Patch-O: Deformable Woven Patches for On-body Actuation

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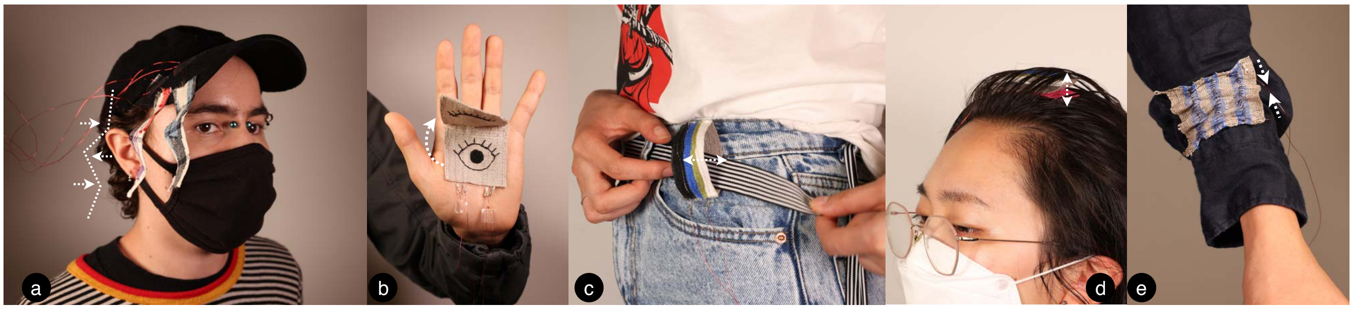

Figure 1: We present Patch-O, a novel deformable interface devised as a woven patch that enables diverse movement-based interactions adaptive to garments or on-skin wear. It supports three basic actuation primitives, including bending (a), expanding (b)(c)(d), and shrinking (e). In the design workshop study and application scenarios, we demonstrate expressive examples, including (a) wave-bending patches as dynamic fringes, (b) a deformable patch for "opening a third eye," as well as functional examples such as a tubular expansion patch which functions as (c) a belt hoop for easy access and (d) a volumizing hair lifter, and (e) a shrinking patch for lifting sleeves under humid weather.

ABSTRACT

We present Patch-O, a novel deformable interface devised as a woven patch that enables diverse movement-based interactions adaptive to garments or on-skin wearing. Patch-O interfaces are uniquely detachable and relocatable soft actuation units that can be sewn or attached to clothing or skin at various locations. To optimize the morphing effect while preserving a slim form factor, we introduce a construction approach that integrates actuators at a structural level and varies the texture and stiffness of the woven substrate locally. We implement three basic actuation primitives, including bending, expanding, and shrinking, and experiment with aggregation parameters to exhaustively extend the design space. A final workshop study inviting textile practitioners to create personalized designs of Patch-O provides insights into the expressiveness of the approach for wearable interactions. We conclude with three applications inspired by users' designs and showcase the aesthetic and functional usages enabled by the deformable woven patches.

CCS CONCEPTS

• **Human-centered computing → Interface design prototyping.**

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Fabrication; Fashion/Clothing; Wearable Computers

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1 INTRODUCTION

Humans started to wear textile products in prehistoric times, and the fabrication methods have continually evolved. With this intimacy and versatility, emergent research of on-body technology has focused on enhancing soft fabrics to be expressive and interactive through embedding a wide range of computational actuating materials [12, 30, 43, 49, 63]. Previous research explored integrating smart materials into fabrics either at a surface level [20, 40] or a structural level [30, 49, 51]. The surface-level approach (e.g., attaching 3D printed structures [40] or silicone-rubber stickers [20]) involves fabricating the non-textile actuation parts independently before adhering them to the fabric surface. While the standalone fabrication process affords diverse actuation designs, the bonding between textile and non-textile materials may lead to undesired rigidity and thickness. On the contrary, the structural approach incorporates smart materials directly at the crafting stage to achieve a slimmer integration (e.g., through knitting [2, 30], or weaving [11, 24, 49, 51]). However, this approach requires either fabricating a whole piece of garment for a predefined actuation or making permanent changes on an existing fabric. In this work, we adopt the concept of *patching* from *mending and repairing* in textiles to *enhancing* clothes. We made woven patches that are slim and deformable by incorporating actuation materials during weaving. As simple as ordinary patches, they can be easily attached or detached to cloth or skin, which affords quick prototyping and versatile actuation effects for test and iteration.

We present Patch-O, weaving deformable patches as soft output interfaces for on-body actuation. Our method involves weaving fabric substrate patches embedded with SMA actuators that can be applied to and deform garments or human skin in a diverse set of movement-based interactions. The patches, which are detachable and relocatable, are woven with unique structural and yarn material combinations, which yields a versatile woven substrate tunable for different actuation mechanisms. Besides, we present five interlacing techniques for integrating the smart material (e.g., SMA wires and SMA springs) at a structural level which affords versatile deformations of the patches: floating warp/weft, supplementary warp, supplementary weft, vias, and hand manipulation. Taking advantage of the structural and textural flexibility of weaving, the woven patch enables slim integration while preserving the expressive weave aesthetics that differentiate our method from previous surface-level integration methods. Embodied in a woven patch, our system is inherently easy to tape or sew on garments, while a direct attachment to the skin is also possible. We systematically experimented with different yarn materials, weaving techniques, and actuation mechanisms and exhaustively identified aggregation parameters within the design space. To collect insights from textile practitioners toward incorporating Patch-O into their creations, we conducted a workshop study that invited participants to craft the woven patches with a floor loom and deploy the device to their everyday garments. Participants found that beyond being able to customize the individual patches, they could also temporarily apply it on diverse garment forms for actuation. Drawing inspirations from users' designs, we identified three applications including a weather adaptive outfit, a style-switching dress, and an aesthetic expressive tank top. Multiple deformable patches are used in each scenario to enhance a complete set of clothing. By transplanting the actuation units for interactive soft fabrics into deformable woven patches, we present a novel reattachable interface enabling diverse on-body actuations. The main contributions of this paper are listed below:

(1) An adaptable and reattachable woven patch interface that enables deformation of soft fabrics and on-skin haptic feedback. We provide details of the fabrication, implementation, and performance of the twelve Patch-O patches. We evaluate our designs through a series of systematic experiments in aggregating, scaling, and arranging the active and passive elements.
(2) Validation of Patch-O with a design workshop session and application demonstrations, which sheds light on the expressiveness and extensibility of the fabrication approach.

2 RELATED WORK

2.1 E-Textile Fabrication Methods: Surface-level, Structural-level, and Reusable Patches as an Alternative Form Factor

Smart fabric interfaces have emerged in HCI and researchers have explored methods for integrating both sensing [9, 28, 36, 42, 45, 46, 50, 63] and actuation [18, 35, 57] elements into the soft fabrics. Most of the methods involve integrating the device components on a ready-made fabric substrate through stitching [8, 47], embroidery [1, 16, 17, 19, 21, 43, 63], sewing [41], felting [4, 25], silk-screening [31], and both inkjet [62] and 3D printing [40]. Since the non-textile parts are only integrated at the surface level, these methods support fast augmentation and afford versatile morphing effects but miss the benefits of constructing the fabric medium that fosters a slimmer and customizable integration and brings aesthetic richness.

To create a structural-level integration, previous work exploited different textile construction methods such as weaving [7, 11, 14, 15, 49] and knitting [2, 18, 44, 56]. Woven fabric is composed of multiple yarns held in tension, with the weft (horizontal) and warp (vertical) yarn groups crossing each other at right angles. Due to the intersecting structure, embedding various materials through weaving is inherently simple. The structural integration has been used for integrating circuits [7, 13, 14, 23, 24, 51], touch surfaces [46, 49, 58, 64], morphing interfaces [52], to textile displays [6, 11, 12]. On the contrary, the knitted fabric is based on a single yarn looping continuously, and can create a more stretchable texture for close-body haptics [30]. However, the range of smart materials which can sustain the stress of the knitting machine's operation is significantly limited compared to woven interfaces. This work adopts the underexplored form of a slim, woven patch as an alternative form factor for incorporating movement-based actuation. The overhead of fabrication time for the patch lies between the surface-level and structural-level approaches. That is, while there is an initial overhead for weaving the patch, we can rapidly apply it to many surfaces with little transition time afterward. Hence, a woven patch has the structural benefits of woven fabric construction (slimness and durability) while retaining the advantages offered by surface-level integration, such as reusability and fast attachment/detachment. Table 1 shows the feature comparison between the three integration methods.

2.2 Deformable Fabric-based Interfaces

Shape-changing fabric interfaces have opened up opportunities for novel on-body interactions. Some enhance aesthetic expression for art and fashion [5, 27, 48, 53]; others incorporate new functions to clothing, ranging from thermal/humidity regulation [59, 61], self-fitting garments [18], to shape changing devices [37, 60]. Different actuation mechanisms have been developed to stimulate the morphing effects, which can be categorized into four types: mechanical, pneumatic, biological, and shape-memory material. Mechanical actuation often relies on motors to create retractional, translational, or rotational force to drive the movable parts [27, 34, 59]. While the motor offers programmable and accurate control of high-loading actuation, it also brings extra noise, thickness, and rigidity to the

Table 1: Comparison between Patch-O and two integration approaches for on-cloth deformation.

SMA Integration Method	Representative Work(s)	Fabrication Time	Detachable & Relocatable	Slim Form Factor	Diverse Actuation	Aesthetically Customizable
Surface-level SMA Integration	Springlets [20], ClothTiles [40]	Short	✓		✓	
Structural-level SMA Integration	WovenSkin [51], KnitDermis [30] Kukkia and Vilkas [4]	Long		✓		✓
Mending Woven SMA Patches	Patch-O (Our method)	Medium	✓	✓	✓	✓

otherwise soft interface, which can limit wearability. Pneumatically actuated interfaces utilize soft composite materials to construct inflation channels expandable with compressed air [48, 60]. PneUI [60] proposed a multilayer structure that enables isotropic and anisotropic deformation characterized by the constraint material. Awakened Apparel [48] devised a folding inflation mechanism to alter the origami pattern on a skirt. Though the pneumatic interface can be soft, it requires pipes and pumps to pressurize the actuators externally. Biological mechanisms combine the sensing and actuating functions from the natural response of living organisms such as natto cells [61], which raise difficulties in programming control schemes. Shape-memory alloy (SMA) has become a promising solution for on-body deformations due to its efficiency and flexibility. While surface-level integration of SMA through 3D printing [40] and sewing [41] have been examined, few investigations have explored structural-level integration directly into the fabric substrate for a slimmer form. Weaving a Second Skin [51] explores a single instance of a woven, structural integration through an SMA spring, yet a comprehensive study of the full range of suitable woven structures remains lacking. We aim to fill this gap through an in-depth investigation of woven structural integration of SMAs, identifying suitable parameters for deformable fabric-based interfaces.

2.3 SMA Interfaces for On-body Interactions

A variety of SMA interfaces have been explored for on-body interactions. Based on the required function and form, three types of SMA products are widely adopted: (1) springs, (2) wires for contraction/elongation, and (3) wires for shape-memory effect. Benefiting from the helix structure, the *SMA spring* can provide the largest displacement and exert significant contraction force. Springlets [20] implements a multi-layer tactile sticker to be worn on the skin, where the SMA spring is embedded in silicone rubber tape that is customizable to different tactile displays. Textile-based on-body interfaces also utilize the SMA spring to generate versatile tactile stimuli that adapt to a variety of body locations [30, 51]. On the other hand, the *SMA wire* offers a subtler shape deforming mechanism but comes with a slimmer, more flexible form factor. Depending on the manufacturing process, SMA wires with an anisotropic structure can deliver a significant shrinking performance in the fiber direction but are not suitable for the shape-memory usages. Natural touch sensations such as stroking and grabbing can be simulated on the arm by arranging the contractable SMA wire segments into arrays or matrices [32, 39]. On the other hand, ClothTiles [40] exploits a 3D-printed base structure to convert the shrinking in length into a bending force applied to garments, and extends the on-cloth actuation mechanisms by aggregating multiple fundamental elements. *SMA shape-memory wire* has an isotropic structure which can be trained to remember a specific shape in the austenite state (around 500°C). Being malleable at room temperature, the SMA shape-memory wire would restore to the trained shape when it is heated to the transfer temperature. Seamless Seams [41] proposed a series of crafting techniques to train, sew, and manipulate the SMA shape-memeory wire onto fabrics to create soft actuation interfaces. By embedding pre-trained SMA wires into sculptural folds and drapes of fabric, SKORPIONS [5] designed a set of deformable garments that move in slow, organic motions.

The aforementioned SMA interfaces often *permanently* alter a garment, and typically target a single SMA actuation mechanism. In this work, we exploit the underexplored form of *woven patches* to make temporary and detachable SMA interfaces. We use the structural richness of weaving to integrate SMA actuators of all types, while also varying the texture and stiffness of the woven substrate locally, for a wider range of movement-based effects.

3 PATCH-O SYSTEM

To bring movement-based interactions into a slim and reusable woven patch, we implemented Patch-O with the following design goals:

(1) **Slim form factor through structural SMA integration**: Five interlacing arrangements were strategically applied for embedding different SMA wires/springs into the woven structure seamlessly.
(2) **Affording customization on functional and aesthetic fronts for an expressive patch**: We incorporate multiple materials/weaving techniques to tune the texture/stiffness of the patch locally, which helps optimize the deformation within the thin form factor. As one of the free-form crafting techniques, weaving a patch also allows customization based on personal aesthetics.
(3) **One patch, many usage scenarios**: Unlike previous on-cloth deformation interfaces that often involve permanent alteration of the garments, we encapsulate the actuation units into patches that can be rearranged, combined, or attached/detached for a variety of use cases. The lightweight, flexible fabric form can be temporarily attached to garments with fabric tape, while hand sewing for a more solid fixation is also feasible.

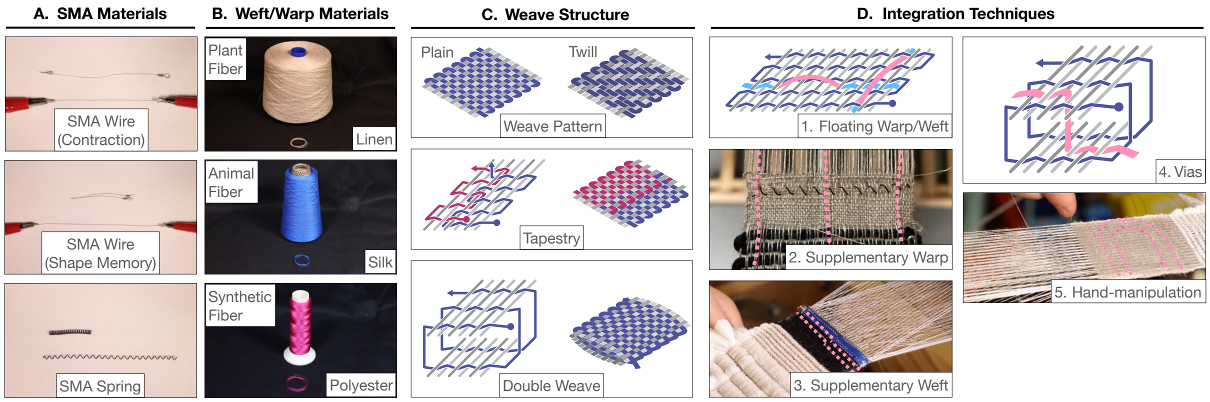

Figure 2: Design menu and choices for composing a deformable patch. The hot pink color lines indicate the trajectories of integrated materials (e.g., floating warp/weft, supplemental warp/weft, vias, and hand-manipulation).

We identified the multi-material design space and implemented three basic actuation primitives: bending, expanding, and shrinking. Each primitive was built upon the choice of SMA actuators and customized woven substrates. We systematically experimented with and characterized the fabric stiffness of different combinations of yarn materials and weave patterns to generate the reference for substrate design. Based on the characteristics of the three basic actuation mechanisms, we describe the aggregation methods associated with the primitives that extend the design space into a diverse range of deforming effects.

3.1 Design Menu of Patch-O

The main design factors for Patch-O include material selection, weave structure, and SMA integration techniques (Figure 2).

Material Selection. Material-wise, the Patch-O interface consists of two main components: (1) shape memory alloy actuators, and (2) woven fabric substrates. The selection of SMA products and yarn materials is therefore pertinent to the material aspect of the design space. Three types of SMA actuators were selected: SMA wire for shape memory, SMA wire for contraction, and SMA spring. The SMA wire designed for contraction can provide a stable and accurate length shrinkage via heating, while the wire designed for shape memory is malleable when cold but can return to its trained shape when heated. The SMA spring is a particular case trained to have a dense helix structure. It can be stretched to more than 200% of the original length and contracts significantly when actuated. The warp and weft yarns were chosen strategically to enhance the movement of the fabric patch on actuation. Certain areas of the patch are required to bend easily while other areas are required to be stiff to ensure a hinge-like movement upon actuation. The machine-spun unbleached linen yarn is stiff, rough and has low elasticity [38]. On the other hand, the silk yarn has a smooth surface with near-constant diameter, which introduces less friction between the weft and warp, and eventually lead to a softer texture against bending [38]. Additionally, silk is known to have a high tensile strength, stretches from 15 to 20 percent, and is mechanically compressible [3, 38]. Therefore, by tactically combining linen and silk yarns in the warp and weft directions, localized physical properties of the woven patch can be manipulated. While we didn't use in this work, polyester is an economical option that can also be incorporated into the patch design.

Weave Structure of Base Substrate. In addition to material variations, weave structures for the base fabric substrate and fabrication techniques for SMA integration were applied selectively during the manufacturing process to accentuate the stiffness and pliability of specific areas. The weave patterns were alternated between plain weave and twill weave. Tapestry was used to create regions with different weave patterns. To create a plain weave, the weft yarn is alternated over and under each warp yarn to create a checkerboard-like pattern. In twill weave, the weft yarn passes over one warp yarn followed by under two warp yarns [29] to create diagonal ribs. We experimented different combinations of materials and weave patterns, and decided the final design through a bending test reported in table 2.

In patches integrating SMA spring, a double weave pattern was used to incorporate the spring between the two layers. To create the double weave, two layers of plain weave interconnected on both sides were created at the same time [55].

Integration Technique for SMA. As shown in Figure 2, five interlacing arrangements allow the integration of SMA actuator to be executed synchronously with the patch's weaving process, which opens up various layout options for the structural-level integration. First, the SMA can be integrated as a floating warp/weft (Fig 2 D.1) to perform an unrestricted deformation and replicate a hinge-like behavior. Second, the SMA can be interlaced within the weave as a supplementary warp (Fig 2 D.2) or supplementary weft (Fig 2 D.3) to ensure that the actuator is clamped in place. Third, in case of multi-layer fabrics, the "vertical interconnect access structure" (vias) proposed by Sun et al [51] was adopted from circuit boards to weaving planes (Fig 2 D.4). The wire-form actuators served as vias for linking the multi-layer cloth for specific deformation design. While integrating the SMA, they can be incorporated at angles other than right angles aligned with warp and weft through hand-manipulation as adopted in lace weaving [24] (Fig 2 D.5). By fine-tuning the integration technique, the actuation behavior could be manipulated.

3.2 Characterization of Woven Substrate for Tunable Stiffness

Table 2: Characteristics of woven substrates

Rigidity Rank (High to low)	Warp	EPI	Weft	PPI	Weave	Mass per unit area (g/m^2)	Bending Rigidity (μ N.m)
1	Linen	40	Silk	22	Twill	189.646	334.813
2	Linen	40	Linen	37	Twill	173.018	304.775
3	Linen	40	Silk	17	Plain	177.273	247.477
4	Linen	40	Linen	26	Plain	157.732	208.804
5	Silk	40	Silk	72	Twill	231.027	36.665
6	Silk	40	Silk	41	Plain	116.613	17.484
7	Silk	40	Linen	26	Plain	124.800	9.672
8	Silk	40	Linen	32	Twill	137.448	9.187

Woven fabric is unique in its tunable stiffness, which is endowed by both the fiber material and the adopted weave pattern. We exploited this feature and utilized the flexibility of weaving to create regions with varying stiffness, which plays an important part in affording the actuation mechanisms. To understand the differences in stiffness that can be created within our choices of materials and weaving patterns, we conducted a bending test for a total of 8 combinations of woven fabric (2 fabric materials × weft/warp setup × 2 weaving patterns). We chose silk yarn (Nm 60/2) and linen yarn (LEA 30/1) in our implementation. The silk yarn has been identified as a suitable choice for making thin woven substrates by previous works [23, 24, 51]. Since the silk yarn has a smooth and soft texture, we chose the linen yarn as the second option which has a similar yarn weight but carries a contradictorily high stiffness. By mixing the two yarn materials and two weaving patterns (*e.g.*, plain weave and twill weave), we were able to weave substrate with different characteristics. As shown in the table 2, we measured the bending rigidity to determine the rigidity rank. We also recorded the PPI (picks per inch) and weight properties as additional factors to be considered in the patch design. All the fabric was fabricated with an 8-shaft floor loom. Based on these results, we choose linen as the warp when we want to create a stiffer region, and silk as the warp when we want to make the region much more bendable.

3.3 Implementing Patch-O

We detailed the implementation of the three basic actuation mechanisms in terms of material choice, fabrication process, and characterization experiments. To determine the suitable voltage for the power supply, we have to standardize a current value for each type of SMA material. We first referenced the technical specification and then tested the actuation time by varying the current value. We then measured the resistance of the SMA and applied voltage accordingly. To connect to the power source, we crimped connectors to both ends of the SMA and soldered solid-core wires that go to a power supply. Based on the experiment results, we propose three standard Patch-O designs which were then tested in a deformation evaluation under 4 attachment cases. For each mechanism, we also identified the aggregation parameters to extend the actuation library of Patch-O, as shown in Figure 3.

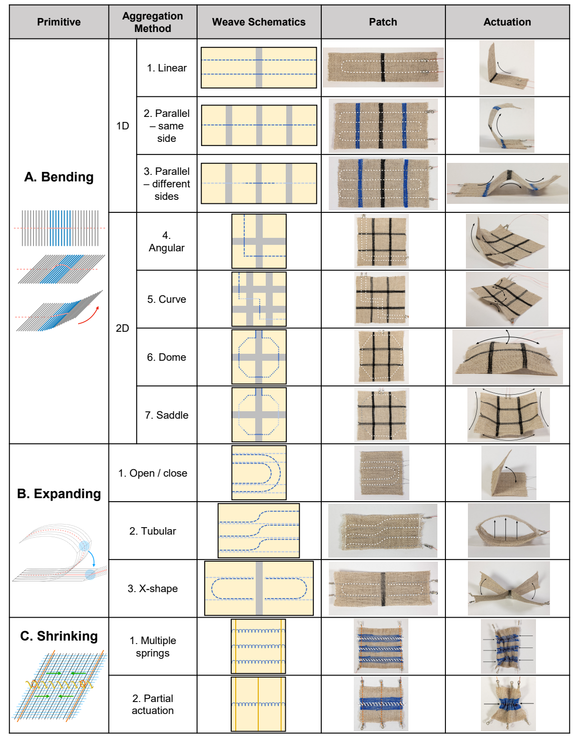

Figure 3: Aggregation parameters based on the three actuation primitives.

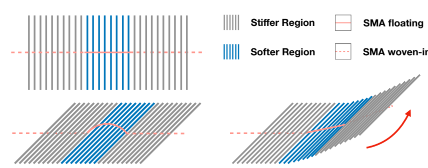

Figure 4: Rationale of the bending mechanism.

3.4 Bending Patch

Inspired by bi-layer research for shape change [40, 54], we translated the mechanism to woven interfaces, with the basic actuation unit of bending consisting of two types of woven regions. We used the SMA wire for contraction (BMF150) in this primitive. The SMA wire is rated with a standard drive voltage of 20.7 V/m and a standard drive current of 340 mA, which would produce 150gf force and 4% kinetic strain. As shown in Figure 4, we wove a stiffer fabric on the two sides to constrain the deformation and anchored the SMA wire as a supplementary weft between the tensioned warps. We designed the central region to be softer but resistant to wrinkles and shrinking. The corresponding section of SMA in the center floats either above or below the softer region. Since the stiffer regions on the sides restrain the SMA, the shrinkage would concentrate at the flexible region in the middle, which pulls the softer part of the fabric on both ends like drawing a bow. The patch would then be bent in the direction curving toward the SMA wire.

Fabrication process. We tested combinations of fabric substrate for both regions and concluded that the substrate pair (1) linen as

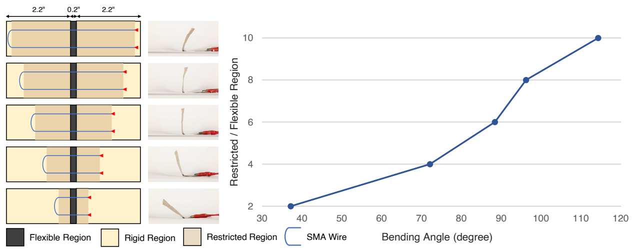

Figure 5: Relation between length of restricted SMA and bending angle.

weft, silk as warp with plain weave, and (2) linen as both weft and warp with twill weave would generate the most desired bending effect. Refer to the bending characteristics in Table 2, we can see the tendencies that linen warp is more rigid than silk warp, and twill weave tends to be stiffer than plain weave. While linen warp × silk weft × twill weave makes the least bendable substrate, we found that using silk weft for the soft region would make it less resistant to shrinking. Hence, instead of changing weft material between the regions, we choose linen as weft for both regions, which still provides enough stiffness difference in bending. For a 4-inch long bending patch, we dressed the loom with linen warp except for the center 0.2" region which used silk. On both sides of the integrated SMA wire is integrated as a U-shape, which crosses the soft regions twice and has the two endings of the SMA located at the same side. ***Characterization experiment.*** To understand the relationship between the bending angle and the length ratio between the constrained and flexible SMA, we fabricated 5 samples on the 4-inch setting with 0.2" soft regions and 2, 4, 6, 8, and 10 times longer constrained region on both sides. As shown in Figure 5, longer restricted regions result in the larger bending angle.

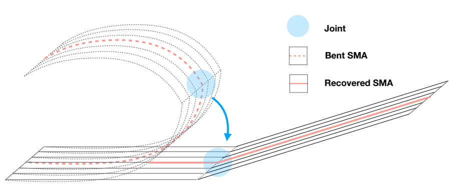

Figure 6: Rationale of the expanding mechanism.

3.5 Expanding Patch

Actuating in reverse to the bending mechanism, which collapses the fabric, the shape memory effect of the SMA wire can be used to expand the fabric from a flat 2D shape to a 3D structure. We adopted the double cloth weaving technique to create such an expandable structure. The technique separates the weaving plane into upper and lower layers, where the two planes can be woven fully in parallel or interacting with each other through selvages or interlacing weft yarns. The basic actuation unit of expanding is defined as a bent joint of SMA connecting the two layers of a double cloth patch through a vias interlacing arrangement. Since the default trained shape of the SMA wire is a straight line, it would tend to recover from the bent status when actuated, which expands and opens the folded double cloth structure, as shown in Figure 6.

Fabrication process. We use Fort Wayne Metals NiTi#8 as the SMA wire for shape memory. The yarn material choice in this mechanism is less restricted. A variety of warp/weft materials can be used to weave the double cloth patch. However, if the top and bottom layers of the patch need to be connected, we suggest using silk warp to make the connecting margin more flexible. A representative design of the expanding patch is the tube shape, where the top and bottom layers are connected on both sides. As shown in Figure 3 B.2, the SMA joints are distributed evenly along the two edges of the tube, and we hand-stitched the SMA wire in the diagonal direction to connect all the joints in one wire.

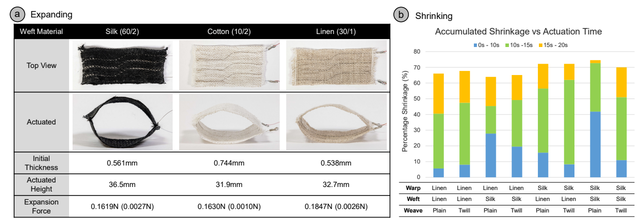

Figure 7: Characteristic experiments of (a) expanding and (b) shrinking mechanisms.

Characterization experiment. To understand how the weft material can affect the expanding effect, we fabricated 3 samples of the tubular patch with silk (Nm 60/2), cotton (Nm 10/2), and linen (Lea 30/1) yarns with a 3-inch wide loom setting. To maintain the stripe structure in the warp direction, we set up linen warp in the center for all three samples, and there are two 0.2" silk warp regions at the margins of the patch, which create a softer texture for a smooth expansion process. Actuated with 360mA for 5 seconds, we measured the flattened/actuated height of each sample, as shown in the table (Figure 7(a)). We measured the expansion force by placing the patch between a digital scale and a fixed rigid plane 5mm above it. Supplying a voltage would cause the expansion and result in a normal force applied to the scale. We found that the silk tubular patch expanded the most, while the cotton tubular patch with the thickest yarn size was the least effective in expansion.

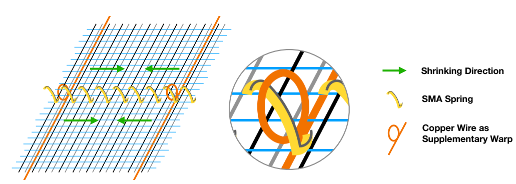

Figure 8: Rationale of the shrinking mechanism.

3.6 Shrinking Patch

Unlike the bending and expanding mechanisms that deform the patch along a line, the shrinking mechanism creates a much more prominent shrinkage across the whole fabric surface by leveraging the SMA spring. The basic actuation unit of shrinking involves looped copper wires for electrical connection and a SMA spring integrated into the weft in a plain weave. We exploited the supplementary warp technique to set up the copper wire along the warp direction, and a small loop was formed with a tweezer to trap the SMA between the coils, as shown in Figure 8. This design allows us to control the segments of the SMA spring that would experience shrinkage.

Fabrication process. Since the SMA spring can create a strong contraction force, using a softer and more stretchable material for both weft and warp would be beneficial. The SMA spring (FLEXINOL Actuator Spring) is first stretched to 7 coils/inch before integration. The SMA spring can stand 3.4A current to achieve a 2-second actuation. For safety concerns, we applied 1A current to the spring in this work. The weaving starts with a loose plain weave structure suitable for integrating the SMA spring. By going through the grid holes in a spiral manner similar to screwing in a screw, each round of the SMA spring clutches the weft and warp, and the structure can be tightened up after integration by increasing the beating intensity of consecutive wefts. We organize the fabrication process into three steps: (1) Do a loose plain weave until arriving at the position for spring integration; (2) make loops with a copper warp; and (3) install the spring and tighten up the plain weave.

Characterization experiment. To assess how the fabric stiffness can affect the shrinking displacement, we installed SMA springs into the 8 woven substrates (described in 3.2) with a 2-inch wide weave. The patches were placed on the table, and we actuated the spring with a fixed current of 1A, and recorded the displacement after 10/15/20 seconds, as shown in the bar chart (Figure 7(b)). Similar trend can be found in the shrinking test, where using silk as the warp would create a less stiff woven substrate. Silk × Silk × plain weave is the combination that creates the woven patch least resistant to shrinking. To rate the pulling force of the patch, we installed a SMA spring with 16 loops, 43mm initial length into a Linen × Silk × plain weave patch, which resists shrinking the most. The patch was hung on a frame and carried a weight placed on the scale. We supplied 1.7V and 1A to the patch and measured the force the patch pulled on the weight 5 times, where we got 402.22gf on average with a standard deviation of 10.43gf.

3.7 Deploying Patch-O on Fabrics

Deployment methods. While the patch can be sewn on the fabric for more secure deployment, we seek a more temporary solution. Through experiments, we found that the double-sided fabric tape provides enough adhesion between the patch and most fabric materials while making the applied patch detachable. Therefore, as the deployment method in the following evaluation and the workshop study, we applied the double-sided fabric tape to cover the non-actuated regions of the patch and attach it to the target fabric.

Patch-O performance on different fabrics. Through characterization experiments, we can identify the most effective design for each type of patch. To understand how the patch can deform fabrics made of different materials, we chose the patches with the best performance in each primitive and deployed them on four types of fabric, including 266.8 g/m^2 100% polyester velveteen, 281.75 g/m^2 100% cotton plain weave, 65 g/m^2 100% polyester plain weave, and 243.3 g/m^2 98% cotton 2% elastane jersey knit. Each type of fabric is cut into a 20cm × 20cm square, and the patch is attached to the center of the fabric. For the bending and shrinking patches, we attach the patch above the fabric. For the expanding tubular patch, we placed the fabric on top of the patch to see how the expansion performed under the weight of the fabric. Figure 9 shows the properties of the four tested fabrics and the performance comparison for each type of patches under the four deployment conditions. All the patches had a performance degradation after being applied on fabric, and we found that the lightweight woven synthetic fabric has the most similar performance to the original on-table actuation. We conclude that it is due to its lightweight form, and the more rigid texture from weaving that leads to the more prominent on-cloth deformation.

ID	Fabric & Material	Weight	Thickness	Density
KS	Knitted, synthetic	10.67 g	0.364 mm	266.8 g/m^2
KN	Knitted, natural	9.73 g	0.451 mm	243.3 g/m^2
WS	Woven, synthetic	2.60 g	0.088 mm	65.0 g/m^2
WN	Woven, natural	11.27 g	0.456 mm	281.75 g/m^2

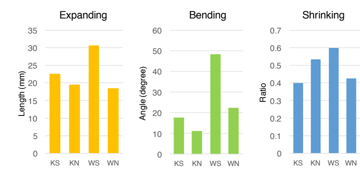

Figure 9: Effective performance of Patch-O deployed on different types of fabric, comparing to direct actuation.

4 DESIGN WORKSHOP STUDY

We conducted a workshop study with four participants with varying textile weaving expertise to (1) gauge the feasibility of creating personalized morphing patches leveraging the primitives we developed, (2) understand how and where these patches can be applied on the body, and (3) probe perceptions towards the patch form factor and envisioned applications. The participants first attended a 1-hour briefing and brainstorming session, where we introduced them to the Patch-O primitives, demonstrated the interactive samples, and introduced how they were woven. Participants then brainstormed ideas for weaving a patch of their choice, and where they would like to place the patch on their existing clothing items. During the brainstorming session, we would discuss with the participants the required weave structure and material combinations to realize the desired patch movement, and where they would like to deploy the garment. Participants then came into the lab for a 4-hour time block to weave their patch and brought their own clothing items for attaching the patch. Since we wanted the participants to focus on the patch design in this study instead of having to figure out how to power the device, we tested the resistance of each patch and assigned the voltage for the participants once they finished fabrication. They then tried on the Patch-O with thin powering wires connected to the power supply. We conducted a 45-minute post-study semi-structured interview to elicit participant reactions. Our participants (anonymized by pseudonyms) include: Ren, a textiles artist with 17 years of weaving experience who runs her own weaving studio; Kendall, a textiles studio assistant with 5 years of weaving experience; Blair, a PhD student in apparel design with one year of experience with weaving, and 12 years of experience with leather footwear patternmaking and design; and Alex, an Engineering and Design undergraduate senior with 1.5 months experience in weaving. We used grounded theory approach [10] to transcribe from video recordings of all sessions. We present each of the participant's project, the techniques they used, and their workflow, followed by results from semi-structured interviews. We provided a $50 USD gift card as gratuity.

Figure 10: Ren's expanding patch for "opening a third eye," which she deployed on (a) the front of a hat, (b) earrings, (c) palm of the hand. The patch was woven with the Expansion Primitive of a double cloth with pre-trained shape memory SMA as a VIAS through the two layers.

Ren's Project: An Expanding Patch for Opening a Third Eye (Figure 10). Ren expressed her love of integrating emotional elements into her textile practice, aiming for the moment when humour and vulnerability intersect. Her weaving often integrates pop culture references which attract the viewer's attention. Ren designed an expanding patch which opens and closes to expose a "third eye." Among the three primitives, Ren chose the "Expanding" primitive and implemented the B.1 "Open/Close" aggregation method described in Figure 3. The sample is a double weave with one margin attached, with the bent joint of SMA connecting the two layers. Referencing linen as her favorite yarn to work with, the warp and weft are both woven with linen, with only the attached margin made with silk warp for easy bending. After weaving the double cloth structure, she then interwove the eye pattern with black yarn. Ren applied the patch on (1) the front of her hat, for the effect of a "third eye," (2) the palm of her hand as a "palm reader," and (3) on the face of her earring for a "creepy yet interesting" effect. Ren felt initially challenged to get the SMA wire to "curve the way [she] wanted to." She mentioned that gaining tactile experience with the stiffness and materiality of the wires through hand manipulation was important for streamlining their work process.

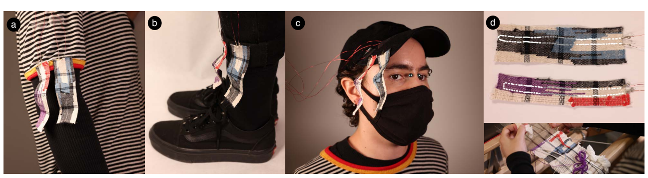

Figure 11: Kendall's wave-bending patches, where they deployed as fringes on (1) the sleeve, (b) pants, and (c) rim of a cap. (d) The patch was woven with the Bending Primitive, with a warp of alternating sections of linen and silk, and SMA wire woven into the weft.

Kendall's Project: Wave-bending Patches as Dynamic Fringes (Figure 11). Kendall integrates abstract, colorful patterns into their weaving practice, preferring the free form nature of tapestry weaving to "make up designs" as they go. Kendall chose the "Bending" primitive and implemented the A.3 "Parallel on different sides" aggregation method shown in Figure 3. Besides, they customized their patch through tapestry weaving with colored cotton yarns for aesthetic purposes. They wove two narrow patches, and attached them to (1) the end of their pants, (2) the edge of their sleeves, and (3) the rim of a cap. When actuated, the patches would transform to a zigzag wave form. They viewed the patches as stylistic add-ons they would incorporate into their garments. In their practice, Kendall typically works with thicker, acrylic yarns, and they mentioned it was a new experience weaving with the thinner yarns to create more delicate shapes. During the tapestry weaving process, the SMA wire would at times bunch up when a longer section was put in at once. Through trial and error they later gained better control of the wire integration.

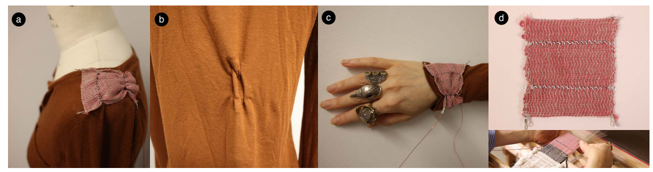

Figure 12: Blair's shrinking patch for form-fitting cloths, where she deployed on (a) the shoulder, (b) the back, and (c) the sleeve for a tailored effect. (d) The patch uses the Shrinking Primitive, with SMA coils integrated in the weft direction into a 2×2 twill weave.

Blair's Project: A Shrinking Patch for Form-Fitting Garments (Figure 12). In her apparel design practice, Blair prioritizes function over aesthetics. A function she found missing from her clothing was the self-fitting capabilities when needed; for example, a jacket becoming more tailored before entering a meeting. Blair selected the "Shrinking" primitive for the strong force it can provide. She implemented the C.1 "Multiple springs" aggregation method described in Figure 3. She wove a patch with two SMA spring in parallel for an aggregated shrinking effect when applied on various garment locations. She customized the design with a 2×2 twill pattern and a reddish yarn, which blended into the top she would later apply it on. She applied the woven patch to various locations on a long sleeved top, including (1) the sleeve, which she envisioned could scrunch up to prevent one's clothes form getting dirty when cooking; (2) the shoulder, which could tighten for an enhanced shoulder line before entering a meeting; and (3) the back of the shirt, which could create a better form-fitting silhouette for professional contexts. She experimented with deploying the patch both on the inside and outside of the top, and preferred the inside since the patch aesthetics was less important to her than the shape change.

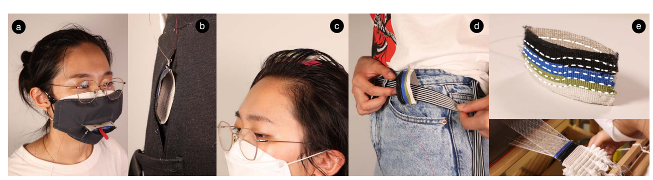

Figure 13: Alex's tubular patch which she deployed as (a) a cartoonish mouth that opens on the face of a mask, (b) a pant pocket opener, (c) a volumizing hair lifter, and (d) a belt loop. (e) The patch was woven with the Expansion Primitive in a double cloth tubular form, with pre-trained shape memory SMA routed through the two layers.

Alex's Project: A Tubular Expansion Patch for Surprising Outcomes (Figure 13). Alex was interested in designs that were "extreme," "absurd," and "purposefully challenging" so that she could be "surprised by the outcome." Alex also chose the "Expanding" mechanism but she landed on the B.2 "Tubular" aggregation method shown in Figure 3. The patch was woven with a double cloth with SMA joints distributed along the sides, which she customized with colored stripes. Intrigued by the tubular expansion, she brainstormed wearable locations that could benefit from an increase in volume or the opening up of a tight space. She attached the patch (1) to a mask which would open and close like a mouth whenever the wearer was talking; (2) inside her pant pocket, which could expand when slipping in her wallet, and then close to keep it snug afterwards; (3) under the upper part of her hair, for the expansion in volume for a formal look; (4) to her jeans as a belt hoop that could expand to make it easier to loop in a belt. In the deployment process, Alex experimented playfully with various patch deployment locations until reaching the ideal setup for each location.

4.1 Observations

Reuse and Reapplication On Diverse Locations. All participants applied and wore their Patch-O on various body locations, ranging from personal clothing items, accessories (e.g., earrings, hats), to skin and its appendages (e.g., hair). The temporary and quick yet sturdy reattachment afforded by the patches allowed playful experimentation with movement on diverse locations. In all instances, participants move their patches around for fine tuning of desired deformation effect before landing on the final deployment locations in the photos. Alex described at length how the temporary attachment of the patches afforded the "sketching of movement" on existing garment items before deciding if they wanted a permanent alteration. Kendall, Ren, and Blair discussed how they have used patches in the past for mends and repairs to extend clothing lifetime, and that the patches were a path for them to "prototype" new functions on existing beloved clothing items instead of having to replace them with "smarter" ones.

Bringing Gradual, Organic Movement to Textiles. Participants found the gradual shape change afforded by SMAs to be surprising, but to resemble deformations typically seen in existing garments. Ren described at length how we would typically only see movement in textiles when affected by forces of nature, such as when textiles are blown by the wind. She described seeing her Patch-O moves as "something like a scene out of Genesis" with her patch "coming to life." Kendall also described the gradual wave form of her patch as "an organic change" and Blair compared the effect of her shrinking patch to commonly seen textural changes in textiles due to wrinkling. Participants appreciated this more gradual movement, since it mirrored existing, albeit non-actuated experiences with textiles in their daily life. Both Alex and Kendall contrasted it with "Iron Man's metal suit" that is "faster," but "more robotic" and "startling." This mirrors observations by Devendrof *et al.* [12] and Howell *et al.* [22] in investigating textile displays, in which the gradual and analog effect of thermochromic inks was preferred over the fast, yet digitized effect of LEDs in the context of wearable textiles, as it better resembles the materiality of textiles. Reactions to the gradual textile movement is also similar to user reactions to KINO [27], a kinetic cloth-climbing robot that is camouflaged with clothing, and moves in an insect, life-like fashion. KINO participants described it as "fashion that is alive [27]" and more "naturally integrated [27]" with the things they wear. We also observe that the *familiarity* of the more organic deformations offered by SMAs may serve as an opportunity for increasing social acceptance, as designing for familiarity in HCI has been identified by Koller *et al.* as a workable strategy for increasing users' comfort towards novel interfaces [33].

Function, Aesthetics, and Personal Identity. Unsurprisingly, as a body adornment, personally meaningful function and aesthetics were both important facets for the design of one's Patch-O. While some participants (Kendall and Ren) prioritized the effective aesthetic expression of their patches, others (Blair and Alex) designed for resolving practical clothing issues which could benefit from a moving patch. However, in weaving the patch, we observed participants considering both dimensions for realizing effective designs. This two-prong consideration towards function and aesthetics mirrors the findings of prior kinetic wearable works (i.e., Kino [27] and ClothTiles [40]). We additionally observed an unique and heightened interest in expressing personal identity tied to the patch form factor. Ren mentioned that patches are important for signaling identity and/or status, and when worn on different body locations, can afford differing "readings" of the "meaning" of the patch by an on-looker. For instance, a patch on the chest can be seen as more formal than one on the forehead, which can be more "absurd" (and her intention and selected location for her patch). She found it useful for "prototyping different meanings" on the body. Besides being attached to the exterior of a garment, patches can also be placed *inside* a garment. Blair preferred her patches to be either worn inside her clothing, or designed in monochrome colors to match her minimalist sense of style. We found Patch-O's fabrication process, which supports customization on both aesthetic and functional fronts, can afford the needs for personally meaningful designs.

Insight on Fabrication Process. Our participants ranged from beginner to expert weavers, with 1.5 months to 17 years of experience. Yet, all were able to pick up the Patch-O primitives easily and successfully created their patches. Importantly, they were able to understand the working principles and needed weave structures within the first 10-15 minutes of the weaving session, and then applied them to their own designs. The bulk of the weaving session was spent on weaving with the thin yarns and SMAs to realize their patch, which took between 40 to 100 minutes. The application process on clothing was also successful; participants applied their patch via fabric tape on several locations. To ease the process of working with the thin yarns, it could be helpful to introduce needle-like shuttles and small tweezers to streamline the weaving process in the future.

5 DISCUSSION AND FUTURE WORK

5.1 Application Scenarios: Exploring Multiple Patch-Os to Form an Outfit

While only one Patch-O device was made and then deployed in different locations for each participant in the user study, here we envision a complete outfit that can be created by combining multiple Patch-O interfaces on a set of clothing. Therefore, we devised three

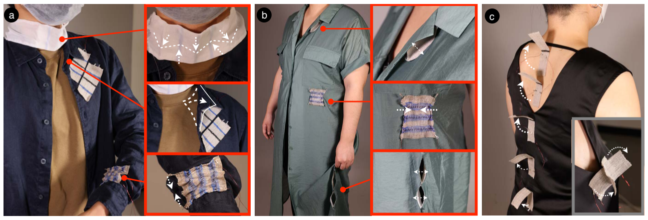

Figure 14: Application examples of multiple Patch-Os forming a shape-changing outfit. (a) Weather adaptive outfit from cold to warm: a bending patch that increases scarf airflow, a curving patch for opening of collar, and a shrinking patch for raising the sleeve. (b) Casual to trendy dress for different social contexts: an expansion patch for lifting collar, a shrinking patch for waistline, and decorative tubular vents. (c) Expressive tank top for preserving one's personal space: bending actuators bend upwards in the back and front of chest when personal space is violated.

smart/expressive outfits for different usage scenarios to further explore application contexts in daily life. We envision future settings in which participants can have "a box of Patch-Os" that they could easily adhere, as desired, throughout their outfits.

Scenario 1: Weather Adaptive Outfit. One of the functional values we see in the Patch-O interface is tuning the coverage ratio of garments on the human body for heat regulation without the need to completely replace the garment. We can create an outfit (Figure 14a) that adapts to weather change from cold to warm with the help of (1) a shrinking patch which can raise the sleeve, (2) a curving patch for opening a collar, and (3) a wave-bending patch placed inside a scarf to help form spaces between the scarf and neck for more airflow.

Scenario 2: Casual Dress to Trendy Dress. Inspired by one of the workshop participants, Blair, we exploit another practical usage of Patch-O for ***self-fitting*** to create a dress that can switch from casual to a more trendy outfit (Figure 14b). Multiple tubular patches were deployed (1) under the collar for volumizing and making a solid shape, (2) attached to the vent in the sides to form a decorative pattern that creates an interesting visual effect, and (3) similar to Blair's design, we installed two shrinking patches on both sides of the waist to taper the waistline for a tailored look.

Scenario 3: Aesthetically Expressive Tank Top. We also see the potential of applying Patch-O on both the skin and clothing for dynamic expression of personal aesthetics. For example, the third outfit is a "self-defense outfit" with bending actuators spiking up like a porcupine when one's personal space is violated (Figure 14c), e.g., when one is on a busy subway. It is composed of a tank top that incorporates a cross-shape patch and multiple bending patches. We aligned the bending patches straight on the back that transform to a bent shape gradient resembling the porcupine's spine. The cross-shaped patch is similarly adopted across the chest, transforming from a flat stripe to a stereoscopic bow knot.

5.2 Design Tradeoffs

With a focus on the diverse actuation effects and the detachability Patch-O enables, we confined the designs within small size patches. While the reusable form factor is suitable for prototyping and iteration, the role of crafting from raw materials is deemphasized in our approach. We acknowledge that this tradeoff could compromise the richer aesthetics offered by crafting e-textiles entirely from scratch. However, we also observed the unique affordances of the patch form factor from the workshop study. Participants were able to apply Patch-O on existing beloved clothing items not only for on-cloth actuation, but also to quickly embellish garments and express personal identity. The patch usage is similar to that of an *appliqué* in quilting, in which fabric patches are layered on top of a foundation fabric for rich designs. We see potential for the Patch-O form factor to serve as a "deformable applique" to complement existing e-textile aesthetics.

5.3 Gaining Deeper Insight into On-Cloth Deformation.

While our Patch-Os have been successfully deployed on various fabrics and on-body surfaces, we acknowledge that the actual on-cloth deformation is affected by various factors ranging from the tension of the body, deployment angle, to fabric structure. Certain weather-specific outerwear, such as thick wool coats and down parkas may demonstrate different attributes. In Section 3.7, we have conducted a preliminary experimentation of the patch's performance when adhered to four common fabric types under lab-controlled conditions. A more comprehensive test with exhaustive conditions is required to understand the exact on-cloth performance of Patch-O.

5.4 Improving Actuation and Control of SMA

In this work, we focus on the design and actuation of a single patch in our implementation. However, when multiple patches need to be actuated at the same time (*e.g.*, example applications in Section 5.1), the controll system should be optimized. The main concern is the difference in voltage requirement due to different resistance and different types of SMAs integrated in the patches. In our case, we connected the wires in series for patches that share the same current requirement, so supplying the voltage that sums up the required numbers can actuate all the connected patches. Nonetheless, this approach can only support the patches made with the same type of SMA products, and all the patches would be actuated simultaneously. To simplify the process of adjusting voltage and current according to each patch design, we used a lab power supply to drive different Patch-Os in the implementation and workshop study. We plan to build a custom PCB board to address the need of powering multiple patches and realize an untethered system design, as demonstrated in previous works of SMA haptic systems [39].

5.5 Reflections on the Weaving Process

In our workshop study, we observed that the most time-consuming aspect of the fabrication process is weaving the patches. As an option to automate the process, woven interfaces can also be fabricated through digital Jacquard looms for scalability and speed. However, we acknowledge that this does trade off the real-time, creative experimentation offered by hand weaving. It could, however, serve as an option for scaling up a finalized design for broader usage.

Further, due to the grid-like nature of weaving, woven designs are often rectangular. However, more free form shapes can improve its expressiveness for on-body applications and support blending in with diverse garments. While a direct solution is to cut out a shape from a textile (and glue or sew edges to prevent fraying), for future work, we can explore efficient ways of weaving free-form silhouettes while maintaining the textile's structural integrity, such as weaving seams into clothing structures that can then be cut to any shape [26].

6 CONCLUSION

We present Patch-O, a deformable fabric interface that enhances garments functionally and aesthetically in the form of a woven patch. Fabricated with versatile yarn materials and shape-memory alloy actuators, the devices are highly customizable for different deformation effects and demonstrating personal aesthetics. The structural integration of actuators within the weaving process also ensures a slim profile that could be installed seamlessly on-cloth. Benefiting from the materials and lightweight form factor, the patches are reusable and easy to deploy on various clothing locations, either temporarily through fabric tape or securely through sewing, and even directly on the human skin. Our findings from an exploratory workshop study reveal that Patch-O's fabrication techniques can be acquired easily by a range of weavers from beginners to experts within a 2-hour weaving session, and that the participants were able to make use of a single patch for multiple deployment locations and various use cases. We also demonstrate the potential of incorporating multiple pieces of Patch-O to form entire outfits adaptive to scenarios of specific wearing contexts. While this work focus on the design and development of movement-based interactions for a woven patch interface, we aim to gain deeper insights from more comprehensive tests of on-cloth deformation and develop a multi-control power system in future work. The high expressiveness enabled by the woven patch form for individuals also points to rich opportunities for broader engagement of deformable soft interfaces with maker and craft communities for diverse perspectives that could enrich the field of HCI.

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