Kinesio tape. 3 insulated copper wires are sewn in a serpentine pattern to conduct current without obstructing the stretchiness.

Many of the PCB modules consist of extended elements for their functionality. As shown in Figure 4, these extensions could either be sensors (*e.g.*, capacitive touch, temperature), actuators (*e.g.*, vibration motor, shape-memory alloy (SMA), thermochromic), or external power. Extending these elements allows re-positioning a sensor or actuator at a different body location away from the main circuit (*e.g.*, temperature sensor).

Regarding power analysis, individual modules draw between 2 to 11.7 mA (M = 2.7 mA) for sensors and 7.3 to 35.8 mA for actuators (M = 8.7 mA). The two actuator modules (SMA, Thermochromic) would draw additional 1023 and 166 mA from the external power when actuating, which are typical values for heating circuits. A 7-module circuit with the most power consuming actuators draws 72.36 mA (active) and 42.33 mA (inactive), while an average 4-module design draws 33.43 mA (active) and 28.22 mA (inactive).

3.3 Mechanical Design

The connection mechanism of a SkinKit circuit is critical in providing customizability, flexibility, and robust circuit connections to the prototyping process. A SkinKit circuit involves two kinds of connection: 1) between wire modules and 2) between a PCB module and a wire module. The former helps form the layout of the circuit, determine the appearance of the device, and overcome challenging body locations. The latter is required to attach and detach the FPCB to and from the skin cloth easily but remain electrically conductive, conforming even to convex and concave skin surfaces. We describe the designs of the two connection mechanisms as following.

3.3.1 Wire Connection. Built on the skin cloth, the wire modules can be tessellated to each other, providing a weak mechanical connection. While this connection is strong enough for previewing the appearance of the device, additional support is required to ensure stable electric signal transmission along the three traces on the wire modules. We exploit the magnetic attraction between pairs of disc magnets to connect the wire modules. By installing the tiny magnets below the traces, the magnetic force can clamp traces onto each other and form a

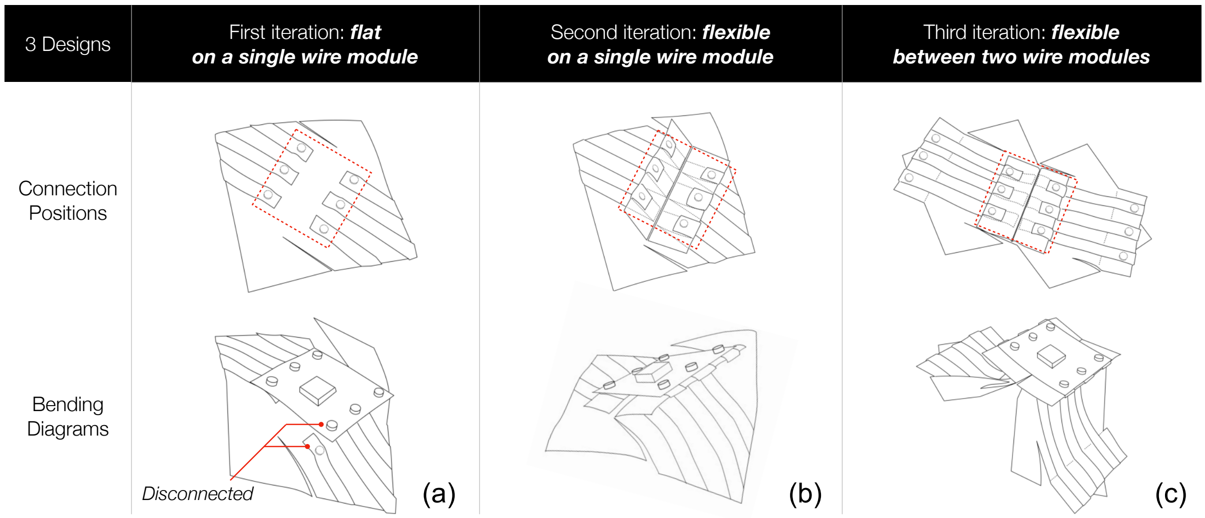

Fig. 6. Iterative design of PCB connections: flat, flexible on a single piece, and flexible between two pieces.

stable connection. Though the magnets increase the thickness at the connection point by 2mm, this mechanism is easy to engage/disengage and preserves strong enough bonding after repeated use.

3.3.2 PCB Connection (Figure 6). Similar to the wire connection, we leveraged magnetism to connect a PCB module to a wire module for the following reasons:

(1) Detachable PCB connection. Based on the design objectives, we expect the PCB modules to be reusable. The magnetic connection enables easy attachment/detachment.
(2) Automatic alignment. The magnets help prevent misalignment or shifting happening at the connection positions.
(3) Consistent signal direction. The magnetic connection only works when the polarities are opposite on the two connecting parts. The different polarities on the two magnet pairs ensure the connection of the PCB modules is always in the same orientation that follows the input-output signal direction.

Though we made the PCB modules with flexible printed circuit boards (FPCB), certain rigid electronic packages constrain the flexibility, making the modules not fully bendable. In other words, the main obstacle in designing the PCB connection is to preserve the flexibility of the soft skin cloth conformed to the skin after attaching the PCB module to it. As shown in Figure 6 (a), we first directly placed the PCB module on the central region of the skin cloth but found the rigid board failed to remain connected with the wire module when bending occurs at a curvy body location. To overcome the bending issue, we introduced an additional layer – named a "flap structure" – on the wire module. The flap structure is made of skin cloth, with a dimension of half the width of the PCB module (10 mm) and 28 mm in length. One side of the flap is connected to the bottom skin cloth piece by the three traces (conductive fabric tape), and three magnets are installed below the ending parts of the traces in alignment with the PCB magnet set. We first placed two flaps in the middle of the wire module as the holder of the PCB (Figure 6 (b)). The flap structure acts as a movable joint that prevents the PCB from falling off while bending. In our last iteration of the design, we aligned the wire connection and PCB connection across two wire modules, as shown in Figure 6 (c)). By doing this, we aimed to simplify the design and reduce the number of connection points required for connecting both PCB and wire modules, which also lead to an overall better electrical conductivity of the device.

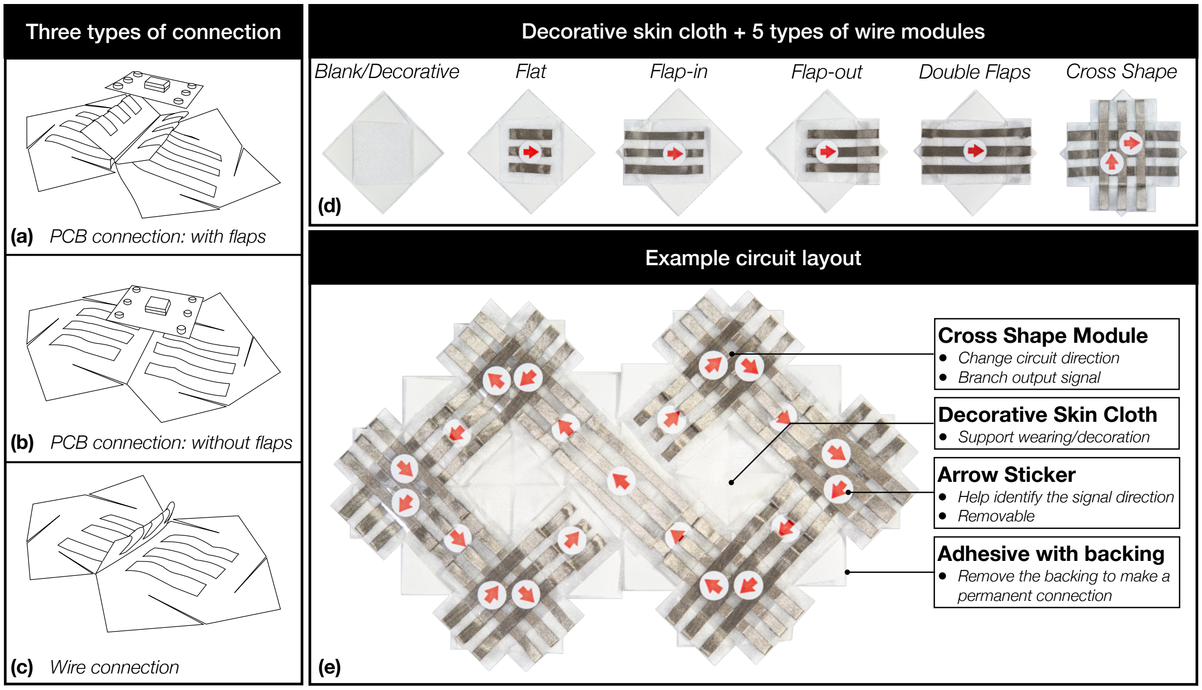

Fig. 7. (a) PCB connection with flaps. (b) PCB connection without flaps. (c) Wire connection. (d) 6 types of circuit units: 5 wire modules and 1 decorative module. (e) Example circuit layout.

3.4 Laying out a SkinKit Circuit

With all the design iterations we've gone through, we finalized five wire modules, as shown in Figure 7, along with one blank (decorative) skin cloth module, and 16 PCB modules, to construct the current version of SkinKit. Three types of connection are then recommended to be used in different situations. Figure 7 (a) shows a "flap-to-flap" connection, where two wire modules with flaps are connected by tessellation, and a PCB module sits on both wire modules' flaps. The flap structure ensures a more stable connection, so we suggest using this type of connection for curvier body locations. A slimmer alternative, shown in Figure 7 (b), is the "flat-to-flat" connection, where neither wire module has the flap structure. We suggest this type of connection be used on a flat and smooth body surface, where the form factor is more demanding than flexibility. The wire connection is realized by the so-called "flap-to-flat" connection shown in Figure 7 (c), where the flap structure folds toward the flat structure, and the two magnet sets attract each other to form the connection. Since no PCB module is connected in this case, users can use the wire connection to extend the circuit, circumvent certain body parts, or rearrange the device for a different geometry.

We listed the 5 wire modules and 1 decorative module in Figure 7 (d). From left to right, we have blank, flat, flap-in, flap-out, double flaps, and four-way cross shape modules. The main difference between the flap-in module and flat-out module is the magnet polarity, which is designed to always match the signal direction (input to output) of the PCB modules. We also added arrow stickers on the wire modules for users to recognize the signal direction easily. They can align the arrow with the ones on the PCB modules to match the magnetic polarity. The cross shape module can make a turn of the circuit or branch the circuit into two ways. An example circuit layout is shown in the Figure 7 (e). The one and only rule in combining the wire modules is to keep the signal direction consistent, which one can easily abide by following the arrows on both wire and PCB modules.

An additional wire module, named stretchable module (Figure 5), was introduced in the final study. The stretchable module allows the SkinKit circuits to extend over highly bendable joints, such as the elbow or the knee. The intention is to allow SkinKit to not be hindered by complex body locations and allow for greater customization and flexibility for where the user can choose to wear their device. The stretchable module is bounded by two triangle pieces of wire modules, in order for it to be compatible with the rest of the available skin cloth pieces.

3.5 Prototyping Work Flow

We summarize the prototyping work flow of SkinKit into the following three steps:
(1) Build and test the circuit sequence. Based on the design, users pick several PCB modules to compose the circuit of the prototype. All programs start with a power module, which always outputs the maximum signal. Connecting power → actuator shows the actuation directly when the power switch is on. To make the device interactive, one can add a sensor module before the actuator to control the signal with either user or environmental input. For example, connecting power → proximity sensor → LED actuator results in an interactive device where the LED lights up whenever an object approaches the sensor. The modifier modules can fine-tune the circuit with preprogrammed functions. Inserting one modifier into the previous sequence, power → proximity sensor → blink modifier → LED actuator, would modify the LED to blink when an object is sensed. Designing and testing the circuit combination can be done on any surface, such as a table, where users can swap modules or change the order of module sequence easily.
(2) Layout the circuit with wire modules. This part involves tessellating wire modules and blank skin cloth modules to create the placeholders for PCB modules and outline the size and shape of the device. Users would utilize the five wire modules and make the three types of connections depending on their needs. Users can design the layout considering the following questions: Where the device would locate on the body? Does the PCB connection need to be flexible? How many PCB modules will be used? What shape of the circuit would fit the body surface best?

(3) Wear and preview the device on the body. One key feature of SkinKit is the reconfigurability of both the wire and PCB modules. Users can preview their prototypes on the body with the temporarily constructed device while the flexibility for layout or circuit modifications is preserved. The first two steps can be repeated before making permanent connections of the wire modules, where the tessellations would be secured by double-sided tape. Once the permanent connections are made and the circuit order is confirmed, users can decorate their device, and apply the medical level double-sided adhesive to adhere the device on their body.

4 STUDY 1: SINGLE-SESSION WORKSHOPS WITH INITIAL PROTOTYPE

To gain a preliminary understanding of *how* and *what* makers can build with SkinKit and to uncover usability issues, we started by conducting a 90-min single-session user study. Our findings were used to refine our final prototype as well as our workshop procedure.

4.1 Method

4.1.1 Apparatus. An initial set of 9 PCB modules were used in this study: three sensors (proximity, light, capacitive touch), three modifiers (volume knob, fade, inverter), two actuators (LED and vibration motor), and one power module (powered by a battery). We exploited the asymmetric tessellation design (Figure 2 (b)) for the wire modules. Participants used a double sided medical grade tape (Vapon clear tape) to affix the SkinKit prototypes on their bodies.

4.1.2 Participants and Session Structure. Nine participants took part in the study: seven females and two males, ages 20-51 (M=28). A pre-study survey was used to collect participants' demographic data and past experiences

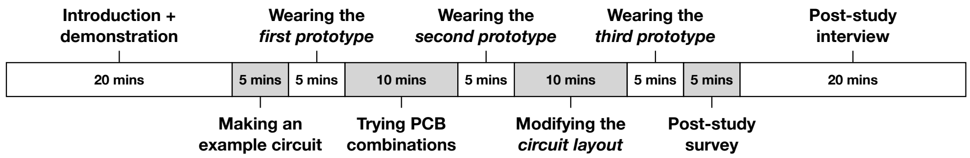

Fig. 8. Study 1 session structure.

with programming, electronics, arts and crafts, and textiles. Five out of nine participants have STEM background (*e.g.*, Information Science, Electrial/Mechanical Engineering) and four participants have design background (*e.g.*, Fashion/Product Design). The study session lasted around 90 minutes, with a team of two researchers facilitating the study:

(1) SkinKit Intro (20 mins). We first explained the workflow of SkinKit and how different types of modules work in a brief introduction. Participants also practiced with one instructive task in this stage.

(2) Building and Wearing SkinKit (45 mins). To understand how participants learned and worked with SkinKit, we designed three tasks, each increasing in complexity and decreasing in constraints. For Task 1, participants were asked to create a simple circuit with designated four PCB modules and four wire modules. For Task 2, participants were asked to construct a circuit with a self-selected set of PCB modules on the same wire modules layout created in Task 1. Finally, participants were asked to create a different layout of the wire modules (*e.g.*, a non-linear shape) and decorate the device with provided additional material (*e.g.*, stickers, marker pens, washi tapes) in task 3. At the end of each task, participants were asked to wear the prototype on their preferred body locations and interact with it.

(3) Post-study survey and semi-structured interview (25 mins). Survey questions in a 7-point Likert scale (1=strongly disagree and 7=strongly agree) were listed in the post-study survey to understand participants' feeling about the size, robustness of the modules and the application/removal process. The semi-structured interview questions were designed to get more in-depth responses and dealt with (1) the learnability of the SkinKit modules, (2) participants' opinions on how and at what stage of the prototyping process SkinKit can be useful, (3) wearability and form factors, (4) preferred body locations, and (5) participants' suggestions on how the kit can be improved.

4.1.3 Analysis. Audio recordings of the semi-structured interviews were manually transcribed to identify salient themes. All qualitative data underwent iterative coding by three researchers independently to identify common themes with a reasonable degree of agreement.

4.2 Findings

We describe key themes and common patterns related to prototyping with the initial version of SkinKit.

4.2.1 Making with SkinKit. All nine participants were able to complete the designated tasks during the study. Results from the post-study survey and interview indicate participants found it straightforward to combine multiple circuits using SkinKit (Median (M)=6 on the Likert scale; 1=strongly disagree, 7=strongly agree), and they reacted positively about the overall prototyping process (M=6).

Overall, participants found it very intuitive to work with the PCB modules, largely due to the use of magnetic connection mechanism and color-coding of the PCBs which make them easily recognizable. Participants also liked the aesthetic of the device and customizing their device through decoration. They reported that the "metallic look" of the traces was aesthetically pleasing (P8), and the prototypes made using SkinKit "could make a very interesting piece of jewelry" (P2).

4.2.2 Wearing SkinKit Device. We evaluated the wearability of SkinKit modules. Overall, participants were neutral about the size of the individual modules (Median (M)=4 on the Likert scale; 1=strongly disagree, 7=strongly agree), though a few participants expressed desire for slightly smaller modules during our interview session. Participants' intention to wear multiple modules in a limited space on their desired body location (*e.g.*, hand, wrist) largely dictates their responses. Interestingly, we noticed mixed reactions to the thickness of the modules. Participants reported that the thickness of the modules was fine (number of participants (n)=4), bulky (n=2), and slim (n=2).

When asked about the robustness of the circuit on the skin, most participants reported the device remained well attached to their body and it didn't fall off after wearing the device (M=6). Participants also reported that the SkinKit was very comfortable to wear (n=5, M=6). Most of the participants didn't feel the device was heavy for them, although some expressed complaints about the weight of bulkier components such as the volume knob and the battery (P1). Regarding body location, the wrist (n=6 out of 9), forearm (n=7), palm (n=2), and neck (n=1) were most preferred for SkinKit applications. Participants reported that the ease of access (P6), ability to see the changes (P3), and comfortness (P2) were the main reasons behind selecting these body locations.

Overall, participants found it easy to wear the device (M=6) and remove it from their bodies (M=7).

4.2.3 How SkinKit Helps Prototyping. We analyzed how SkinKit might help on-skin systems' prototyping process. Participants particularly liked the modular approach of SkinKit. One participant (P4) mentioned SkinKit as "Legos but with wearable technology". Due to its modular approach, participants in general found it very easy and fast to interchange modules between wire/decorative modules (P4, P8). During our post-study survey, almost all the participants, irrespective of their backgrounds, rated SkinKit positively when asked about the learnability (Median (M)=7 on the Likert scale; 1=strongly disagree, 7=strongly agree)) and the level of easiness to prototype with SkinKit (M=6). Our study result is consistent with other related works [12, 38] where they found that the modular approach, in general, helps in the learnability of the toolkits.

Overall, our study results suggest that SkinKit can be used with the existing crafting process or can be used as a standalone system irrespective of the stage of the prototyping process. For instance, designers can use SkinKit to modify or add value to the existing crafting and art tools (*e.g.*, an artist can use SkinKit to quickly add some interactivity such as an LED light or a haptic display on their prototypes without having any background in programming or electronics). An engineer can use the tool to test the functionality of the circuits which could help them to make a quick decision about their final products. For hobbyists and wearable technology enthusiasts, SkinKit can be a simple prototyping tool that can help them make wearables in no time.

4.3 Outcomes

A main objective of the first study is to understand the challenges participants faced while working with the SkinKit to identify areas for improvement. We identified the following issues and made improvements in the next iteration.

- Tessellation: All 9 participants reported the tessellation process as the most difficult and time-consuming task. The asymmetric tessellation pattern makes better mechanical connection, but largely increases the difficulty in making wire module connections.
- Device mobility at joints: Though the flap structure design helps overcome curvy body locations, the wire modules can only support static surfaces, not including movable parts such as joints.
- Size and thickness: Though most of the participants were satisfied with the current size/thickness of the system, they still suggested us to have a more lightweight structure of the PCB modules.
- More versatile module library: Participants reported their interests in DIY modules to add to the Kit during the interview. They also suggested including more sensing/actuation options to extend the possible circuit combinations.

Table 2. Demographic data of study participants. Items include gender; professional background; skill set self-rating on Likert scale, 1=no experience, 7=very experienced (Arts and Design; Textile-related Crafts; Software Programming; Electronics); time spent on building and decorating the final project.

ID	Gender	Professional Background	Art+Design	Textile-craft	Program-ming	Electronics	Final Project: Time Building	Time Decorating
Category D: Designers								
D1	F	Apparel Design	6	6	1	1	17:00	0:00
D2	F	Fashion Design	7	7	4	3	11:00	29:00
D3	F	Information Science	5	5	3	3	56:00	26:10
D4	F	Apparel Design	7	7	2	3	8:23	42:10
D5	F	Interior Design	7	5	3	4	12:26	15:40
D6	F	Fashion Management	6	6	2	3	49:00	14:00
D7	F	Interior Design	5	3	1	1	24:10	38:40
D8	F	Apparel Design	7	6	4	3	11:48	15:56
D9	F	Fashion Design	6	6	4	4	10:34	12:08
D10	F	Interior Design	5	4	2	3	22:23	30:01
Category E: Engineers								
E1	M	Electrical Engineering	3	1	5	6	27:42	6:00
E2	F	Information Science	4	3	7	4	16:00	32:57
E3	M	Electrical Engineering	1	1	4	6	11:37	0:00
E4	F	Global and Public Health	4	3	2	5	11:34	16:49
E5	M	Electrical Engineering	3	1	5	6	30:34	23:10
E6	F	Fiber Science	2	2	2	2	29:00	25:50
E7	F	Fiber Science	2	1	2	3	16:57	3:05
Category H: Hybrid								
H1	F	Computer Science	4	5	6	3	29:00	4:00
H2	M	Apparel Design	6	6	5	5	26:21	24:00
H3	M	Industrial & Labor Relations	6	5	2	5	16:25	22:15
H4	F	Industrial & Labor Relations	5	5	4	6	26:10	25:03
H5	F	Information Science	5	3	5	2	13:36	39:17
H6	M	Electrical Engineering	7	3	4	5	33:00	113:26
H7	F	Mechanical Engineering	3	6	6	5	25:27	40:56
H8	F	Computer Science	5	2	6	5	20:00	32:21

5 STUDY 2: MULTI-SESSION WORKSHOPS WITH FINAL PROTOTYPE

With a refined SkinKit platform and workshop protocol, we ran a multi-session workshop to gain deeper insight to how makers of all backgrounds can use and understand SkinKit through a two-day workshop on 25 participants.

5.1 Method

5.1.1 Apparatus. Inspired by previous on-skin device projects and the feedback from the pilot study, we expanded our module library from the initial 9 module set to 16 PCB modules in total. Out of 16 modules, 5 were sensors (proximity, light, capacitive touch, temperature, and atmospheric pressure sensor), 5 were actuators (LED, vibration motor, buzzer, SMA, and thermochromic), 4 were modifiers (volume knob, fade, inverter, and blink), and 2 were power modules (main power and external power). We also re-designed the tessellation pattern to limit the connection between the wire/decorative modules down to the 6 types mentioned in the system design. By using the symmetric tessellation pattern, users can rotate the wire modules into all four directions, as shown in Figure 7 (e). A stretchable wire module was also introduced to support joints and mobile body locations. Same as the pilot, participants used double sided medical grade tape to affix the SkinKit prototypes onto their bodies. Scissors, tweezers, and a full-body mirror were also provided to assist the prototyping process. The sessions were recorded for post-analysis.

5.1.2 Participants. To gain insight on how makers of different backgrounds use SkinKit, we recruited participants with design (*e.g.*, Fashion/Interior/Architectural Design), STEM (*e.g.*, Computer/Information Science,

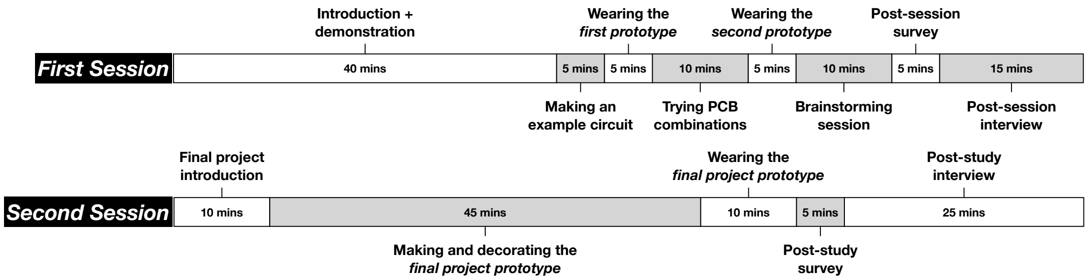

Fig. 9. Study 2 Multi-session workshop session structure.

Electrical/Mechanical Engineering), and "hybrid" backgrounds crossing Design and STEM fields. In total, 25 individuals: 10 designers (aged 19 to 51, 10 female), 7 engineers (aged 19 to 27, 3 male, 4 female), and 8 with hybrid skillset (aged 19 to 31, 3 male, 5 female) participated. In terms of ethnicity for the 25 participants: 5 were White (non-Hispanic); 4 were Black (non-Hispanic); 12 were Asian or Pacific Islander; 1 was North African; 1 was Multiracial Asian/White. Table 2 presents the background and demographics of the participants. In reporting our findings, we annotate participants via their background: engineers (including scientist) (E), designers (D), and hybrid (H) background. We used participants self-reported score in the pre-study survey to categorize them based on their background (*e.g.*, a participant with a score of 5 or more in art and crafts was categorized as designer). Out of the 25 participants, four also took part in our 1st study, while the remaining 21 are newly recruited for this study. Participants reported their professions based on their graduate research or work experiences.

5.1.3 Session Structure. The multi-session workshop (Figure 9) consisted of two 95-minute sessions conducted on two days. A team of two researchers facilitated both sessions.

Session 1 Procedure: (1) SkinKit Intro (40 min). The session started with a brief introduction of the SkinKit toolkit. We later introduced all the modules to the participants and demonstrated how to build a circuit with SkinKit using a sandbox (pre-assembled skin cloths). For demonstration, participants were asked to build an example circuit following the instructions provided by the researcher.

(2) Building and Wearing SkinKit (25 min). Two tasks introduced and facilitated learning of SkinKit. For Task 1, participants created a simple circuit with four designated PCB modules and one of each five types of wire modules: flat, flap-in, flap-out, double flaps, and 4-way cross shape module. Participants were specifically asked to practice tinkering different layout of the wire modules through tessellation. For Task 2, participants were asked to play with all 16 PCB modules and construct a circuit with a self-selected set of desired modules, either using the same wire module layout in Task 1 or using a sandbox wire module layout. At the end of each task, participants were asked to wear the prototypes on a unique body location using a double sided medical tape and interact with the system.

(3) Brainstorming session with SkinKit (10 min). In preparation for the final project, a brainstorming session took place consisting of three aspects: technical (function of the device), aesthetics (device appearance), and body location (where to wear it?). Participants drew or wrote down ideas on paper.

(4) Post-study survey and semi-structured interview (15 min). The survey and interview dealt with how participants learned and experienced SkinKit, along with motivations for and ideation of their final project.

Session 2 Procedure:

(1) Final project intro (10 min). The session started with a brief overview of the participants final project ideas and answer any questions participants might have before they start their final project.

(2) Building, decorating, and wearing the final project (55 min). Participants worked on the final projects. This session was open-ended, affording participants total freedom to create projects of personal choice. Participants

Table 3. Summary of sensors/actuators used in each design and the chosen body locations.

Summary Data of Final Projects (Number of Designs)					
Sensor	Proximity (12)	Touch (10)	Barometric (3)	Temperature (2)	Light (2)
Actuator	Vibration (14)	LED (14)	Buzzer (6)	Thermochromic (2)	
Body Location	Forearm (6)	Wrist (3)	Hand (3)	Back of Neck (3)	Arm (3)
	Shoulder (2)	Chest (2)	Face (1)	Calves (1)	Foot (1)

first built their prototypes and later aesthetically customized using decorative materials (*e.g.*, color pencils, washi tape, gems) provided to them or brought in by themselves.

(3) Post-study survey and in-depth semi-structured interview (30 min). A 7-point Likert scale (1=strongly disagree and 7=strongly agree) was used for the survey. The semi-structured interview gathered in-depth response to using SkinKit to prototype a personal project. All data is analysed following methods described in 4.1.3.

5.2 Findings

We present findings uniquely afforded by the multi-day evaluation: (1) what the participants designed and built for themselves with their final projects, (2) how SkinKit helps prototyping for makers of different backgrounds, (3) making with final version SkinKit, and (4) wearing with the final version SkinKit.

5.2.1 Final Projects: What Did Participants Build with SkinKit? Unlike the built artifacts from the single session workshop, the final projects (**Figure 10**) shed light on what makers of different backgrounds *can* and *choose* to create with SkinKit. For analysis, we focused on project themes, how participants used modules in their designs, and the complexity of the artifacts themselves, following other kit analysis [38].

Health and Wellbeing. Nine participants designed applications for health and well-being. Three developed a temperature sensor for detecting fever due to COVID-19 (E7), allergies (E1), and body temperature increases when exercising (E3). E3 (**Figure 10 (A)**) designed a *Temperature Sensor* worn on the chest, which would trigger the *Vibration Actuator* when body temperature increases unusually during exercise. Three other designs were for sensing and curtailing bad habits, such as detecting nail-biting (H1), bad posture (D10), and face touching during the COVID-19 pandemic (H8). Two participants (D2, H5) designed devices for relieving stress and restlessness. D2 wore the prototype on her cheek (**Figure 10 (B)**), using the *Barometric Pressure Sensor* for detecting deep breaths, and a *Vibration Actuator* to remind one to do so. A *Capacitive Touch Sensor* was also integrated for fidgeting when feeling restless.

Safety. Five participants designed safety applications. Four designs, all by female participants, were motivated by street safety issues under less than ideal lighting conditions (D1, E2, D3, D8). For instance, D8 (**Figure 10 (C)**) created a "wearable flashlight" with two *LED Actuators* worn on her calves, using a *Blink Modifier* for a flashing effect. Other safety applications include a device for maintaining social distancing from others during the pandemic, created by H3 (**Figure 10 (D)**). Designing for the back of the neck, H3 used a *Proximity Sensor* which would trigger a *Vibration Actuator* when someone got too close. He chose the back of the neck since it was an exposed (H3 had short hair), yet discreet body location.

Notification. Three participants (D4, D5, H4) designed notification devices to alert them of essential calendar events or surrounding environmental changes. H4 created a device along her right shoulder and down her arm which would vibrate after detecting a vehicle getting close to her when jogging with headphones (**Figure 10 (E)**). It consisted of a more complex branching circuity with two sets of *Proximity Sensors* and *Vibration Actuators*

Fig. 10. Final projects: Health and wellbeing (a temperature sensor for detecting changes in body temperature (A) & an atmospheric pressure sensor for detecting deep breaths (B)); Safety (a wearable flashlight when walking/running at night (C) & a proximity sensor to alert user when someone get too close (D)); Notification (a device to alert user of events or surrounding environmental changes (E)); Social (a device for communicating with loved ones or friends (F); Aesthetic/Fashion-Driven (an on-skin device aesthetically customized with a beaded trim (G); Dance/Sports Training (a device for on pointe training in ballet).

which respectively went across her shoulder and down her arm. An *Intensity Modifier* adjusted the intensity of the vibration output.

Social. Two designs focused on social communication with loved ones or friends (H2, E5). H2 designed a device for "transferring one's heart to another person," a heart-shaped device worn on the hand (**Figure 10 (F)**). It is consisted of a *Light Sensor* detecting if the hand was being held by another person, which would then light up the *LED Actuator* and trigger the *Vibration Actuator*, to vibrate one's heat to the loved one in response.

Aesthetic/Fashion-Driven. Two designs, both by participants with design backgrounds (D6, D7), were fashion and aesthetically driven. D6 took historical fashion inspiration from the flapper dresses popular in the 1920s (**Figure 10 (G)**). She brought her own decorative materials–a beaded trim, attached to the edge of the on-skin interface that ran from the shoulder down the back. The trim would sway along the side of the shoulders when walking. The circuit is consisted of a *Blinking Modifier* connected to two *LED Actuators*: one on the front of the shoulder, and the other extended via a *Stretchable Module* to the back.

Dance/Sports Training. Two participants (H6, H7) created designs for dance or sports training. H6 designed a device worn on the feet for on pointe training in ballet (**Figure 10 (H)**). In on pointe training, the heel should be as far away from the ground as possible. H6 designed a circuit with two branches: one along the ball of the feet, and the other along the heel. Since the ball of the feet will touch the ground first when falling, H6 put a *Capacitive Touch Sensor* near the ball of the feet, which lights up the *LED Actuator* as a preventive signal to the dancer. When one's heel approaches the ground, the *Proximity Sensor* on the heel triggers the *Buzzer Actuator* for a more salient alarm.

Assistive Technology Two participants (E4, D9) explored applications of assistive technology. D9 designed a *Proximity Sensor* worn on the wrist for the blind that would trigger a *Vibration Actuator*, adjustable by an *Intensity Modifier*, when the wearer is about to bump into an obstacle.

5.2.2 How SkinKit Helps Prototyping for Makers of Different Backgrounds. SkinKit aims to support makers with different backgrounds in prototyping on-skin devices. During our post-study interviews, participants reported several benefits of SkinKit: they described their experience as easy and straightforward (number of participants (n)=9), fun (n=12), enjoyable (n=3), engaging (n=1), a unique experience (n=1), and it provided a chance to be creative (n=3). Participants also reported SkinKit as flexible, *e.g.*, easy to switch around modules and combine skin substrates in different circuit layout (n=6), modular (n=2), customizable (n=1), and appreciated the capability of outlook previewing on the body (n=4). As one participant noted:

> *"It's easy to choose the shape of the circuit or the arrangement of different modules you want, and it's also easy to test things out and change your ideas, if needed."* — (D3)

When compared with other toolkits, participants described SkinKit as being more flexible, wearable, and easier and faster to prototype with. SkinKit has the ability to improve the crafting process by adding functionality and interactive elements in the existing crafts (n=4), adding another "layer" to the existing crafting techniques (n=1), and making skin friendly wearable devices (n=3). Many participants (n=18) showed interest and described benefits in integrating SkinKit in exisiting prototyping/making practice.

We also compare and contrast differences and similarities in usage across participants with different backgrounds. Engineering participants are familiar with the PCB modules; all possessed prior experience in physical computing. They spent the least time on both constructing/decorating their final projects (avg: 20 mins/15 mins), and they used the least number of the wire modules to build the circuit (avg: 6, range 3 to 10). This can also allude to their attitudes toward the aesthetic aspect of the SkinKit prototype. They tend to put less attention on decoration (E1, E3), and prefer creating a "cover" for the device either with cloth (E3), or additional fabric pieces (E5). According to E2, the main purpose of decoration is to make the device look "cool" but also "socially acceptable." Most of the engineers also demonstrated interest for more complex PCB module functions, including communication mechanism (*e.g.*, bluetooth) (E2, E3, E4), and more sensing options (*e.g.*, gas, IMU, force, color sensor) (E3, E5).

On the contrary, participants with design backgrounds were more passionate in decorating their device to reflect personal style. Half of the design participants (5/10) brought additional decorating material for the final project. They wanted their devices to be sparkly/reflective (D3, D8, D9) or similar to certain types of clothing and accessories (*e.g.*, flapper dress, sweatband, etc.) (D6, D10). While some of them held a conservative attitude toward incorporating technologies with their current hand craft practices (D1, D2, D3, D7), many regarded working with SkinKit as a "fun" (D1, D2, D4, D6, D10) and "unique" (D6) experience for exploring the technological aspects of on-body design.

Most of the participants with hybrid backgrounds (engineering+design) described working with SkinKit as a rich opportunity of integrating electronics with crafts in the form of on-skin devices. They used more wire/decorative modules than the other groups in the final project (avg: 8, range 6 to 15), and they also tend to spend more time trying different combinations/decorating the device (avg: 23 min/37 min). They described SkinKit as providing an easier/quicker way to create a wearable circuit (H1, H2, H6, H7), and appreciated the advantages of a lightweight form factor (H6) and how it expanded interaction possibilities onto the skin (H8).

5.2.3 Making with the Final Version SkinKit. In the post-study surveys, many participants reported the workflow of making a circuit with SkinKit is easy to learn (Median (M)=7 on the Likert scale; 1=strongly disagree, 7=strongly agree) and reacted positively towards the prototyping process overall (M=6). Majority of the participants found it intuitive to work with the PCB modules and skin substrates to create diverse circuit layout geometries, and they didn't find it challenging to make different circuit combinations. On the contrary, participants decorated their devices differently, where we investigated how and why participants would visually improve the prototype on top of the provided modules. Some decided to take a minimalist approach (number of participants (n)=4), while the others consider it challenging, as it might interfere with the circuit (n=3). Nonetheless, all the participants were able to build personally meaningful and fully functional final projects using SkinKit, demonstrating its user-friendliness and versatility.

When asked about the difficulties during the fabrication process, participants reported concerns such as being afraid of breaking the delicate components (D7, H4, E5), feeling hard to separate the tiny magnet pairs without using tweezers (E4), lacking choices of layout direction other than the right angles (H1). Compared to the initial version, participants reported that the symmetric tessellation technique was more straightforward. The arrow marks on both PCB and wire modules helped participants orient the designs in the right order. The labels and color-coding on the PCBs helped participants identify modules quickly.

5.2.4 Wearing the final version SkinKit. In general, participants reacted positively towards wearing the SkinKit modules on their bodies and found it comfortable to wear (Median (M)=5 on the Likert scale; 1=strongly disagree, 7=strongly agree). They also found it easy to apply the modules and remove them from their bodies (M=6), and the modules remained well attached to their bodies for the study duration (M=6). Participants were positive about the size and thickness of the modules (M=6) and generally liked the aesthetic of the device (M=5). In the post-study interviews, participants reported SkinKit as lightweight (n=2), comfortable (n=14), bendable (n=1), flexible in terms of body location (n=2), and body conformable (n=2).

All SkinKit devices stayed well adhered during the final study, and none of them fell off after being applied to different body locations. Nonetheless, when we asked about potential issues regarding wearing the SkinKit device for longer periods in-the-wild, participants reported concerns ranging from whether the device would be affected by body movements (E1, H4, H5), damaged by water (E1, D5, H2, E7, E4, E5, D10), or get caught in clothing (D3, E7, H3). These are longer term wearability concerns we aim to address in future work (see 6.2).

6 DISCUSSION AND FUTURE WORK

6.1 Toward On-skin Bio-sensing Systems

This paper aims to explore the materials and methods for constructing an on-skin prototyping platform. The modules included in the current version are solicited from prior HCI on-skin interface literature and user feedback from the pilot study to demonstrate the feasibility of the SkinKit. Many of these sensors and actuators focus on enabling everyday interaction (*e.g.*, touch and display) with less focus on health monitoring, which is a promising application area for on-skin interfaces. For future work, we envision adding more modules that take full advantage of the unique context of the skin surface, including a set of biosensors to enable the construction of personalized health monitoring systems. This would require further investigation of suitable on-skin sensors and technical refinements to our system. We will also improve and standardize the module specification and add infrastructure such as wireless communication mechanisms to realize an extensible platform for skin-based bio-sensing.

6.2 Robustness, Durability, Waterproofing

This paper focuses on usability, engagement, and affording creative design with SkinKit rather than addressing long-term wearability concerns around robustness, power consumption, and waterproofing. While stretchability and longer-term wear tests are needed to characterize robustness and durability, we did not see a single module detach from the skin during evaluation nor lose electrical/mechanical connection. Participants also found the constructed devices comfortable to wear. The modules can also be waterproofed by spin-coating a thin silicone layer over electronics, as demonstrated by other on-skin systems [**?**]. For our power modules, we also constructed a signal switch to control the actuation for conserving power in prototyping. Thin film batteries, which are now increasing in power efficiency while maintaining a slim form, can also be leveraged for future prototypes but with a price trade-off.

6.3 Mass-Manufacturing for In-The-Wild Deployment with Broader Populations

The scalable production of soft-circuity prototypes [22] and hardware systems [39] remains a prime challenge in wearable and ubiquitous computing. This is further exacerbated for on-skin interfaces, an "extreme" form of soft-circuity, due to the unorthodox fabrication methods used to achieve slim forms [80]. For the evaluative studies in this paper, over 400 (12 per person/study $\times$ 34 participants) skin cloths were manually manufactured by the authors. To realize broader deployment in the future, techniques, machines, and approaches for mass-manufacture of slim on-skin traces is needed. Scaleable manufacture of the modules can enable the deployment of SkinKit outside laboratory settings, placing it in the hands of broader populations, including children, seniors, and those under-served in computing.

6.4 Trade-Offs Between Modularity and Craft Materiality

The modularity of SkinKit enables one to construct a self-contained on-skin interface from scratch in under an average of 23 minutes (per final project), a drastic improvement from the reported time of current on-skin interfaces fabrication processes (*i.e.*, 3.5-11 hours [34, 70, 77**?**]). It is also important to note that these time-consuming fabrication processes [34, 70, 77**?**] typically only generate on-skin traces, which are not inclusive of integrated hardware electronics for sensing and actuation like SkinKit. While modularity significantly "lowers the floor" [60] for one to begin prototyping on-skin interfaces, it does limit the full expressiveness and materiality afford by pure craft-based approaches [53], in which one crafts interfaces from an unlimited resource of raw materials. We designed SkinKit not to replace, but to complement existing craft-based prototyping processes. Also as observed in our final study results, designers who worked with crafts found SkinKit to be a useful complement for existing practices and an effective tool for adding a lot more interactive elements in traditional arts and crafts.

7 CONCLUSION

We presented SkinKit, the first construction toolkit for on-skin interfaces. We enabled fast low-fidelity prototyping by manipulating the tangible plug-and-play modules. SkinKit modules are easy to attach and remove but still offer robust connection in a slim form factor. Our single- and multi-session workshops with 34 maker participants shed light on the prototyping feasibility and wearability of SkinKit. Our findings reveal that SkinKit is intuitive, flexible, and accessible to makers across STEM and Design backgrounds, as evident through the personally meaningful and functionally and aesthetically expressive on-skin devices they developed. SkinKit modules are highly customizable and may work as a standalone system or in concert with other crafting practices and materials, making it rich in potential for diverse maker populations. Furthermore, SkinKit can be worn on challenging body locations not afforded by current wearable devices, *e.g.*, directly on the shoulder and knees, which require high flexion. While this paper focuses on realizing usability and affording creative design with SkinKit, in future work, we aim to investigate scalable manufacture of durability-tested modules to enable engagement with broader populations. SkinKit expands current wearable toolkits to the emerging realm of on-skin interfaces, opening up new material, application, and engagement potential for diverse communities.

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