ECSkin: Tessellating Electrochromic Films for Reconfigurable On-skin Displays

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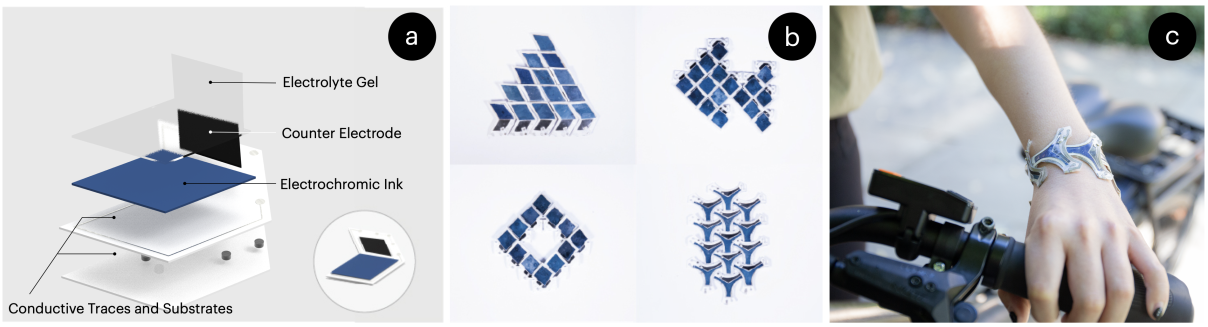

Fig. 1. We present ECSkin, a construction toolkit for fabricating on-skin electrochromic displays. (a) The ECSkin module structure contains an electrolyte gel, electrochromic ink, counter electrode, and conductive traces stacked on a silicone-based substrate. (b) ECSkin provides adaptive designs and customizable display shapes. (c) An ECSkin display is flexible and soft, easily conforming to complex body parts.

Emerging electrochromic (EC) materials have advanced the frontier of thin-film, low-power, and non-emissive display technologies. While suitable for wearable or textile-based applications, current EC display systems are manufactured in fixed, pre-designed patterns that hinder the potential of reconfigurable display technologies desired by on-skin interactions. To realize the customizable and scalable EC display for skin wear, this paper introduces ECSkin, a construction toolkit composed of modular EC films. Our approach enables reconfigurable designs that display customized patterns by arranging combinations of premade EC modules. An ECSkin device can pixelate patterns and expand the display area through tessellating congruent modules. We present the fabrication of flexible EC display modules with accessible materials and tools. We performed technical evaluations to characterize the electrochromic performance and conducted user evaluations to verify the toolkit's usability and feasibility. Two example applications demonstrate the adaptiveness of the modular display on different body locations and user scenarios.

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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

Wearable displays are becoming pervasive as they facilitate new output channels for social and health interactions [8]. Among wearable form factors, on-skin displays that conform to the skin surface are ideal for broad applications from visualizing personal informatics and health monitoring to everyday notifications [29]. This seamless integration enhances versatility of displaying information or artistic expressions, offering a unique and dynamic way for wearers to interact with technology and express themselves. To serve and address emerging on-skin interactions, thin-film display technologies with an accessible, electrically controllable visual output are desired [10, 30, 31, 59].

Electrochromism (EC) is one of the promising color-changing technologies with unique advantages in its low power consumption, effectiveness under ambient light, and compatibility with various substrate materials. Researchers in the field of material science have been devoted to fundamental EC material synthesis for new color variety, higher color contrast, and faster activation [64]. However, the fabrication of these cutting-edge EC technologies is often inaccessible due to high costs, specialized equipment, and required expertise. To this end, HCI researchers have sought to democratize EC technology through user-friendly fabrication tools and novel applications for everyday user interaction. Recent EC display research, for example, TransPrint [24], explored accessible fabrication methods for customizing film-based flexible EC displays where ink depositing techniques such as inkjet printing were used. However, the printing fabrication process is constrained by the design that is sealed within a fixed casing, where display patterns cannot be reprogrammed or animated. [17, 24, 28]. In addition, fabricating larger-size EC displays (e.g., comparable to a palm size) can be challenging as it leads to uneven coloring and long response time. Compounding the lack of a skin-conformable form factor and critical reconfigurability that allows users to adjust and recreate the display contents remains unexplored. To overcome the challenges above, we present ECSkin, a reconfigurable construction toolkit for creating modular EC displays on the skin.

ECSkin enables personal on-skin displays by arranging and combining the premade flexible EC modules using tessellation patterns to form scalable display shapes with congruent module units. Each EC module consists of two parts: a display area and a connection area. The display area shows a pixelated color-changing block printed with the EC ink, while the connection area provides power and ground and serves the connection between the adjacent modules via magnet connectors. Compared with prior work of modular textile non-emissive displays [11, 17, 26], ECSkin achieves a conformable form factor that complies with diverse skin surfaces. Besides, without the need of attaching modules to a fixed circuit board layout, ECSkin allows users to edit and adjust display shapes and patterns for design iterations. Table 1 shows the comparison between ECSkin and relevant non-emissive wearable display research in terms of modularity, form factor, and reconfigurability.

ECSkin leverages a plug-and-play construction approach to create flexible displays conformable to the skin. To demonstrate the viability of the modular designs, we adopted and streamlined the screen-printed fabrication with choices of accessible electrochromic materials that can be readily replicated in any HCI labs. Technical evaluation regarding the color contrast, activation time, and form factor showed the considerable performance improvement of display achieved by the modular approach.

Table 1. ECSkin compared with previous wearable non-emissive display research based on the design criteria for on-skin modular displays.

Non-emissive Display	**Modular**	**Flexibility**	**Reconfigurability**
ECSkin	Yes	Flexible	Shape and Pattern
Project Primrose [11]	Yes	Semi-rigid	Pattern
WearECkits [17]	Yes	Rigid	Shape and Pattern
ECPlotter [26]	No	Flexible	changeless

To gain user feedback on the usability and wearability of the modular ECSkin display, we recruited 12 participants to experience prototyping, wearing, and interacting with the personalized on-skin electrochromic display. Insights from the workshop study indicated diverse usage scenarios and validated the prototyping workflow. To further validate the reproducibility of the modular design, 4 of the 12 participants rejoined a follow-up fabrication study. With a user manual and materials provided, all 4 participants successfully fabricated modules in new tessellation patterns Based on insights collected in the study, we developed a computational tool that accepts user-defined tessellation patterns and exports new module designs. To demonstrate potential use cases, we presented 2 exemplary applications on different body locations and reflect on the proximities of a public/private display in collocated interaction scenarios [15, 30].

We summarize the contributions of this paper as follows:

- ECSkin, a modular construction toolkit for reconfigurable and scalable electrochromic displays.
- User evaluations of ECSkin as extensible and customizable on-skin displays.
- The exploration of on-skin display design space and the software design tool that supports users in on-skin display customization.

2 RELATED WORK

2.1 Flexible Display Technologies for Wearables

The recent advance in visual output technologies has enabled soft and conformable displays suitable for wearable and on-skin applications. Emissive technologies produce high-contrast images, emitting bright, vibrant colors with an inherent light source. The most representative emissive display technology is light-emitting diodes (LEDs), which have been widely adopted in research and commercial products since they are low-cost and readily available [7, 38, 41]. Made with thin film polymer instead of the traditional semi-conductor diodes, polymer light-emitting diodes (PLEDs) are more lightweight and flexible to be laminated onto the skin [63]. Similarly, inkjet-printable electroluminescent (EL) materials emitting light in response to electric current can create custom thin-film monochrome displays [46, 59]. Emissive displays made of optic fibers can transmit and display light dynamically through thin fiber tubes and can be integrated into textiles or wearables [3, 22, 53, 57]. Relying on the light emission, emissive displays are less visible under intense ambient light such as sunlight.

Alternatively, non-emissive displays render the image by absorbing, reflecting, refracting, or scattering the ambient light. They work well in an outdoor environment and can display natural, eye-friendly colors. One representative non-emissive material is E-ink, known for its low power consumption and direct sunlight visibility for electronic papers and e-readers, but also can be integrated into clothing and wearable devices [10, 12]. While E-ink suppliers focus on commercial products, upcycling broken E-ink devices is a potential approach to overcome the difficulty of accessing E-ink material and creating custom-shaped displays. [21]. Similarly utilized for flat panel displays, researchers have employed liquid crystal (LC) materials to develop non-emissive displays for wearable applications. Due to their unique properties between liquid and solid crystals, liquid crystals have diverse usages, *e.g.*, reflected-backed polymer-dispersed liquid crystal (PDLC) can create custom shapes, light-diffusing electroactive displays for textile substrates [11], and thermochromic liquid crystal (TLC) can be integrated into textiles through embroidery for e-textile displays [14]. Besides TLC, thermochromic inks made of leuco dyes have a broader color range, are integrated into on-skin interfaces and e-textiles, and are actuated by passive or active heating [31, 58]. Another ink-based technology, photochromic inks, can change from transparent to different colors when exposed to specific wavelengths of light. Photo-Chromeleon proposed a re-programmable multi-color texture by mixing multiple photochromic dyes into a single solution [27]. The non-emissive color-change technologies mentioned above are suitable for displaying subtle interactions with the organic color transitions. Nevertheless, the actuation methods demand substantial power or specific light projection, making an alternative technology with a more straightforward and low-power control mechanism more desirable for on-skin wear.

2.2 Wearable Electrochromic Displays

Electrochromism (EC) is an emerging color-changing technology that responds to electrical stimuli, operating more efficiently than thermochromism or photochromism. Due to low power consumption, it is easy to regulate heat for EC displays even after a prolonged activation. Besides power efficiency, the technology has the benefits of low-cost materials, accessible fabrication through variable printing techniques, and easy integration with electronics. The phenomenon involves a reversible color or transparency change caused by electrochemical oxidation or reduction that alters the molecular structure and optical properties. Although electrochromism is still in its infancy, with limited commercial products for smart windows, electronic price tags, and electronic paper, as it's not reaching the ideal performance of mature display technologies yet [62], the technological potential has drawn interest from material science and human-computer interaction researchers to continue studying the performance, emerging materials, and potential applications [6, 20, 42, 61].

Structured as multi-layers of thin film materials, electrochromic displays can be fabricated in a free-form shape and flexible form factor using various techniques such as screen printing, inkjet printing, airbrushing, and syringe depositing 2D plotter [24, 26, 28, 50]. The feasibility of crafting flexible EC displays has enabled various applications for wearable and on-skin interfaces. Based on the natural response time required for the color transition, wearable EC displays can be designed through the lens of slow technology and render slow behaviors characterized by the display patterns and structures [28]. By replacing the permanent electrolytic layer with transient lotions and creams, Lotio proposes a lotion-mediated EC display that leverages the natural use of lotion to temporarily activate a skin-worn EC sticker after applying it on the skin [50]. Following the TransPrint [24] fabrication techniques, various flexible free-form EC displays have been deployed in diverse wearable and textile applications, including footwear, dress neckline, jackets, and face masks [18, 19, 23, 25]. The substantial advances in electrochromic technologies have successfully democratized non-emissive displays through accessible fabrication techniques and decomposable materials [51]. However, the size and fabrication overhead often limit the fabricated displays when re-designing the pattern. To support the exploration of EC displays as a subtle output modality for wearables, WearEC Kits proposes two toolkits, Transparent and Programmable WearEC Kits, to enable designers to prototype programmable and transparent flexible EC displays quickly [17]. Though suitable for textile and wearable interfaces, the programmable modules do not conform to the skin due to the rigid electrical components and connectors. Besides, the flexible modules are confined by the display size and response time trade-offs. Thus far, a toolkit for on-skin display that supports scaling of the display size and enables rapid and adaptable prototyping is yet to be developed. This gap in the literature is what we seek to address with the implementation of ECSkin.

2.3 Wearable Computing Construction Toolkit

Emerging construction-based toolkits for wearables have stimulated and encouraged people to craft customized designs [47]. The LilyPad Arduino [4] and EduWear [32] are groundbreaking endeavors that integrated electronics into textiles to create wearable circuits that can be stitched onto garments. Subsequent studies and commercial products of textile-based toolkits, like the Flora [1] and fabrickit [52], extended the notion and addressed crafting challenges. The following research continued investigating various materials and interactions to expand modular sensing and actuation alternatives [2, 13, 36, 43, 54, 55]. Besides supporting the fabrication, attempts were made to simplify programming through customized software environments featuring graphical tools, facilitating novice learning and coding [32, 45, 49]. Recent wearable toolkits often deploy a plug-and-play tangible construction approach to reduce the programming requirements further. These toolkits were implemented with a decentralized system, where the pre-programmed circuit modules sequentially receive and transmit the control signal to operate according to the connection order [5, 33, 35].

Early wearable and e-textile toolkits for non-emissive displays have been designed to allow non-experts to customize subtle visual output on wearables [17, 56]. Nonetheless, the form factor of the modules includes rigid circuit components that protrude and do not conform to the skin, and they are not intended for skin attachment. Designed for prototyping on-skin circuitry, on-skin construction toolkits utilized slim, flexible printed circuit boards and traces to integrate electronic components onto skin-conformable interfaces [34, 35]. While various sensing and actuating modalities have been proposed for interfacing human skin with diverse interactions, the potential of a scalable on-skin display technique has not yet been explored. ECSkin aims to expand the design exploration of on-skin interface prototyping using modular toolkits, emphasizing scalable and accessible non-emissive display techniques. The significance of such a prototyping toolkit lies in providing an extensible platform for exploring innovative interactions and facilitating the creation of personalized on-skin displays tailored to individual needs.

3 ECSKIN

ECSkin is a construction toolkit designed for customizing on-skin displays proficiently through the modular plug-and-play-making process. The module's flexibility and reconfigurability enable an accessible prototyping process designed for users without extensive hardware or crafting background. Inspired by the art of tessellation, we designed the display modules in monohedral shapes that tile a surface periodically to create versatile patterns.

This section elaborates on how we design ECSkin modules based on tessellation patterns, material preparations, fabrication processes, and control schemes. Further, we propose a prototyping workflow for end users to design and assemble customized displays using ECSkin.

3.1 Monohedral Tessellation

This research aims to devise a free-form surface display by easily connecting several electrochromic modules, such that the display area on each module seamlessly aligns with the others, forming customizable 2D display patterns. We implement monohedral tiling patterns where every tile in the tessellation is congruent and translational symmetric. These patterns offer the advantage of a scalable screen print design.

Besides the display area of the tessellation pattern, another design consideration is the underlying connection mechanism. As shown in the example module design diagram (Figure 2), the module design starts from the surface elements, including an equilateral triangle, a square, and a hollowed triangle that can form a tiled surface. Grouping adjacent elements as the display area, we exemplify the tessellation design with three shapes of the prototile (marked in blue), including a diamond, a square, and an arc tile. The final stage of the design process entails identifying the connection part (marked in red) that (1) overlap with a minimum of two adjacent modules and (2) is connected with modules along at least two axes. Each ECSkin module consists of one display area

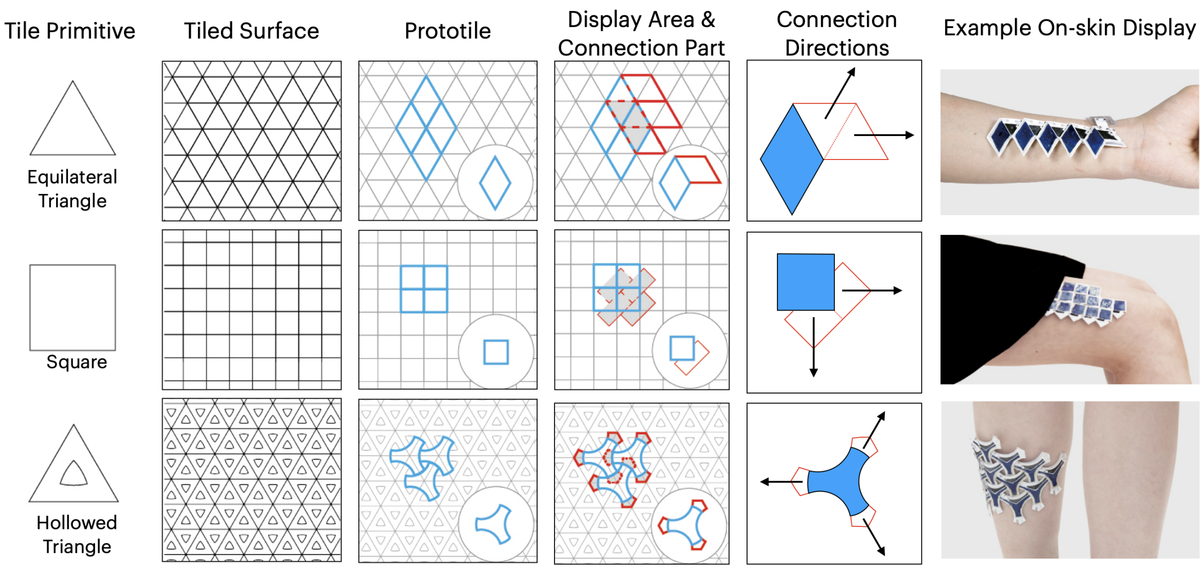

Fig. 2. ECSkin leverages the tile primitives, where the tessellation prototile (marked in red) is a combination or cutting of one or multiple tile primitives, and the designed connection parts (marked in blue) require linking at least two adjacent modules in different directions. Utilizing magnetic attachment, ECSkin modules can be combined into customizable shapes that conform to different body contours.

and one connection part. When combining adjacent modules, the display area will overlap on top of the nearby connection part, holding paired magnets, enabling them to connect seamlessly through magnetic attachment. The shape of the display can then be customized with different tessellation designs and module combinations.

3.2 Electrochromic Materials Preparation

The phenomenon of electrochromism involves the change in the color of specific materials in response to the application of an electric potential. This transformation is driven by a reversible *redox*, a process in which one substance or molecule is reduced and another oxidized. This redox reaction modifies the material's electronic structure, leading to a corresponding change in its optical properties and ultimately resulting in a color shift. The composition of the layers can be either vertically stacked or co-planar [24]. We chose the co-planar design for a thinner profile. We fabricated the proof-of-concept modules using commercial PEDOT:PSS conductive ink. The materials afford an accessible fabrication that can be reproduced in an HCI lab with basic printing appliances and chemical fume hoods. While the color-change performance might not be optimal compared with cutting-edge electrochromic material science research, we aim to validate the feasibility of the modular approach, which can be incorporated with any advanced high-performance materials. The multi-layer module structure is illustrated in Figure 3.

- **Substrate.** The flexible substrate is made of silicone tattoo paper and textile stabilizer. The substrate served as the base material adhering to the skin, where the electrochromic and counter electrode inks are separately printed on another substrate material, vinyl sticker paper[1]. After curing, the ink-printed sticker papers and conductive traces are assembled and stacked on the base silicone substrate.

[1]https://www.amazon.com/JOYEZA-Premium-Printable-Waterproof-Resistant/dp/B088QWPMH7

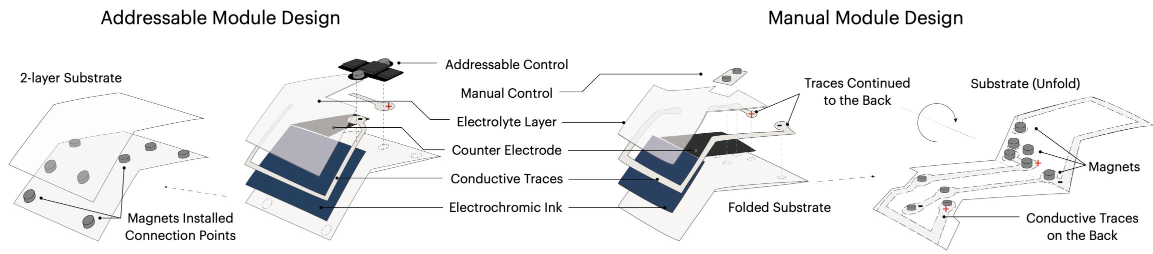

Fig. 3. The basic structure of an ECSkin module has three layers: The top layer is the electrolyte gel; The middle layer is co-planed by the electrochromic ink and counter electrode; The bottom layer is a skin-friendly and conforming silicone-based substrate. For addressable modules (left), the connection part is only for magnetic attachments, where magnets are installed between the two-layer substrate. In contrast, the connection part of the manual module (right) requires both electrical and magnetic connections, which we designed the folded substrate to allow traces to route to the back of the module for transmitting voltage to the next module.

- **Electrochromic Layer.** PEDOT:PSS ink[2] formulated for screen printing were purchased as the electrochromic material and deposited on sticker papers through the according printing methods.
- **Counter Electrode Layer.** Dispersed Carbon Nano Tubes (CNT)[3] screen-printed on the sticker paper.
- **Electrolyte Gel Layer.** Following the electrolyte-making process for electrochromic displays and high capacitance gate dielectrics [28, 39], we prepared the transparent rubbery ion gels by spinning 4:1:10 mixture of [EMI][TFSA][4], PVDF, and acetone on a hot plate at 85 °C for 30 minutes. Once the PVDF is dissolved, the mixture was then transferred into a glass petri dish and baked for 24 hours in a 60 °C oven for solvent casting.
- **Conductors.** Two conductive materials are used to make traces and connect electrodes: conductive fabric tapes[5] were cut and adhered to the silicone tattoo paper, and silver chloride ink[6] was painted between traces and electrodes to increase conductivity.

3.3 Display Module Fabrication

We summarize the three-step process for fabricating the electrochromic display module.

Step1: Print on Sticker Papers. The electrochromic ink is printed on the vinyl sticker paper by screen printing (Figure 4a&b). The thickness of the electrochromic ink layer can affect the color change performance significantly. We chose 110 mesh number screens to yield a thin and uniform layer of electrochromic ink, which results in good color contrast. Similar to the EC ink, the counter electrode is screen printed on vinyl sticker paper using CNT dispersion. The ink-printed substrates are heat-cured in a 90°C oven for 30 minutes.

Step2: Assembling Layers. After ink-printed stickers are cured, we cut and stack the layers based on a co-planar structure, where the CNT ink and electrochromic ink layers adhere on top of the silicone substrate in parallel (Figure 4c). To cut and transfer conductive traces to the substrate, we adhered 2-inch wide conductive fabric tape to a vinyl film and set up a desktop cameo cutter to cut trace designs on the tape without damaging the vinyl

[2]https://www.sigmaaldrich.com/US/en/product/aldrich/768650
[3]https://tuball.com/additives/batt-h2o
[4]https://www.sigmaaldrich.com/US/en/product/aldrich/711691
[5]https://lessemf.com/product/cobaltex-fabric/
[6]https://kayakuam.com/products/agcl-675-silver-silver-chloride-ink/

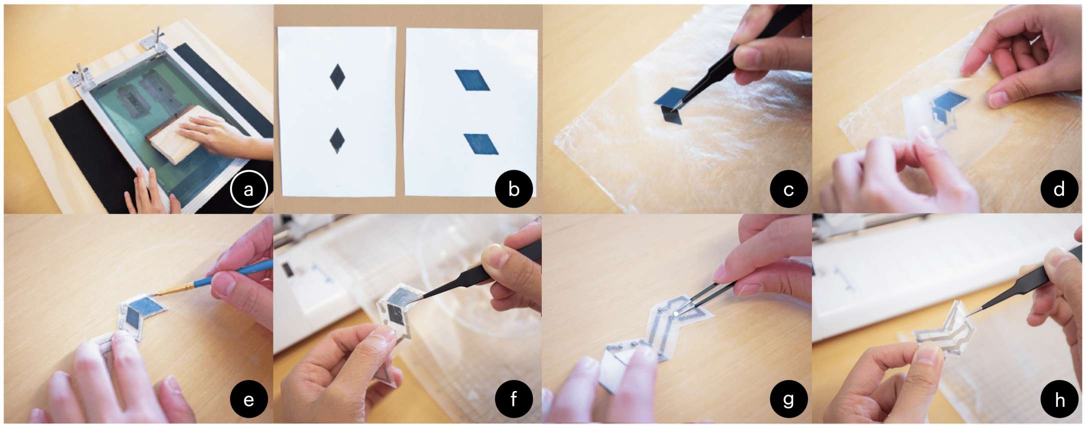

Fig. 4. The fabrication process of a ECSkin module involves: (a) Screenprint the electrochromic and counter electrode inks. (b) Printed ink layers on white vinyl stickers. (c) Remove sticker backings and adhere to ink layers on the silicone-based substrate. (d) Transfer conductive fabric traces to the substrate. (e) Paint silver chloride ink between the EC ink and traces. (f) Cut and apply electrolyte gel to cover the EC ink and counter electrode. (g) Install magnets to the back of the substrate. (h) Attach vinyl film for insulation backing.

layer. Figure 4d shows the process of transferring traces to the module. Silver chloride ink was further applied between the electrodes (ink layers) and the traces to provide stable voltage connections (Figure 4e).

Step3: Install Electrolyte, Magnets, and Control Parts. The electrolyte gel was cut in the shape that can cover the electrochromic ink and the counter electrode. After placing the electrolyte layer on top of the inks, we flipped the module and installed the magnets on the back of the substrate with double-sided tape (Figure 4f&g), where we referred to earlier modular toolkits' designs that utilized magnetism for connecting modules [33, 35]. The substrate was then folded and adhered to secure the magnets, with an additional vinyl film attached to the back of the module for insulation 4h). With magnets installed, the manual or addressable control parts can be attached magnetically to the module.

3.4 Control Schemes

To dynamically control the display patterns, two control schemes, including addressable and manual controls, are designed and implemented for distinct application needs.

Addressable Control. The addressable control scheme provides a real-time pattern change by integrating ICs on each module. As shown in Figure 5a, the DS2413 addressable switch is surface-mounted on a custom flexible printed circuit board, where two flexible ZIF connectors[7] link the adjacent modules sequentially from the microcontroller (Teensy 3.2). The 1-wire protocol allows each DS2413 device to communicate with the microcontroller by its unique 8-byte address. To program the pattern, the IC addresses are recorded, which allows users to modify the status of specific modules with Arduino codes uploaded through USB cables from a laptop. The modules are connected row-by-row, where modules in the same row are connected with a 3cm flexible printed trace. Figure 6 shows the schematic of the addressable modules, where the microcontroller and addressable switches can be powered by the same 3.7V LiPo battery. Besides, braided flexible wire connectors were fabricated for between-row connections based on previous on-skin toolkit conductor designs [34].

[7]https://www.amphenol-cs.com/0-50mm-pitch-flex-connectors-59453061110echlf.html

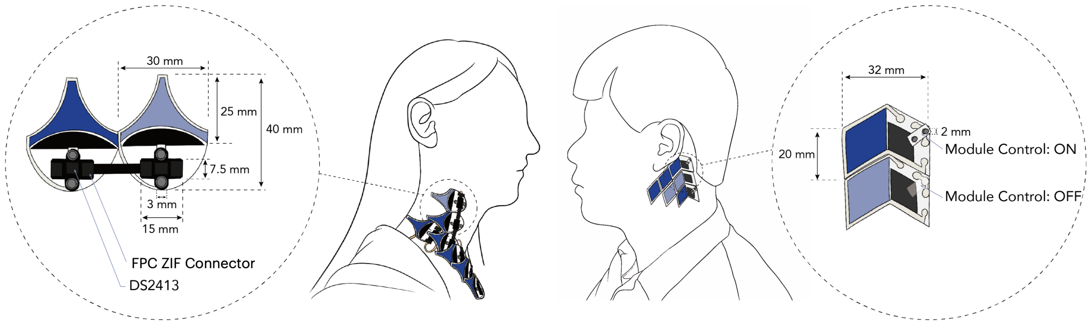

Fig. 5. Example diagrams of two ECSkin display control schemes. (a) An addressable EC module with a digital switch can be controlled using the 1-wire protocol. (b) A manual EC module can be activated only when the magnetic module control switch is attached to the counter electrode.

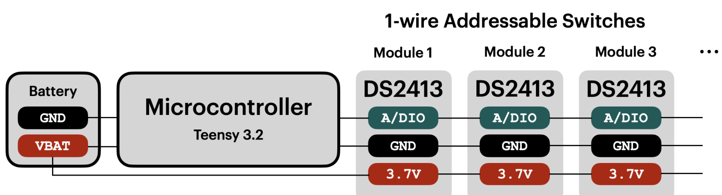

Fig. 6. System architecture of the addressable EC display design.

Manual Control. For scenarios that do not require displaying multiple patterns or real-time pattern changes, a manual control scheme provides quick and straightforward pattern manipulation. As shown in Figure 5b, a magnetic conductor piece connects the counter electrode to the power circuit on every module by default. To selectively turn off specific modules to show the designed pattern, users can remove certain manual control pieces and reconfigure the pattern through detachments and re-attachments. The manual control scheme has the advantages of a minimized control part and an intuitive reconfiguration process. However, the pattern cannot be changed during the display use and requires manual effort in modifying modules.

3.5 Prototyping Workflow.

We summarize the prototyping workflow for making customized ECSkin displays with ready-to-use modules:

(1) **Module Connection.** The EC modules need to be first aligned in the same orientation. By attaching the back of the display area to the connection parts, two modules can be connected through the matching magnet pairs. For manual control modules, the connection is only made by magnet pairs, while addressable modules require crimping traces between mechanical connectors of the circuit boards.
(2) **Layout Configuration.** To decide the device shape, the participants work on a table and experiment with different combinations of the modules.
(3) **Pattern Control.** To customize the display patterns, users would remove the conductor pieces with tweezers when using the manual control modules. For addressable control that uses a microcontroller to handle the module switches, users can program the patterns and upload scripts via a laptop.

(4) **Device Testing.** Once the design is confirmed, the user can connect the battery and power switch to the end module and test the display patterns.
(5) **Application.** After testing the device on the table, the final step of prototyping involves applying skin-safe double-sided adhesive to the back of modules and adhering to the chosen body location. To avoid the device falling off, we suggest not choosing hairy body parts or body joints that undergo drastic movements frequently.

4 TECHNICAL EVALUATION

To investigate the performance of the ECSkin displays, we carried out a technical evaluation using square-shaped modules with addressable and manual controls. The display area of the addressable module is 30 mm x 30 mm, while the manual module is 15mm x 15 mm. We characterize EC modules by measuring (1) color contrast, (2) switching time, and (3) power consumption. We also report on (4) module profiles and flexibility to highlight the skin-conformable form factor.

4.1 Color Contrast

The *Color Contrast* was measured using a spectrophotometer (X-Rite Ci78008)[8] that averages the color of the entire display area. We used a metric widely adopted in the field of material sciences [37, 65] , where the color contrast (ΔE^*) measures how the human eye perceives color difference, with higher values indicating greater contrast. The metric has a minimum value of 1, a JND (Just Noticeable Difference) value of 2.3, a value larger than 6 suggesting an obvious difference, and a maximum value of 100 indicating the opposite color [16, 48]. Specifically, it is defined by the difference between two colors in the CIELAB color space (L^*, a^*, b^*) using the following formula:

$$\Delta E^* = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2}$$

Using a power supply, we first measured the ΔE^*_{max} under 2V to 5V input, where ΔE^*_{max} is the maximum color contrast measured 2 minutes after activation. In addition, a 3.7V measurement was added to evaluate the LiPo battery we used. As shown in Figure 7a, we performed five repetitions and averaged for each voltage measurement. When powering with 5V, the manual module design has a highest E^*_{max} of 35.4 on average, and the addressable module has a highest E^*_{max} of 25 on average, all exceeding the minimum ($E^*_{max} = 6$) for an obvious color difference. As a reference to another visual clarity metric commonly used in HCI display research [24, 50], the Web Content

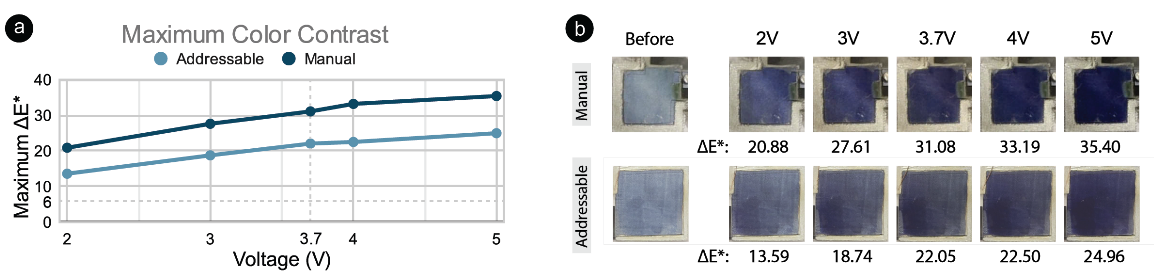

Fig. 7. (a) Maximum color contrast measured on manual and addressable modules (b) Color transition of ECSkin modules before and after applying voltages ranging from 2V to 5V

[8] https://www.xrite.com/categories/benchtop-spectrophotometers/ci7x00-family/ci7800

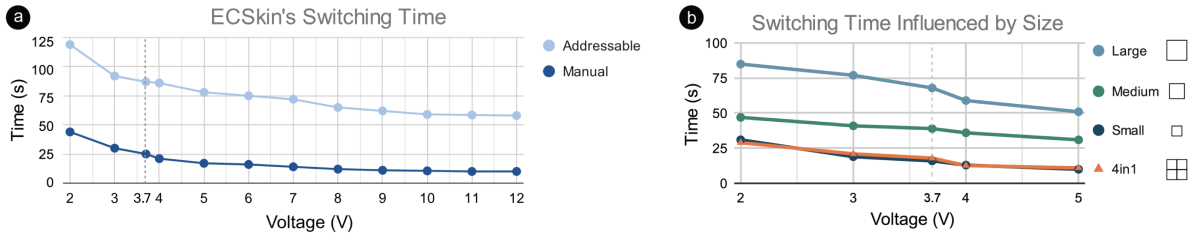

Fig. 8. Switching time performance comparison for (a) ECSkin's addressable and manual modules, and (b) different sizes, including small (2.25 cm^2), medium (6.25 cm^2), large (12.25 cm^2), and a 4-joint-in-1 display.

Accessibility Guidelines (WCAG) contrast ratio (C_r) of the manual module at 5V is 3.68, exceeding the minimum ($C_r = 3$) required for readability [24].

4.2 Switching Time

The *Switching Time* is the duration for the display to transition from a colorless to a colored state, measured from the initial voltage application until the full display area reaches saturation. We recorded videos of the color transition, extracting the average color per second and calculating the time taken to reach the color contrast threshold ($\Delta E^*_{max} - JND$) to indicate the switching time. Measurements were taken from 2V to 12V, including a 3.7V battery input. Figure 8a shows the trend of switching time decreasing with the voltage input increase. However, this effect becomes less significant around 9V. When powered by a 3.7V LiPo battery, the switching time is 25 seconds for the manual module and 87 seconds for the addressable module. With a voltage step-up converter boosting voltage to 12V, the switch time can be reduced to 10 seconds for the manual module and 58 seconds for the addressable module.

The switch time can be largely affected by the size of the display area. The modular design of ECSkin allows large displays to be divided into smaller sections, activating simultaneously to reduce switching time. To investigate the impact of display sizes and modularity on switching time, we experimented with three square module sizes: 2.25 cm^2, 6.25 cm^2, 12.25 cm^2, and compared them to a jointed display comprising four small modules matching the size of the largest display. As shown in Figure 8b, with the same display pattern, the switching time of the jointed display is 3~4.5x faster than that of the large display, highlighting the advantage of modularity.

4.3 Power Consumption

Electrochromic displays draw current during color transitions, which is referred to as the switching current. We conducted measurements using a KAIWEETS KM100 digital multimeter. At an applied voltage of 5V, the peak switching current is 0.54mA for the addressable module and 0.51mA for the manual module, resulting in a maximum power consumption of 2.7mW. When using a 3.7V 150mAh LiPo battery, the switching current reduces to 0.4mA for the addressable module and 0.32mA for the manual module.

Linking multiple modules may lead to voltage drop due to the trace resistance. The conductive fabric tape has a surface resistance rated $< 0.1\ \Omega$/square and the silver chloride ink has a surface resistance $< 0.075\ \Omega$/square. A noticeable color difference between modules can happen when the voltage drops by 0.5V, causing ΔE^* to exceed the JND value. We measured the voltage drop by connecting a 3.7V battery to a series of manual and addressable modules. Note that connecting modules in parallel would result in a smaller voltage drop, and here, we only report the worst-case scenario. Averaging on three repetitions of measurements, connecting 15 manual modules in a line would result in a 0.08V voltage drop, whereas connecting 15 addressable modules would only cause a 0.002V voltage drop. With wider traces or higher voltage, the effect can be further reduced. By estimation, the color change across the tessellated displays would be even in most cases where less than 100 modules are connected.

4.4 Module Profiles and Flexibility

ECSkin modules comprise multiple layers, including a silicone-based substrate, ink printed on sticker paper, and electrolyte gels. The thickness of a manual module is 2.5 mm (weight: 0.67 g) and 2.3 mm for the addressable module (weight: 1.73 g). A 4x4 tessellation structure of the manual square modules showed little resistance to lateral bending, with a bend radius of 1 cm before the connection breaks. A three-point Instron flexural test reported 0.11 MPa flexure stress at 10.1% flexure strain with a flexural modulus of 2.73 MPa, comparable with thermoplastic material such as EVA (7 MPa) or plasticized flexible PVC (1 MPa)[9].

5 USER EVALUATION

To validate the feasibility of customizing on-skin displays with ECSkin, we recruited participants from diverse backgrounds to experience prototyping with the toolkit. We designed the studies to answer the research questions: (1) With pre-fabricated ECSkin modules, can users create on-skin displays to address different usage scenarios? (2) In cases where a different tessellation pattern is desired, can users customize new module designs by following a fabrication guideline? The user evaluation is two-fold: understanding the usability of ECSkin through a workshop study and investigating the modular design extensibility by a follow-up fabrication study.

5.1 Workshop Usability Study

The study aims to understand *how* and *what* novice users could learn and design the modular EC displays with the toolkit. Besides examining the feasibility of ECSkin, qualitative findings of user preferences were also collected. The study is conducted in a workshop format to uncover usability issues and design opportunities, which is widely adopted by prior toolkit research [4, 33, 35]. Based on the participants' experience prototyping, assembling, and wearing the ECSkin devices, we also hoped to gain insights into potential application usages of the modular on-skin displays.

5.1.1 Participants. 12 participants, aged between 22 and 33 (M=24, SD=3), 8 females and 4 males, from a local university were recruited to design, fabricate, and wear their customized prototype. A pre-workshop survey collected participants' demographic data and past experiences with programming, electronics, and arts and crafts. 9 out of 12 participants have an engineering background and 5 of them are familiar with art and crafting.

5.1.2 Method. 6 designs of pre-fabricated ECSkin modules were provided during the workshop, including the diamond, square, and arc shapes for both manual and addressable versions. Participants chose one of the designs to prototype the brainstormed application (Figure 9). All the display patterns were tested by a looping sequential display program. To adhere the device to targeted body locations, skin-safe double-sided tape is applied to the insulation layer of the module for use.

Procedure. The participants were first introduced to the electrochromic display technology and a detailed walkthrough of the ECSkin prototyping process. Following this, they were asked to brainstorm design ideas that would specify the shape of the display, the displayed pattern, the body locations to wear the prototype, and how users may interact with the device. Upon completing the brainstorming phase, the participants had an hour of prototyping the device with the researchers' help. After experiencing wearing the prototype for 10 minutes, the participants filled out a post-workshop survey to provide feedback on the usability and wearability of the device. To better understand the potential of ECSkin from the participants' viewpoint, a 20-minute semi-structured interview was performed by the end of the workshop, where the participants elaborated on the prototyping

[9] https://omnexus.specialchem.com/polymer-properties/properties/stiffness

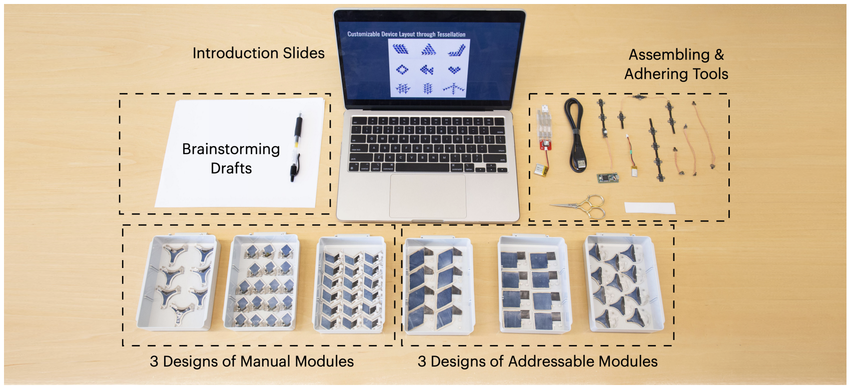

Fig. 9. Materials and prototyping tools provided in the workshop study.

experience and shared their thoughts envisioning future on-skin display technologies. The participants received a gratuity of $15 upon completion of the workshop study.

Analysis. For quantitative data, we recorded the time participants spent prototyping the display, the number of modules used, and the control scheme they chose for implementing the application. We aim to understand the fabrication cost and effort in fabricating customized ECSkin devices. Qualitative data, including the brainstorming ideas and the interview recordings, were transcribed and iterative coded by three researchers. After discussion and reaching a reasonable agreement, common themes were identified to support the findings of the study outcome.

5.1.3 Result and Findings. All 12 participants brainstormed at least 3 ideas of envisioned applications of ECSkin devices, and chose one idea to implement. All participants successfully implemented the selected idea during the prototyping stage. We summarized study results into four topics: implemented projects, quantitative measurements, Likert scale user preferences, and qualitative analysis. Figure 10 shows participants' projects with customized on-skin displays worn on various body locations.

Implemented Projects. The conceptual prototypes are made without implementing the input/sensing functions. While the prototype can show the designed display patterns, the triggers will be implemented with keyboard control using the Wizard of Oz method [9].

Four participants (P4, P8, P9, P11) implemented an ECSkin display that can be combined with health-related sensors. P4 created an EC necklace combining three rows of addressable modules (Figure 10d). With a sensor attached to the skin, the device is envisioned to track the wearer's body temperature and change color by levels. P8 created EC armbands that track the progress of the workout (Figure 10h). P8 envisioned that by integrating sensors that can monitor the body fat around the wearing location, the color change of the armband would signal the user when toning is completed. P9 proposed a private multi-functional health monitor worn on the inner forearm (Figure 10i). Three rows of EC modules can keep track of three bio-signals, including blood sugar level, blood pressure, and heart rate. When any bio-signal indicator surpasses the threshold, the corresponding row of modules shows a color change to warn the users. Similarly, P11 devised a heart-shaped display that shows color change when exceeding the heart rate threshold (Figure 10k). He chose to wear the device on the outer arm to share the display information with both the wearer and nearby caregivers.

For displaying data from digital devices, P2 chose to implement the ECSkin device on the forearm for IOT applications (Figure 10b). Through wireless connection, each module can be mapped to smart home furniture, such as light control, where the module's color represents the status of linked devices. P3, P5, and P7 implemented

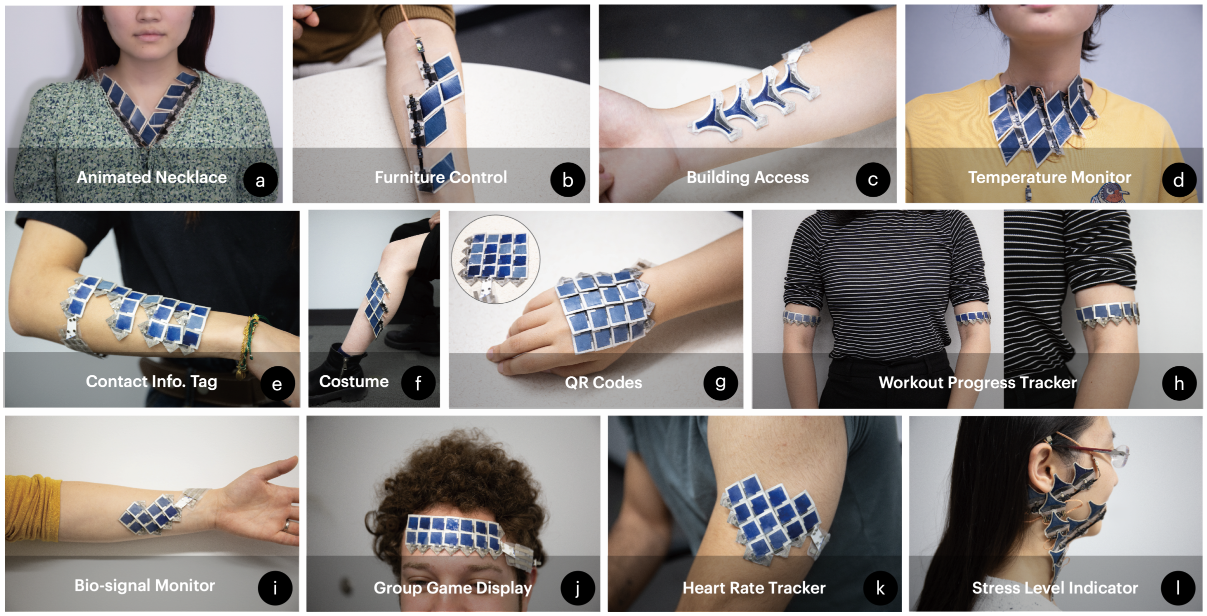

Fig. 10. Prototypes made by the study participants. Personal Health Monitor: (d), (h), (i), and (k); Notification Display for Digital Devices: (b); E-Label: (c), (e), and (g); Networked Interaction: (j); Public Broadcasting Display: (l); Aesthetic Display: (a) and (f).

ECSkin displays as E-labels. Manual-control modules are designed and configured into specific patterns to show building access (Figure 10c), contact information for elderly users (Figure 10e), and QR codes (Figure 10g).

P10 and P12 designed ECSkin devices that can be worn on the face. P10 implemented a rectangle display wearing on the forehead (Figure 10j). When multiple users in a group setting wear the displays, the devices can generate patterns for people other than the wearer to see, enabling various networked interactive group games. On the other hand, P12 designed a public broadcasting display that covers the cheek and the neck (Figure 10l). The modules' color change would grow like vines from the neck to the face according to the wearer's mood, which indicates the wearer's stress level to signal the co-workers in a working environment subtly.

For aesthetic purposes, P1 and P6 implemented on-skin displays as clothing accessories. P1 proposed a necklace-like device with two rows of addressable diamond-shaped modules (Figure 10a). It is designed to gradually change color from the middle to the sides, catching people's attention while complementing various types of clothing. P6 designed the scale-like device to be part of the costume at lower-body (Figure 10f). Attaching to the calf, the addressable modules can show color change to simulate the transformation into a mermaid tail.

Quantitative Measurements. On average, participants spent 25 minutes (SD=10.4) accomplishing their design and putting the device on a desired body part. Depending on the application usage, participants used 4 to 18 modules to complete the design. Seven participants implemented their designs with manual modules, and five used the addressable version, where multiple display patterns are required.

By averaging the material cost for fabricating the ECSkin modules, we estimate the cost for each designed display. The expense for the workshop-implemented devices ranged from \$14.72 to \$62.58 (USD). Nonetheless, all the fabricated devices were assembled from the same set of modules. For example, the most frequently selected

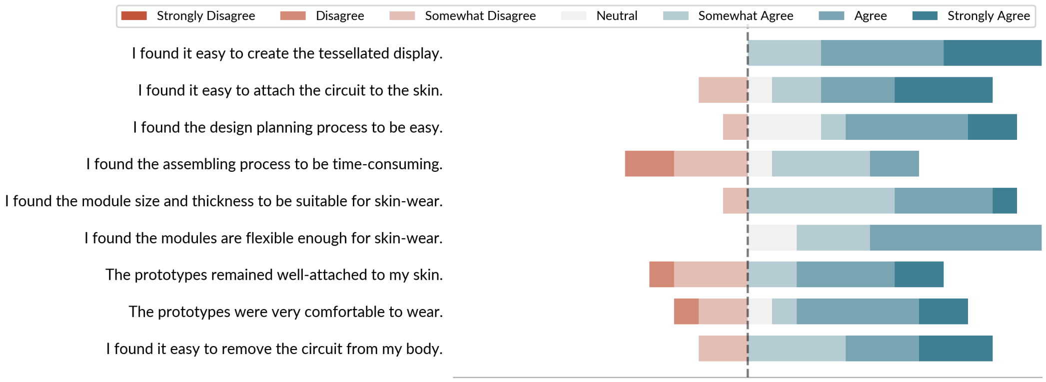

Fig. 11. 7-point Likert scale responses from the post-study survey.

Table 2. The code frequency (number of participants > 3) from post-study interviews about prototyping with ECSkin.

Usability			Customizing & User Perception		
Theme	**Sub-theme**	**Frequency**	**Theme**	**Sub-theme**	**Frequency**
(a) Learnability	Easy to Connect	7	(f) Design Guideline	Body Curves	3
	Easy to Adhere	4		Resemble Objects	3
(b) Design Process	Shape: Easy to Design	8		Noticeable	3
	Pattern: Easy to Design	8	(g) Wearing Perception	Cool	4
(c) Reconfigurability	Shape: Reconfigurable	10		Fashionable	4
	Pattern: Reconfigurable	8		On-skin Lego	3
(d) Form Factor	Suitable Thickness	9	(h) Improvement	Module: Smaller Size	8
	Suitable Flexibility	6		More Flexible	7
	Suitable Size	5		Module: Thinner	4
(e) Wearability	Conform to the Skin	6		Robustness	4
	Comfortable	5		On-body Fabrication	4
	Stable Attachment	4		Connection Guidance	4

tessellation design, square shape manual module, was reused for 6 times. Only one of the 19 provided modules was found to malfunction after the study.

Likert Scale User Preferences. In the post-study survey, participants filled out 7-point Likert scale questions to provide their preference toward the toolkit usability in each fabrication step. They appreciated the easiness of making on-skin displays with ECSkin (Median (M)=6 on the Likert scale; 1=strongly disagree, 7=strongly agree). One concern raised by 7 out of 13 participants is that the first time assembling can be time-consuming (M=4.5). However, they agreed on the module form factor (size and thickness, M=5) and flexibility (M=6) to be suitable for on-skin use cases. Regarding the experience interacting with the prototypes, they reported the ECSkin device is well-attached to the skin (M=5.5), comfortable to wear (M=6), and easy to remove from the body (M=5.5). As summarized in Figure 11, participants generally responded favorably of the toolkit usability and their experience with ECSkin.

ECSkin Usability. We present the qualitative result by categorizing participants' interview feedback into topics and common themes. In Table 2 (a) to (e) we report themes regarding the overall usability of the ECSkin toolkit.

In terms of ***Learnability***, many participants found the fabrication process easy to learn, especially the connection between modules (number of participants (n)=7)) with intuitive magnetic alignment. The prototyping process is smooth and adhering the device on the body is straightforward (n=4). Regarding the ***Design Process*** and ***Reconfigurability***, while the participants have limited experience prototyping wearables, they commented designing the device shape and the display patterns are easy (n=8). During the design iteration, they appreciated the reconfigurability of the modules that allowed them to change the shape (n=10) and pattern (n=8) using the same set of modules. However, P3 and P4 commented on challenges in modifying the display patterns. P3 struggled to design a gradual color change in a sequence of modules with manual control but found the modules could only change color simultaneously, and P4 did not have the software programming skills to control the addressable modules. These concerns indicated limitations for both control schemes: the manual control does not support animated displays, and the addressable control has a prerequisite of programming background.

Regarding the ***Form Factor***, participants provided insights on the module dimensions in consideration of the design, prototype, and wearing experiences. Most participants reacted positively to the module thickness (n=9) and considered the overall flexibility of the device to be acceptable (n=6). Participants also commented on the device ***Wearability*** when attaching the device to the skin. They agreed that the modular display can conform to the skin (n=6) and are comfortable to wear (n=5). Overall, the lightweight display devices stayed well on the body (n=4).

Customizing and User Perception. Table 2 (f) to (i) records main themes from participants' feedback specifically toward their implemented designs. Participants described their ***Design Guideline*** as conforming to body curves (n=3) or resembling familiar objects or accessories (n=3). Depending on the application scenario, some participants designed the wearing body locations to be very noticeable (n=3). In contrast, others wanted the display to be discreet or hidden underneath clothes for private or formal occasions. Participants are pleased by the customized display with ***Perceptions*** of it as cool (n=4) to wear. When put around the neck, the on-skin displays remind them of fashionable accessories (n=4). Three participants mentioned that the modular design is similar to Lego but in a soft, skin-wearable form.

By reviewing the fabricated prototypes, participants proposed several directions for future ***Improvement*** of the current version of the toolkit. They preferred to use smaller-sized (n=8) and more flexible (n=7) modules that are thinner or more conformable to the skin (n=4). The device attachment needs to be more robust to ensure that it does not fall off from the body (n=4). Participants also suggest enabling an on-body fabrication workflow (n=4) to allow users to iterate and make adjustments to the prototype directly on the body. To improve the toolkit learnability, additional guidance in indicating connection parts (n=4) could be helpful for novice users.

5.2 Fabrication Case Study

The goal of the fabrication study is to evaluate the proposed workflow for customizing and fabricating new designs of ECSkin module. With the raw materials and a user manual provided, we aimed to verify if participants could fabricate addressable ECSkin modules using customized tessellation patterns. Besides, by observing the design and crafting process and collecting user feedback, we hoped to learn the difficulties in fabrication and opportunities to support users during the design iterations.

5.2.1 Participants. 4 of the 12 participants volunteered to rejoin the follow-up fabrication study on a different day, consisting of 2 females and 2 males aged between 22 and 27 (M=25, SD=2.2).

5.2.2 Method. During the fabrication study, raw materials for fabricating ECSkin modules were prepared (Figure 12). Each participant had one piece of silicone substrate, two pieces of sticker paper with either electrochromic

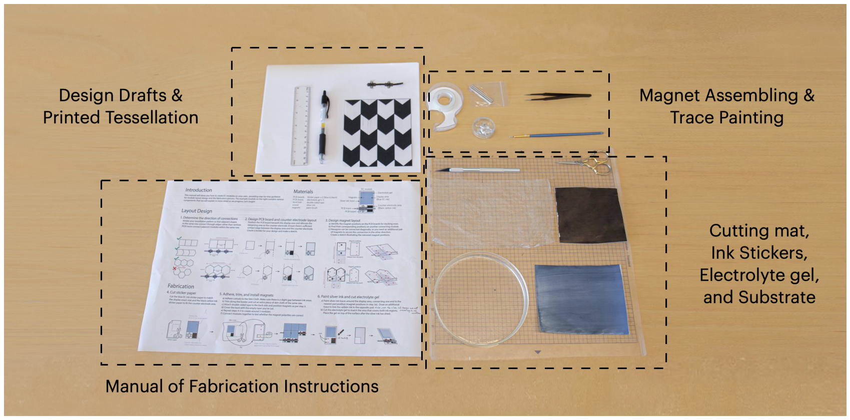

Fig. 12. Materials and prototyping tools provided in the fabrication study.

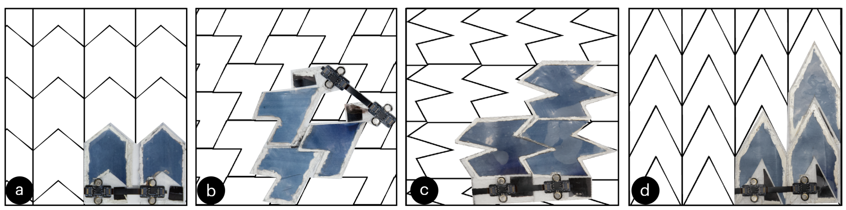

Fig. 13. 4 Participants fabricated ECSkin modules made with customized tessellation patterns. (a), (c) and (d) are compensated deformations of parallelograms, while (b) is from hexagons.

ink or carbon (counter electrode) ink printed on top, one piece of electrolyte gel layer, and magnets. Scissors, an Exacto knife, and double-sided adhesive were also provided for cutting and assembling. Besides, each participant's chosen tessellation patterns were printed on printer papers for their design reference.

Procedure. To evaluate the customizability of the ECSkin modular design, participants were tasked to fabricate ECSkin modules based on their designs of new tessellation patterns utilizing an online tessellation creator tools[10]. The 2.5-hour, single-session follow-up study started with an introduction to materials and guidance on a 1-page fabrication manual. The detailed content of the manual can be found in Supplementary Materials. Based on the tessellation pattern, the participants needed to design the connection area, counter electrode area, addressable switch placement, and magnet pairs for module connections before assembling. We designed the fabrication study with minimal guidance in order to investigate potential challenges users may encounter in a real-world scenario. During the fabrication process, the observing researchers would not proactively assist the participants unless issues were encountered. The participants had a maximum 2-hour period to finish fabricating the customized ECSkin modules. They received an additional gratuity of $20 upon completion of the follow-up study.

Analysis. For quantitative data, we recorded the time participants spent fabricating the modules and the number of modules made to understand the fabrication effort. Qualitative data, including the fabrication challenges and the improvement, were transcribed and summarized from the interview recordings.

[10]http://www.shodor.org/interactivate/activities/Tessellate/

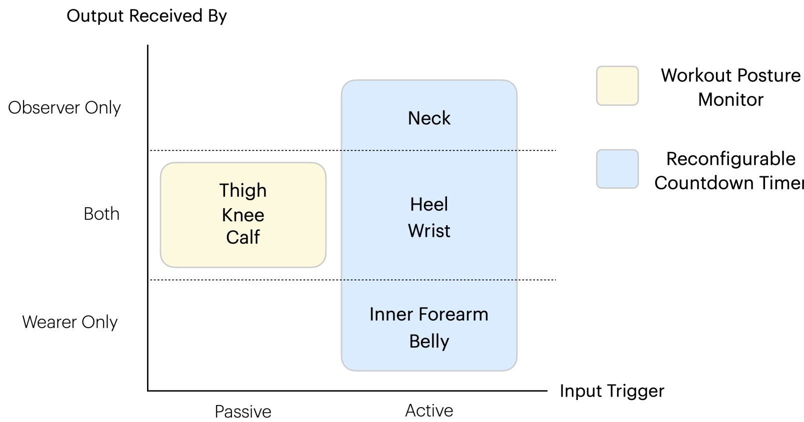

Fig. 14. Interaction design space of example applications modified from social wearables framework [8].

5.2.3 Result and Findings. All four participants successfully fabricated their own modules, as shown in Figure 13. The fabricated modules were tested by connecting to addressable switches and a battery to show color change. All participants fabricated unique tessellation designs. According to the definition of tessellation pattern, three designs are compensated deformation of parallelograms, and one is compensated deformation of hexagons. P2 and P4 made paper prototypes that specified the magnet positions, display area, and connection part to verify the design validity. On average, they spent 2 hours and 17 minutes to finish module fabrication, where P1 made two modules and P2, P3, and P4 made three.

Fabrication steps that participants found challenging include *placing magnets* and *aligning addressable switches*. During the fabrication process, two of the participants asked researchers for assistance. P1 was confused by the module structure and could not follow the manual. They could continue after a researcher explained the multi-layer module design in detail. P4 had difficulty installing the magnets with the correct polarities, so a researcher demonstrated the know-how in unifying the magnet polarities and effective ways to install magnets. During the interview, participants commented on unclear design criteria, including defining PCB placements to align with modules in a row (P2) and setting boundaries for connection areas (P3).

6 APPLICATION

ECSkin enables reconfigurable on-skin displays in different shapes and patterns worn on various body locations. We envision future on-skin interfaces with such customizability to be adaptable for varied social and personal scenarios. Referring to the design framework for social wearables by Dagan *et al.* [8], the interaction design space is illustrated in Figure 14. The two axes of the design space distinguish the input triggers and the output receiver. A designed input can be *passive* when it's performed by sensors of the wearer's bio-signal or surrounding environment. Conversely, the manual input can be *active* when the wearer directly triggers it. The display can be private for the wearer or public and noticeable for the wearer and the surrounding observers. Occasionally, the display can be worn on specific body locations that are only visible to observers. To highlight the versatility and adaptivity of ECSkin, we present two example applications: ***Workout Posture Monitor*** composed of three patterns of addressable modules and ***Reconfigurable Countdown Timer*** made of arc-shape manual modules.

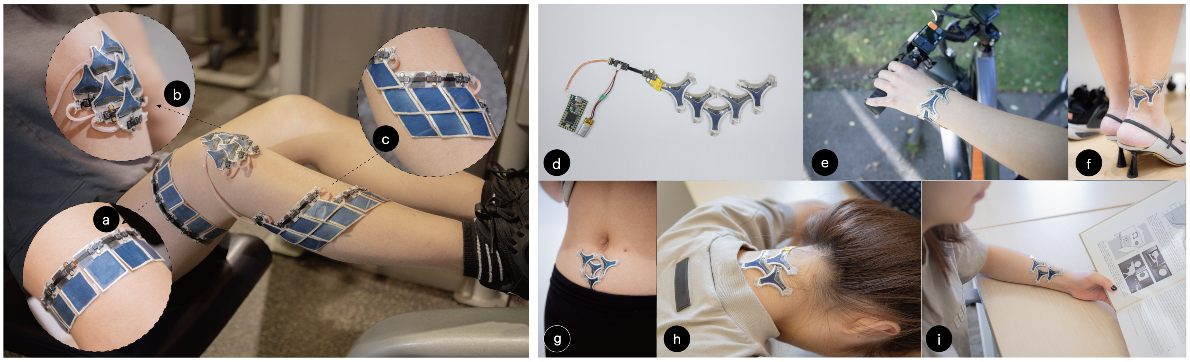

Fig. 15. ECSkin Applications: (Left) Workout Posture Monitor made with a three-segment ECSkin display. (a) Square modules connected in a round-band on the thigh. (b) Arc-shaped modules are tessellated into a knee pad. (c) Curved display on the calf made of diamond-shaped modules. (Right) Reconfigurable Timer designed with manual arc-shaped ECSkin modules. (d) An untethered device made with an MCU and a battery. (e) Wrist timer for bicycling. (f) Heel timer to prevent injury wearing high heels for long. (g) Belly timer for changing sanitary pads. (h) Neck timer as a gentle alarm. (i) Inner forearm timer as a hydration reminder.

6.1 Workout Posture Monitor

Designing on-skin interfaces across multiple body locations can be challenging as the human body consists of complex contours with varied structures and curves. In a usage scenario where a lower-body posture monitor requires the on-skin display to be tessellated from the thigh, the knee, to the calf, we propose utilizing a combination of three tessellation patterns: diamond, square, and arc modules to achieve a flexible and conformable wearing experience (Figure 15a, b, and c). Square modules were used for linear or right-angle shapes, which were used to form a round-band display segment on the thigh. The arc-shaped modules were tessellated into a knee pad to make a more flexible and stretchable surface to cover the knee. The last segment of a curved-shape display was made of diamond-shaped modules to connect from the knee to the upper calf. Users can wear a custom number of modules based on the number of repetitions, and the EC modules worn on different body parts provide specific monitoring of the training movement. In this example, we incorporated IMU (inertial measurement unit) sensors and proximity sensors to utilize the three-segment display for assessing knee angle — ensuring it doesn't extend beyond the toes — and the leg position by measuring the distance between the thigh and lower leg in lower-body exercises. Considering the transition time for modules to change colors, we designed the display to record a posture error rather than warning the user in real time. When improper posture is detected during a specific repetition, a color change will be activated on the corresponding module. Upon completing a training set, users can review the number of color changes among the repetitions in each segment of modules to monitor the progress.

6.2 Reconfigurable Countdown Timer

The detachable and modular on-skin display can support wearing on various body locations for different usage scenarios. To illustrate the potential of such a customizable display, we provide example interactions throughout a day of an imaginary target audience profile, Agnes. We present an example ECSkin display made of arc-shaped manual control modules as count-down timers. When a set countdown is over, the timer display changes color to provide a subtle visual notification to the wearer (Figure 15d).

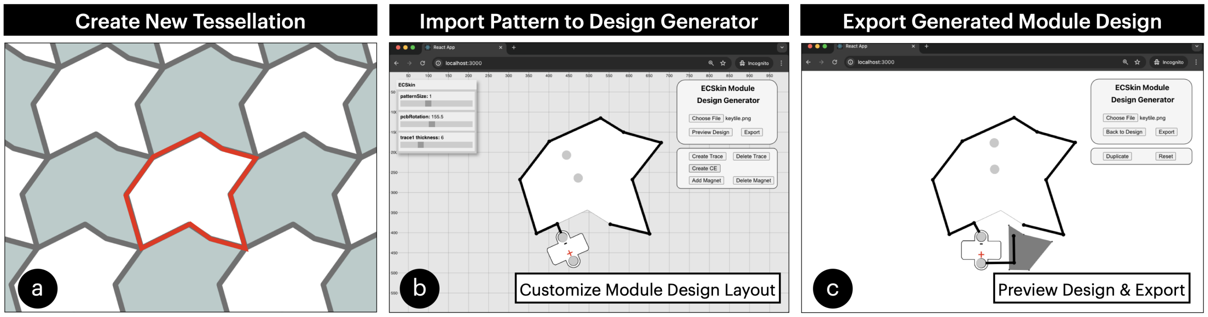

Fig. 16. The design workflow with software supports: (a) The user designs a new 1-way symmetric tessellation pattern and saves the prototile as a figure. (b) After uploading it to the ECSkin web app, the software tool supports the user to customize the design, such as adjusting the pattern size, rotating the addressable switch PCB, and adding circuit components. (c) Once the initial setting is confirmed, the user can fine-tune and export the design in SVG (Scalable Vector Graphics) format.

In the morning, Agnes set a timer and wore the display around the wrist. As for the morning aerobic exercise, she tracks her 30-minute bicycle ride before heading to the office (Fig 15e). After arriving at the office, Agnes puts on a pair of high heels. She modifies the timer display into a V-shape to fit the ankle-high heels (Fig 15f). The timer display changes color after continuous walking for three hours, and either the colleagues in the office or Agnes herself would notice the color change so she can swap to flats to prevent injuries or pain. During the menstrual period, Agnes would wear the display on her belly to notify herself of changing sanitary pads every 6 hours (Fig 15g). In the noon break from work, Agnes takes a power nap. To avoid an alarm noise disturbing colleagues in her open office space, she modifies the shape of the timer display and wears it on the back of the neck (Fig 15h). When the display changed color after 20 minutes, a colleague sitting next to her would gently nudge her to wake up. Next, Agnes continues to work and have some reading sessions in the afternoon. She set up a timer on her inner forearm to remind herself to keep hydrated every 2 hours (Fig 15i). Throughout the day, the same set of modules are reconfigured for private or public scenarios, where Agnes can personalize the device in shapes that fit the desired body parts.

7 DISCUSSION

7.1 Software Design Tool

We summarized user feedback from the fabrication study to better support the process of designing ECSkin modules with new tessellation patterns. We implemented a software tool that generates the module design layouts based on the following geometric rules.

(1) Tessellation patterns should be designed in 1-way symmetry (tiled in the same orientation).
(2) Components including the Electrochromic (EC) ink, the counter electrode (CE), and the addressable switch PCB should be positioned closely but not in contact.
(3) The conductive traces should connect the voltage to CE, and connect the ground to EC.
(4) Magnets are placed according to the overlapped position of the display area and the connection parts.

Figure 16 demonstrates the 3-step workflow for generating new designs of ECSkin modules with customized tessellation patterns. We used React UI library with P5 JavaScript library to implement the design tool and GUI. The browser-based design tool has been tested on Google Chrome on a Macbook Pro.

7.2 Modular Electrochromic Display

The motivation of this work originates from the limited *reconfigurability* of current wearable electrochromic displays. Our approach divides the entire display area into pixelated modules and enables the on-skin display to become more adaptive and sustainable. As illustrated in our Application of the Reconfigurable Countdown Timer (Section 6.2), without the need to fabricate multiple devices for different designs, the same modules can be recycled and reconfigured for multiple personal applications. At the same time, the technical evaluation of the proof-of-concept prototypes shows the potential of the modular approach in shortening the activation time by pixellating the display pattern with smaller display modules. We envision the modular design of EC displays as having the potential to address the technical limitation of long response time and provide new opportunities in diverse on-skin interaction scenarios.

While the modular approach affords better performance and customizability, we observed additional wiring demands regarding the control schemes. Since the modular display is dynamically constructed, an extensible powering network has to be implemented. For manual control designs, the power and ground are transmitted from the overlapping connection parts of neighboring modules, where the risk of shorting can increase when modules are connected. Although the addressable module designs have integrated the powering traces into bus wires, the between-row connections must rely on varied lengths of flexible traces. When designing the EC display modules, the tradeoff between the module size and construction overhead needs to be considered. For the wearable display context, we suggest a module dimension between 0.5 cm^2 and 3cm^2.

7.3 Enriched On-Body Visual Expressions

Throughout the workshop study, we investigated user perceptions toward the usages of on-skin visual displays (Section 5.1). Besides using the display interfaces for personal notification, we recorded many envisioned applications for utilizing the visual display as an additional communication channel for interpersonal scenarios. Worn on various body locations, the displays can provide transient and interactive expressions that enhance the visual presentation of the wearer. They can be tokens or symbols recognized by certain social group members or broadcasted statements that draw attention from unspecified audiences. Whether practically used or aesthetically pleasing, the ECSkin display technology offers a complimentary non-verbal communication channel for expressive output modalities in social and communicational situations.

7.4 Broader Usages of ECSkin

In this work, we focused on designing and implementing the *visual output* technology. Nonetheless, recent advances in on-skin technologies have supported a wide range of sensing options that can be integrated into modular circuitry [34, 35]. ECSkin are compatible with other on-skin systems, where the on-skin display devices can be connected as output for visualizing the sensor data.

While we designed ECSkin to be a visual output modality suitable for on-skin context, it does not imply the display can only be situated on the skin. Beyond the on-skin context, multiple workshop participants discussed the possibility of utilizing ECSkin for prototyping textile or room-scale displays during the post-study interview. Since we designed the modules with strict requirements of the form factor to meet the high standard of skin conformability, we are confident that the display system can be easily transplanted to mediums or platforms other than the skin, which can further broaden the usage of the electrochromic modular display.

7.5 Material Skin-Safety

ECSkin comprises bio-compatible materials, including silicone substrate, CNT electrodes, and PEDOT:PSS electrochromic ink. However, the electrolyte material [EMI][TFSA] is listed as toxic if swallowed. To avoid direct skin contact with the electrolyte caused by liquid leakage, we blend the electrolyte with structuring polymers into solid ion gels and layered on the module [39]. When wearing an ECSkin display, only the silicone substrates would attach to the users' skin with all the electrical components insulated. Nonetheless, additional transparent shielding or sealing of the display is recommended to address any potential safety concerns.

7.6 Technical Prospects

Based on the findings from the user evaluation, we identified directions to advance the proposed technology.

(1) **Color Versatility**. The existing ECSkin implementation exclusively facilitates a monochromatic color transition, shifting from light blue to dark blue. To enhance displays with increased information density, arrays of the ECSkin module must be integrated, pixelated, and individually controlled. The display color range can be expanded by incorporating other formulas of the electrochromic materials [6, 44].
(2) **Battery**. Though the electrochromic modules have low power consumption, a battery or powering circuit is still necessary. To address the sustainability and wearability concerns, recent advances in power harvesting technologies pointed out the way to a self-powered electrochromic display, *e.g.*, powered through energy harvesting mechanical movements such as stretching the display [60].
(3) **Color-Change Performance**. ECSkin modules are made of the readily available commercial PEDOT:PSS ink. To further improve the display performance with higher color contrast and faster activation time, automatic ink decomposition techniques can be used to control an ideal thickness of the ink layer [28] or printing with advanced electrochromic materials suitable for flexible displays [40].

8 CONCLUSION

We presented ECSkin, an on-skin construction toolkit for creating modular electrochromic displays. ECSkin leverages the monohedral tessellation pattern to tile, scale, and customize the display surface. Each display module combines to adjacent modules through magnetic connections, and a detachable circuit control supports individual module actuation in either manual or addressable schemes. We characterized the performance of the implemented electrochromic technology through technical evaluation. Besides, we investigated the toolkit usability in a workshop study and evaluated the feasibility of customizing module design in a follow-up fabrication study. Learning from participants' feedback, we then proposed two exemplary applications based on an interaction design space. Our future work seeks to optimize the fabrication process, the module performance, and the versatility of display colors and incorporate a digital design tool to support broader usages of ECSkin. We envision the continuous evolution of modular display construction and performance, with the potential to emerge as the next generation of personalized wearable displays in place of contemporary mobile devices.

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