ClothTiles: A Prototyping Platform to Fabricate Customized Actuators on Clothing using 3D Printing and Shape-Memory Alloys

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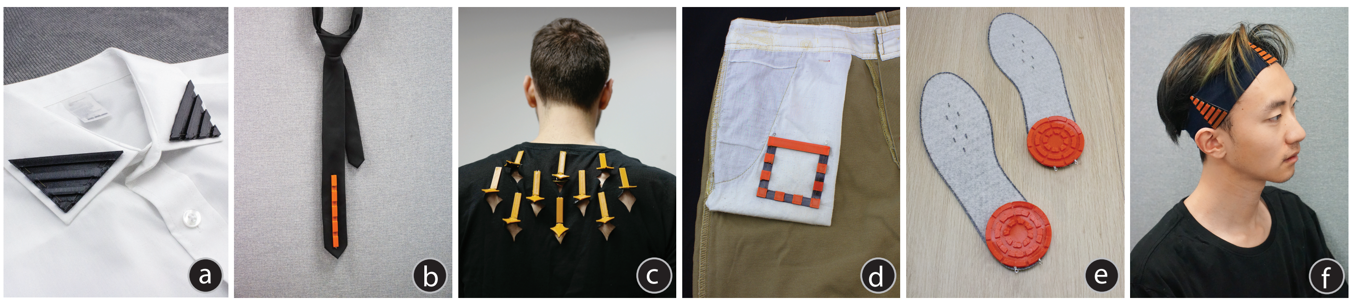

Figure 1: ClothTiles allow to design versatile actuator layouts and deformations for functional and aesthetic cloth applications.

ABSTRACT

Emerging research has demonstrated the viability of on-textile actuation mechanisms, however, an easily customizable and versatile on-cloth actuation mechanism is yet to be explored. In this paper, we present ClothTiles along with its rapid fabrication technique that enables actuation of clothes. ClothTiles leverage flexible 3D-printing and Shape-Memory Alloys (SMAs) alongside new parametric actuation designs. We validate the concept of fabric actuation using a base element, and then systematically explore methods of aggregating, scaling, and orienting prospects for extended actuation in garments. A user study demonstrated that our technique enables multiple actuation types applied across a variety of clothes. Users identified both aesthetic and functional applications of ClothTiles. We conclude with a number of insights for the Do-It-Yourself community on how to employ 3D-printing with SMAs to enable actuation on clothes.

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CCS CONCEPTS

• **Human-centered computing → Interaction devices**; *User interface toolkits.*

KEYWORDS

Clothing, Textile, Actuation, Smart Textiles, Shape-memory Alloy, Do-It-Yourself

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1 INTRODUCTION

People spend almost their entire life span in contact with clothing [25]. Clothing offer a unique interaction space due to the rich mechanical and physical properties of body-worn textiles such as bending, stretching, folding, and compression [46]. While a large body of research is focused on smart clothing in HCI [1, 8, 18, 20, 33], the actuation dimension of clothing has often been ignored. Existing approaches for actuation of clothing proposed using solenoids [2, 40], pneumatic actuators [3, 5, 26, 60], Ohmic-heating [7, 9, 11], electroactive actuators [15, 58], or water-responsive composites [38].

Recently, Nabil et al. [30] proposed a set of crafting techniques to embed interactive morphological capabilities into fabrics using machine sewing. However, creating customized and versatile actuators embedded with clothing remains a complicated task, making it difficult to explore design ideas for actuated clothing or iterate on functional clothing designs.

In this paper, we present ClothTiles, a prototyping platform created using an easily customizable and versatile fabrication technique for enabling actuation in on-textile interfaces. Our method utilizes commonly available materials such as flexible 3D printing filaments, SMA wires, and different types of clothing. The proposed fabrication technique is a two-step method: firstly, it 3D prints localized structural elements with targeted properties onto the piece of clothing to define a desired actuation behavior; secondly, an SMA wire is added for actuation. We demonstrate the concept of clothing actuation using a fundamental ClothTiles element, and then we systematically explore ways of aggregating, scaling, and orientating one or multiple fundamental elements, to enable an extended actuation mechanism in clothing. We chose 3D printing due to its ease of fabrication and the possibility of generating precisely localized structures, including localized control of the substrate's rigidity, altogether allowing us to generate a versatile actuation behavior. These cloth actuators can be simply integrated into different locations of ready-made clothing such as tops, pants, shirts, and other wearable accessories. In summary, the main contributions of our work are twofold.

- An easily customizable and versatile fabrication technique to prototype various actuation types on clothing by aggregating, scaling, and orienting fundamental elements. We provide the details of the fabrication, implementation, and types of operations of ClothTiles.
- Validation of ClothTiles with a user feedback session and use-case demonstrations. Based on the validation, we present design implications explaining the features, constraints, and limitations of the ClothTiles fabrication technique.

2 RELATED WORK

2.1 Actuation in Clothing

Our work is inspired by wide variety of shape-changing interfaces proposed in literature [54–57]. Specific to actuation on cloths, fabrication methods and actuation principles can be broadly categorized into two approaches: structure-level and surface-level actuation. Structure-level approaches integrate an actuation mechanism directly into the clothing [2, 30, 53] using methods such as knitting, weaving, or crocheting. Albaugh et al. [2] explored the ways of employing machine knitting and pulling yarns using an external system to deform soft objects. In contrast, we present an alternative approach which uses a 3D printed substrate that supports embedding SMA actuators and creates localized bending effects on clothes effectively by precisely controlling the actuator's rigidity. Moreover, ClothTiles allows embedding actuators on existing ready-made clothing, compared to knitting new clothing from scratch. Similarly, *Weaving a second skin* [53] employs weaving SMA springs to achieve a single deformation type on textiles, whereas we present a method to perform different types of deformations. Mechanisms based on such approaches can be partially machine fabricated, but it requires knowledge about textile-working, and the resulting deformation can be hard to predict. Surface-level approaches attach actuators directly onto clothing [6, 32, 38, 40, 43] using methods such as glueing or 3D-printing. Finer control of the deformation is possible by this combination of rigid surface material and the soft clothing. A plethora of actuation methods are available based on this concept [37], ranging from (manual) tendon activated deformations to gels which swell when moistened and shrink again when drying. For instance, *Hydrogel-Textile Composites* [38] proposes actuators using hydrogels that primarily respond to externally supplied water. Sprinkling water on wearable clothing can be discomforting and potentially impractical. In contrast, ClothTiles uses SMA wires that can be actively controlled using Joule-heating, without relying on water. Combining actuating materials is often achieved by 3D-printing directly onto clothes [35, 49]. Our work is inspired by efforts on 3D-printed tendon-actuated deformations of clothing [40]. In this work, we explored the ways of using the limited force and deformation generated by SMA wires to enable actuation in clothing.

2.2 On-body Shape-Memory Alloy Interfaces

Shape-Memory Alloys (SMAs) have become one of the state-of-the-art class of materials for generating deformations due to its high energy density [19], high efficiency in terms of large-amplitude actuations [24], reduced size and weight [29], and flexibility of arranging in different shapes [41]. In the Wearable Computing domain, SMAs have been utilized to generate different types of deformations to recreate tactile feedback on the skin such as squeezing [6, 16, 52], tickling [21], compression [45], and skin stretch [48]. However, those interfaces have been embedded in rigid or cumbersome hardware structures. As a potential solution, *Springlets* [17] proposes the ways of using SMA springs embedded in flexible adhesive plasters on the skin to generate 6 different sensations that are *Pinch*, *Directional Stretch*, *Press*, *Pull*, *Drag* and *Expand*. Correspondingly, *Touch me Gently* [29] presents a forearm augmentation that can recreate the natural touch sensation by applying shear-forces on the skin using an SMA wire-based plaster-matrix. *In Contact* [47] introduces a wearable design space using SMA springs, that can generate three types of skin stretching mechanisms to facilitate mediated social touch. Although those interfaces exhibit unique mechanisms of providing feedback on the skin, still there is a need to explore the ways for integrating them in real-world utilizations such as clothing. Recently, Sun et. al commenced a fabrication approach as an extended woven practice to explore design possibilities, and they have investigated the ways of integrating SMA springs into fabrics [53]. *Seamless Seams* proposed a crafting method to investigate how SMA wires can be embedded into fabrics to enable morphological actuations [30]. By varying the stiffness of certain regions of the fabric with sewing threads, they generate different types of actuations on the cloth. In our method, however, with 3D printing combined with SMAs achieve more diverse ways of actuating clothes as its has a wider capabilities. For instance, one of the most potent capabilities of 3D printing combined with SMAs is that having a precise localized control of the thickness of the substrate to generate specific deformations.

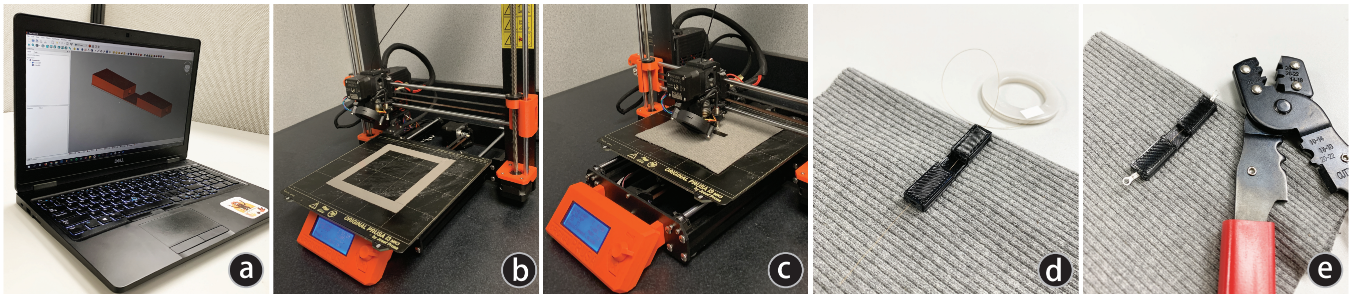


Figure 2: ClothTiles's fabrication process: (a) Designing the shapes using the open-source software; (b) Preparing heating-bed of the 3D printer with the double-sided tape; (c) Printing the flexible substrate on the cloth; (d) Passing an SMA wire through the holes of the 3D printed substrate; (e) Crimping ferrules from the ends of the SMA wire.

2.3 3D Printing on Fabrics

Fabrics own a unique set of physical characteristics such as folding, bending, and stretching [46], and those properties can be controlled by refining the rigidity of the cloth in different regions. In general, varying the stiffness of the fabric is accomplished by employing several fabrication techniques such as attaching with rigid objects, sewing seams or embroidery, and sandwiching fabric layers [40]. Rivera et al. [40] introduced a set of techniques to integrate 3D printing with textiles to achieve diverse deformation types using a standard thread pulled manually or using a motor. While further expanding its design space [40], in ClothTiles, we employ an SMA wire to actively actuate the cloth actuators while providing the possibility to control the substrate's rigidity to achieve specific deformations. Alternatively, 3D printing on fabrics has been identified as a less labor-intensive technique as well as it has been explored to understand the boundary between flexible and hard materials [39]. Inspired by origami and kirigami structures, 3D printing on fabrics also has been applied to vary the structural behaviors of the clothes [36, 51]. *BodyHub* [34] directly 3D printed connector systems into garments to interconnect multiple wearable systems with integrated conductors. *FabriClick* [13] presents a design exploration of embedding mechanical push-buttons into fabrics by employing a workflow of 3D printing. Furthermore, there is a series of works that have been done focusing on dependencies of 3D printing on fabrics such as printing velocity, nozzle and bed temperature, extrusion width, and polymer flow [23, 35, 49, 50]. In this work, we leverage those findings to compile 3D printing on clothing effectively.

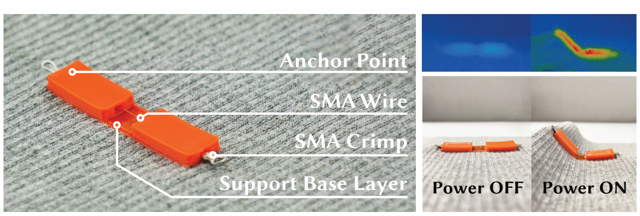


Figure 3: The composition of the ClothTiles's basic element. Anchor points assist keeping the rigidity of the element, meanwhile keeping the SMA wire in place with the support of the SMA crimps. When the current is applied, the generated heat (70°C) activates the SMA wire, thus the cloth actuates. The support base layer generates a bias force that brings the cloth back to its default shape when the power is off.

3 CLOTHTILES

We present ClothTiles created with a novel prototyping technique to enable actuation on clothes by leveraging on 3D printing and SMAs. Inspired by bi-layer actuation phenomena [54], we propose different types of bending actuations on garments. We utilize 3D printing to vary the rigidity of the clothing to create the bi-layer effect and SMA wires to generate internal forces by passing a current through it. In this section, we discuss the implementation, describe the basic element of ClothTiles, and demonstrate how versatile and customized actuation behavior can be realized by aggregating, scaling, and orienting this basic element.

We chose 3D printing due to its precision and ease of fabrication. The possibility of designing structures with precisely localized thickness using 3D printing allows us to control the direction and the type of deformation on cloths. This precise control of the substrate's rigidity enables us to define the amplitude (i.e., bending angle) of the clothe deformation at the design phase.

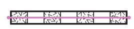
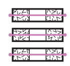
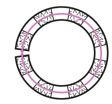
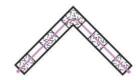
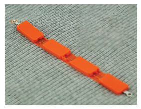
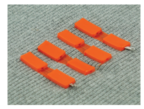
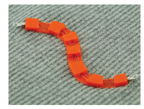
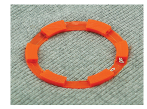
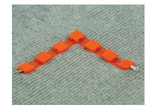
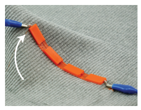
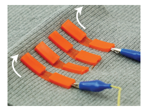
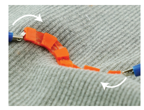
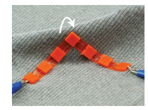
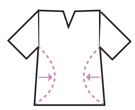
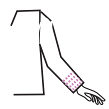
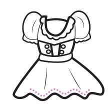
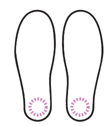
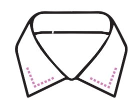
3.1 Implementation

3.1.1 Source materials. In terms of the raw materials, we used a *Cotton Polyester blended Rib Knit* (54% Cotton, 38% Polyester, 8% Elastane) as the clothing base mostly to showcase different methods in the design space. For our prototypes, we chose BMF150 SMA wire which has a diameter of 0.15mm. This wire contracts 4% of the total length of itself while generating a 1.44N force when 340mA (standard drive current) current is applied. For the flexible 3D printer filament, we used a thermoplastic polyurethane material (*NinjaFlex flexible filament - 1.75mm*). We used the *Original Prusa I3 MK3S* 3D printer to print the flexible substrates on the clothes.

3.1.2 Fabrication. Fundamentally, ClothTiles's fabrications process incorporates a two-step method as shown in *Figure 1*. The initial step is printing the flexible substrate on the cloth, and the next step is attaching the SMA wire through the printed substrate.

Step 1 (Flexible 3D Printing): All the CAD designs were completed using an open-source software toolkit (*FreeCAD 3D parametric modeler [12]*). Before the actual printing, there are certain requirements to be fulfilled regarding the print settings and the heating bed. Users can print with the standard 0.4mm nozzle tip, and the fill density of the substrate should be at least 50%. The printing speed is 80mm/sec, and the temperature of the heated filament is 240°C. Importantly, the Z axis offset must be changed based on the cloth's thickness to prevent the nozzle being jammed in the clothing. For instance, we

Table 1: We propose five aggregation methods: *Linear, Perpendicular, Curved, Circular,* and *Angular* to generate different actuation types on the clothes by combining several base elements in diverse patterns.

Form	Linear	Perpendicular	Curved	Circular	Angular
3D-print path					
Fabricated Element					
Actuation					
Examples					

applied a 0.15mm offset for 0.5mm thick *Cotton Polyester blended Rib Knit*. In order to place the cloth on the heating bed firmly, we applied a double sided-tape [42] (*3M 5952 VHB Foam Tape*) in between the cloth and the bed (see *Figure 2b*). This adhesion can be reused for several iterations on different clothes after cleaning carefully with Acetone. The cloth should not have any wrinkles over the printing area, otherwise the cloth must be ironed properly. After following the above steps, users can execute 3D printing on the cloth.

Step 2 (Attaching the SMA wire): The second step is to attach the SMA wire through the 3D printed substrate. We manually passed the SMA wire through the apertures of the printed element. Then we placed two ferrules at the two ends of the wire and crimped them using a crimp tool. In this case, the SMA wire must be fully stretched. Afterwards, the connection points of the power source can be attached to the two ends of the SMA wire. One way to make the connections is soldering ordinary conductive wires to the crimped ferrules. This could be useful if the connecting wires do not restrict the normal activities of the wearer or affect the aesthetic aspects of the cloth. If that is a concern, users can connect the power source to the SMA wire stitching conductive yarns to the electrodes.

3.2 Base Element

The fundamental element of ClothTiles comprises of a 3D printed substrate and an SMA wire arrangement (see *Figure 3*). The 3D printed anchor points assist varying the rigidity of the clothing. Additionally, it holds the SMA wire together with the cloth and facilitates the force distribution through the surface. The SMA wire generates the required internal force for the deformation by shrinking, when the current is applied through it. The cavity inside the 3D printed substrate must be larger than the cross-sectional area of the SMA wire, to slide through. Moreover, the SMA crimps define the ends of the SMA wire while attaching the wire to the anchor points. Crimps are the contact points for the power supply. The thin bottom-most layer of the 3D printed part is called support base layer, and it supports regaining the neutral state of the shape by providing counter-forces during the deformations. Having a variable stiffness enables achieving localized control of the thickness of the 3D printed substrates, thus allowing us to regulate the actuator's behavior types [40]: positioning of the actuation, the direction of actuation, and the degree of the bend.

We propose a set of simple manipulation and implementation techniques of this basic element that allow to control different aspects of the actuation behavior and create advanced actuation mechanisms. We discuss the result of aggregating the primitive structures in various ways, analyze the effect of scaling different parameters from the base element, and mention several possibilities of attaching the actuators at different orientations. Finally, we investigate more advanced actuators that consider combinations of these techniques.

3.3 Aggregation Techniques

We propose five ways to combine the ClothTiles 's basic elements to realize different deformation types over an extended area, as shown in *Table 1*. The chosen aggregation technique determines the direction and the shape of the deformation. We describe the strengths and limitations with insights about the properties of the deformation and placement.

The *linear* aggregation mechanism enables transformations over a longitudinal area, allowing an arch-shaped bending along the cloth. A more significant deformation can be gained by a longer length of the SMA wire [28]. However, the base-layer holds the arch-shape of the deformation during the actuation, and if it is not stiff enough, the expected arch shape can be collapsed. The *Perpendicular* aggregation facilitates bending the cloth over a lengthwise area, folding the cloth to a certain angle. A greater area can be folded

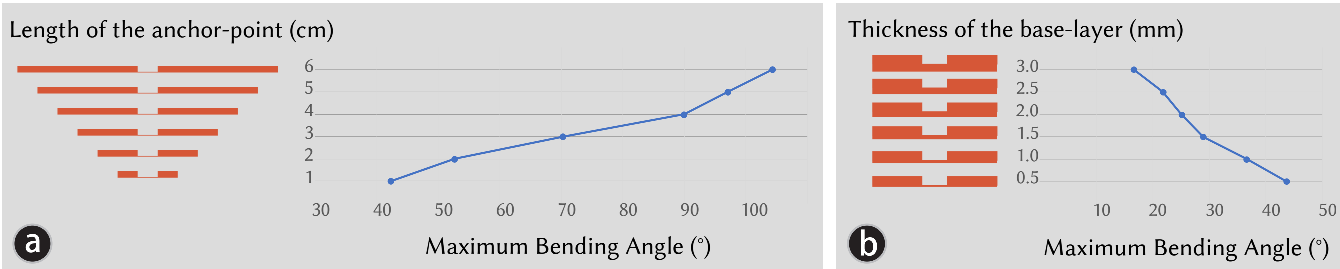


Figure 4: Effects of the changes in geometrical parameters of ClothTiles: (a) Changes in the maximum bending angle with-respect-to the length of the anchor point (Note that when the length of the anchor point increases, the SMA wire's length also increases at the same time.); (b) Changes in the maximum bending angle according to the thickness of the base-layer. The maximum bending angle is the difference between the angles between two anchor points in deactivated and activated states.

along a line, by integrating a higher number of elements orthogonally. If the orthogonal gap between basic elements are higher, the sharpness of the fold might be affected depending on the flexibility of the clothing. The *Curved* mechanism enables deformations along curved paths to render twisting effects on the cloth. Mostly, this can be useful at the edges of the clothes to retain certain aesthetic aspects of the cloth designs. The *Circular* aggregation technique comprises an arrangement of round-shaped base elements over the clothing along a circular-path. This helps performing swelling effects over the clothes. The intensity of the deformation goes up with the radius of the circle, as the displacement length is proportional to the original SMA wire length. Forming *Angular* structures enables placing rigid elements over cornered regions of the cloth to render pulling or pushing effects. A stronger deformation on a smaller area can be achieved by having longer sides. In order to get a concentrated deformation around the corner area, longer anchor points must be placed on the sides.

3.4 Scaling Techniques

The contraction length of a shape-memory alloy (SMA) wire is proportional to its original elongated length. The longer the SMA, the larger contractions can be invoked. By embedding the SMA into the fabric in a zig-zag pattern, and scaling different parameters of the base element, one can control how the resulting deformation forces are used. We propose three different ways of scaling the basic element of ClothTiles as shown in *Figure 5*.

Using *width-wise* scaling, we can render a more distributed force over a larger area of clothing. By embedding the SMA in a zig-zag pattern, we can increase the SMA length along with the width,

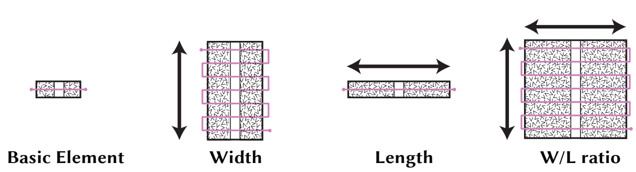


Figure 5: Using a zig-zag pattern, and scaling the width and length of a basic element, one can control the deformation area and its bending angle.

and this will retain the same bending angle. Using the *length-wise* scaling technique, one can obtain a larger SMA length to achieve a stronger deformation force that can increase the bending angle (see *Figure 4a*). Hence, by controlling the *W/L ratio*, one can tailor an element to affect a specific area with a desired deformation intensity.

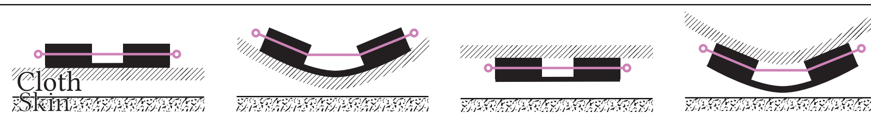
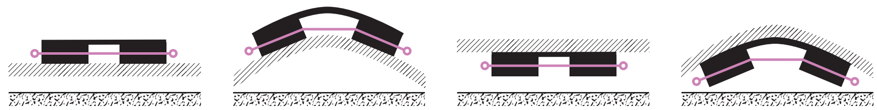
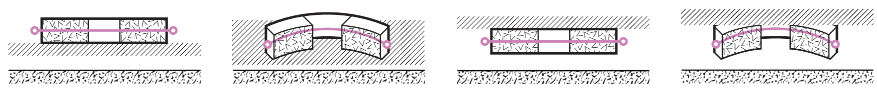
Effect of the rigidity of the 3D printed substrate: With 3D printing, we can achieve multiple levels of stiffness on the clothes by varying the thickness of the 3D printed elements, and having different levels of rigidity in the clothing allow us to control diverse levels of actuation in terms of displacement. For instance, if the thickness of the base-layer is thin, the cloth actuator can achieve a significant deformation (see *Figure 4b*).

3.5 Directionality

We propose two placements where the cloth actuator can be placed: outside and inside (in between the skin and clothe) the clothing. In each placement, we identify three directions along which the cloth actuator can be oriented. Based on each arrangement, several properties of the cloth actuation such as the bending direction, visibility to the outside, type of the sensation, and the cloth actuation would be determined. We categorize the actuation primitives based on the orientation of the basic element as shown in *Table 2*.

When the 3D printed element is placed over the cloth (outside), it is isolated from the skin of the wearer. When the actuator is activated, the generated deformation would be perceived via the cloth movement. Depending on the bending direction of the element, we propose three types of actuations in the cloth: *Upwards*, *Downwards*, and *Planar*. We can achieve bending in the up and down directions perpendicular to the clothing by employing *Upwards* and *Downwards* mechanisms. Surface level deformations can be achieved by placing the base element along the surface as shown in the third row of the *Table 2*. In this case, the rigidness of the support base layer needs to be lower than the stiffness of the clothing; otherwise, the bending actuation would take place through the more flexible region, which leads to an unintended deformation. On the other hand, the actuator can be placed below the cloth (between the cloth and the skin). In this case, the 3D printed element is not entirely isolated from the skin of the user, and the actuation would be perceived via the 3D printed piece.

Table 2: We propose different placement methods of the base elements to define different orientations of placing the actuators on clothes. Primarily, this enables us to control the direction of the bending, visibility to the outside, and perception on the skin.

Bending Direction	Over the cloth		Below the cloth	
	Neutral	Actuated	Neutral	Actuated
Upwards				
Downwards				
Planar				

3.6 Advanced Actuation Mechanisms

A unique set of actuation mechanisms can be achieved by combining above mentioned primitive structures (aggregation and scaling). Particularly, different combinations of aggregating and scaling mechanisms can be integrated together to achieve unique deformation types on the clothes as shown in *Figure 6*. With those combinations, the directionality can also be incorporated depending on the application context: i.e. bending direction, visibility to the outside, perception on the skin. Two of the bending directions, *upwards* and *downwards*, can be applied with every combination of aggregation and scaling mechanism without any constraint.

As examples, we present two combinations of primitive features that can create unique bending structures compared to the primary actuation types mentioned under aggregation and scaling mechanisms. The cloth actuator shown in *Figure 6a* incorporates *linear* aggregation mechanism together with a variable scaling mechanism in a longitudinal direction to generate a more intense pulling effect from a specific point (tip of the triangle) on the cloth. Further, we combined *circular* aggregation method with distinct scaling measures of radius (see *Figure 6b*), and when the actuator is activated the clothing surface deforms as a spherical-cap.

4 CO-CREATION DESIGN STUDY

An increasingly common approach in design research is co-creation: the researcher and the person formerly known as the user work closely together [44]. In order to observe how a potential user would engage with the ClothTiles prototyping toolkit to create different cloth actuators, we performed a co-design study. The user, who is the non-expert designer in this study, went through the entire creation process together with an expert's assistance. The duties held by the expert who mostly remained in the background without influencing the user are primarily threefold: 1) helping users understand the design space of ClothTiles; 2) maintaining consistency among participants by helping only with tasks that are unrelated to the ClothTiles concept (i.e. how to do 3D CAD or send a job to a 3D printer); and 3) observing the users throughout the session. We also wanted to understand whether users can use our toolkit for a realistic task and how quickly users understand the concept. Further, we wanted to validate if our proposed prototyping process is usable for the users and to identify the applicability and usefulness of ClothTiles on clothes. Based on the feedback received from the session, we also fabricated six applications to understand the feasibility, constraints, and limitations of ClothTiles.

4.1 User Feedback Session

Participants & Procedure: We invited six participants (gender-balanced) aged between 27 and 30 (M = 28.2, SD = 1.09). Each participant was asked to bring one of their own clothes they desired to modify during the user feedback session. The session consisted of two stages: Stage 1 (Design together) and Stage 2 (Fit-on time).

Stage 1 (Design Together) began with a brief introduction of the design capabilities of ClothTiles. The researcher explained the essential design techniques such as aggregation, scaling, and directionality to the participant using a handout with example illustrations (similar to *Tables 1 and 2*). These illustrations did not include any example application. This helped the participants to understand the scope and the boundaries of our fabrication method. Next, the participants started making sketches and notes about a cloth actuator design and explained to the researcher how they would use the different concepts to realize their idea (see *Figure 7a*). In this step, the researcher made sure that he understood the design of the participant but did not help the participants to apply the concepts for realizing an idea. The sketched designs were then converted into CAD designs with the expert's help, and 3D printed. As some participants did not have extensive knowledge in 3D-printing, the expert provided support with the basic 3D modeling and printing tasks. Finally, the participants went through the assembly process, including routing SMA wires, crimping, and soldering under the expert's supervision.

In Stage 2 (Fit-on time), the objective was to collect the user reactions and qualitative feedback about the cloth actuator they designed. To achieve that, the researcher let the participant control the cloth actuator as they desired by connecting the cloth actuator to a power supply via a tactile switch. This way, the participants

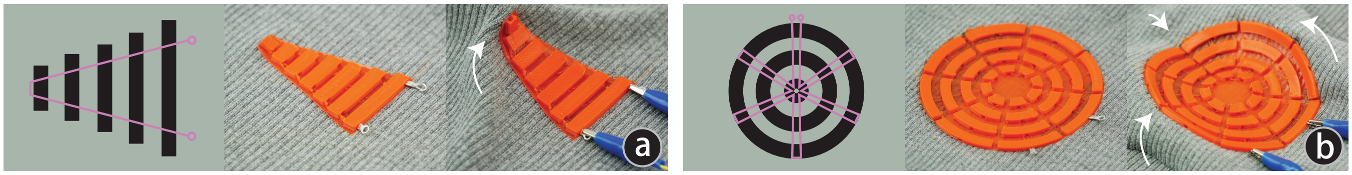


Figure 6: Primitive dimensions can be further combined to generate unique deformation types. (a) and (b) are some of the example combinations we demonstrate. (a) pulls upwards from the tip of the triangle using a concentrated force and (b) deforms similar to a sphere-cap when activated.

could examine how the cloth deforms when switching between the active and inactive states of the actuator. After walking through the entire fabrication process and experiencing the cloth actuator independently, the users were asked to fill out a questionnaire. The questionnaire included open questions about their general experience of the co-design study. The participants were also asked to rate their satisfaction with the outcome and the perceived simplicity of the fabrication process on a 7 point Likert-scale (1-lowest to 7-highest).

Functional versus aesthetic clothing: Our user feedback session showed that participants used our platform to create prototypes for different purposes. The focus of the users seemed to shift mainly between functional and aesthetic applications. Three of the six participants (P1, P2, and P6) intended to design functional add-ons to enhance their clothing accessories. P1 had an issue with his face mask generating vapor on his spectacles when breathing and wanted to create an actuator that lifts the face mask creating an open to pass the exhaled air in less crowded areas, as shown in *Figure 7d*. The generated pulling sensation over the nose resulted in a release of tension of the face mask. The participant found not only that the functionality is working, but also the visual appearance of his modification to be appealing. Furthermore, P2 wished to integrate a wrist compressor (see *Figure 7e)* in his workout gloves to receive subtle notifications about the hand-grip forces. P3 wanted to integrate a slight-massager (see *Figure 7c*) on her eye-mask. All of the participants stated that the implementation worked well to accomplish the intended tasks. On the other hand, some of the participants were concerned about integrating slow aesthetic deformations onto their clothes. P5 wanted to actuate the wrinkles of her frock slowly by actuating the cloth actuators placed inside the gown. She wanted to visualize the moving parts of the frock to others and did not want to feel anything on her skin. P3 came up with a 3D-printed dog (see *Figure 7b*) that can wiggle its tail. Large part of this dog was for aesthetics, and only the tail incorporated ClothTiles elements. This was an interesting extension of ClothTiles design space, which enable visually-noticeable deformations on the clothes. In terms of the aesthetic aspects as well, participants were satisfied enough with our fabrication process. We could verify the participants' satisfaction with the outcome by their comments on the question, "*Were you able to implement what you desired as it is?*" we asked after the fit-on time: "*I wanted my dress to look like a windblown skirt and it was exactly what I had in mind*" [P5];"*I wanted to create my puppy's logo and it all happened very well given the fact it is sentimental for me*"[P3]. Ultimately, it is clear that ClothTiles potentially can fulfill both functional as well as aesthetic aspects of clothing up-to user expectations.

Insights about the fabrication process: All of the participants successfully completed the intended task and were satisfied with the outcome. They seemed to be able to grasp the simple working principle of SMAs quickly, i.e., how they contract and apply our proposed concepts to realize their cloth actuator designs. After experiencing the entire fabrication process, participants rated "*How satisfying was the fabrication process?*" with reasonably high scores (M = 6.17, SD = 0.75). On average, one participant spent around 2 hours (M = 115.2 min, SD = 27.71) engaging with the study, and it was their first time experience with the ClothTiles fabrication process. To design the intended shape in stage 1, including the introductory session, all participants spent approximately half an hour (M = 29.6 min, SD = 3.29). As mentioned earlier, while designing the actuator, the expert assisted participants in understanding the design parameters, converting the users' sketches into a 3D models, and sending it to 3D printer. The majority (five out of six) of the participants stated that the fabrication process was easy and simple to follow, given that the users had some knowledge in 3D modeling and printing.

We could confirm the straightforwardness of following our prototyping toolkit with the feedback provided by the participants. Participants positively expressed their opinions on "*Please describe your thoughts on the fabrication process?*" in the questionnaire at the end of the study; "*I think it's straight forward and easy*" [P2], "*it was easy and the process was quick*" [P4], "*Very simple design and easy to process*" [P5]. P1 specifically mentioned, "*way faster than other methods I have experienced from commercial places (screen printing and embroidery); they usually take ages. This is just couple of hours*". We could also verify the simplicity of our prototyping process with the higher rating (M = 6.33, SD = 0.52) received on "*How easy was the fabrication process?*" in the questionnaire conducted right after stage 2 of the user feedback session. However, the 3D printing time was the most time consuming part and it mainly depended on the intended design done by the participant. As mentioned before, one participant wanted to print his pet's (*a dachshund dog*) illustration on his t-shirt as a logo and to actuate it's tail like wagging (see *Figure 7b*). It took a significant amount of time to design and print as we had to design the 3D model of the dog before embedding ClothTiles's design primitives for that. Therefore we establish, time consumption of the ClothTiles fabrication process mainly depend on the 3D model building and printing.

4.2 Example Applications

During our studies we observed that participants preferred to use our technique to design on-cloth actuators mainly for two purposes; 1) adding functional aspects to their clothing and 2) creating expressive artifacts. (see *Figure 1a-1f*). Inspired by the results from

Figure 7: (a) Participants involved in the fabrication process together with the assistance of an expert. (b) One participant designed a t-shirt logo of his pet dog and made its tail wagging. A variety of applications (done by the participants) were conceivable that add functional and aesthetic aspects to clothing: (c) eye-mask massager, (d) face-mask loosener, (e) wrist compressor.

our participants, we developed a set of clothing actuators to further demonstrate the potential of ClothTiles for functional and aesthetic clothing applications.

Functionality: Interfaces associated with silent feedback modalities can invoke a private communication channel between the wearer [17] and the technology, such as a mobile phone. This can be useful in several use-cases such as when receiving a call while being in a meeting or when privacy is crucial. With the help of our previously proposed primitives that bend inwards, ClothTiles could be used to deliver discreet feedback. Cloth actuators that are attached on the inside of the clothing could tap the user's skin and reduce the visibility of the actuator deformation to the outside. We propose one ClothTiles actuator that, in place of a ringtone or vibratory cue, pokes the user from inside a pocket upon receiving a call (see *Figure 1d*). Furthermore, inspired by *GymSoles* [10], we integrated a silent feedback mechanism into a pair of fabric insoles as shown in *Figure 1e*. This enables the users to receive subtle haptic clues in the feet when they are interacting with foot interfaces such as force sensing smart insoles.

Aesthetics: 3D printed layer can be elaborated and placed outside the clothing to gain public attention, and only selected parts can be actuated to add more dynamic behavior. The deformation can be designed in a way that it is bending away from the body. In that way, the attention of the wearer would not be taken away. To demonstrate this capability, we fabricated a shirt collar to deform up and down creating a waving effect as shown in *Figure 1a*. In addition, we developed a necktie (see *Figure 1b*) that bends outward from the wearer.

Combining both concepts together could render haptic sensations on the wearer and visual perception for other people. In this case, we attached the cloth actuators outside of the cloth to attract public attention by performing more visible deformations, while providing subtle feedback on the skin. We demonstrate this with a silent navigator head-band (see *Figure 1f*) that can convey spatial information [4]. We also modified a t-shirt that can actively increase the air-flow in order to cool down the body of the wearer (see *Figure 1c*). These examples show how aesthetics can go well together with functionality.

5 DISCUSSION

Effect on the thickness of the substrate: Unlike in sewing or embroidery, 3D printing supports having multiple rigidity levels on the clothing. This enables an extended localized control of the thickness of the substrates when combining with SMAs. As shown in the *Figure 4b*, the thickness of the base layer is one of the main determining factors that defines the intensity of the deformation. Further, embedding different thickness gradients (from lower thickness level to a higher thickness level) on the base-layer would enable different types of bending deformations, even though the shape of the cloth actuator looks similar. In that way, designers may come up with various kinds of creative mechanisms to achieve precise controlling of the cloth actuators while having a greater actuation resolution.

Permanent versus temporary cloth actuators: One potential advantage of embedding SMA wires using 3D printing is that the designer can choose to fabricate the flexible 3D element as a permanent substrate or temporary substrate. Mainly, the durability of the adhesiveness between the cloth and 3D printed piece is based on the Z-axis offset of the 3D printer nozzle while printing. For instance, we used *Cotton Polyester blended Rib Knit* for most of the designs we explored, and 0.15mm Z-axis offset of the printer nozzle. This achieved a stronger bond between the cloth and the actuator, which was impossible to separate even by applying force by hand. When users wanted a temporary actuator, we adjusted the z-axis offset of the nozzle to 0.25mm for the *Rib Knit* we used. In that case, we could take out the actuator from the clothing by pulling apart when the user does not need the actuator further.

Positioning actuators in areas inaccessible for machinery: Occasionally, there could be types of clothing where the 3D printer does not have access to print on, due to several reasons such as having uneven surfaces or possessing a surface with less-friction. In similar cases, we printed the 3D substrate separately and later attached it to the clothing using fabric glue. However, this process takes around 2 hours to gain full adhesion, and to make it washable; it takes approximately 48 hours. After the complete attachment, the glued 3D printed element behave the same as a standard 3D printed element on clothing directly. Sticking previously printed components would be significantly helpful for the fabrication process when attaching 3D printed elements on both sides of the cloth.

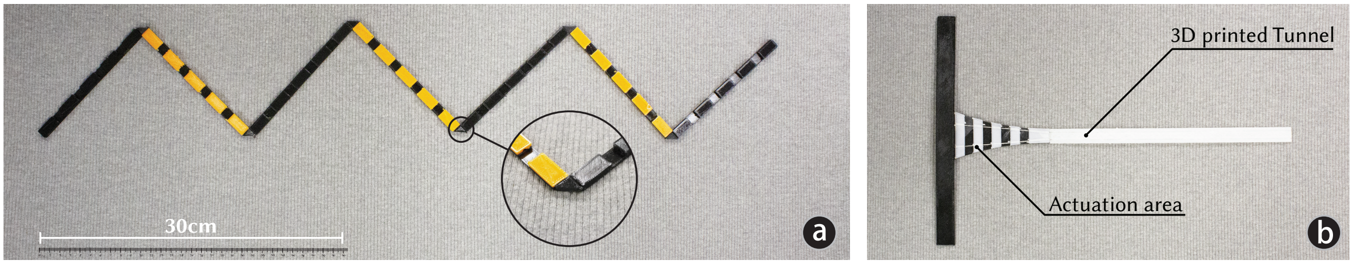


Figure 8: We propose ways to 3D print cloth actuators that are larger than the heat-bed of the 3D printer by combining distinct elements that are printed separately (a). We found a way to render a significantly larger force over a compacted region using a 3D printed tunnel.

More extensive deformations: The displacement length of the SMA wire is proportional to the actual length of the wire. The SMA wire we used in the proposed applications and use-cases contracts (*BMF150*) approximately 4% of the neutral length of it. Therefore, if the designer requires to achieve a more significant deformation, it is necessary to employ a longer SMA wire while maintaining a greater non-flexible area in the 3D printed substrate than the bending regions. For instance, in the user feedback session, P5 wanted to gain a significantly larger area (approximately 25cm× 15cm) to deform her frock without stiffening other regions of the cloth. In that case, we utilized a longer (30cm) and stiff 3D printed element, similar to a tunnel (see *Figure 8b*) to hold the excessive SMA wire length. It enabled a longer SMA wire to be freely moved when the current is applied. This 3D printed tunnel enabled delivering a significantly larger deformation over a smaller region with a highly concentrated force.

3D printing actuators larger than the print-bed: When designing cloth actuators, some designs could be larger than the heat-bed of the 3D printer. For instance, the heat-bed of the 3D printer we used was 254mm × 265mm in size, and it was a challenge for us to print substrates larger than that region. To address this issue, we propose printing the substrates separately in a way that they can be attached after printing. Furthermore, when printing, other than the base layer and anchor points, designers can create connecting joints, as shown in *Figure 8a* to connect two primary actuators. By designing those joints with a cavity having the same diameter (similar to the hole in the base element) enables the SMA wire to move inside the combined and extended cloth actuator freely.

Effect on different types of clothing: Several parametric measures of clothing such as the elasticity, rigidity, and weight determine the type of actuation on the clothes [30]. For example, if the stiffness is very low, the cloth can be twisted in an unintended way. Similarly, if the rigidity of the cloth is too high, the deformation would be weaker than expected. In this case, designers can employ multiple SMA wires in a single cloth actuator to gain a higher bending force. There are heat sensitive clothes such as *Silk*, *Nylon*, or *Lycra*, and those types of clothing should be avoided with 3D printing as those could get melted due to the heat of the nozzle and the heat-bed. In this case, we printed the 3D printed bases separately and integrated them afterward using fabric glue. For instance, the eye-mask brought by P6 was manufactured with a silky material, and we followed the same procedure mentioned above and effectively developed the application she needed.

6 LIMITATIONS AND FUTURE WORK

Heat isolation: When the 3D printed substrate is placed outside of the clothing, generated heat in the SMA wires did not propagate onto the skin of the wearer. This was further confirmed when we specifically asked about the temperature aspects of ClothTiles from the participants. However, when the cloth actuator is placed inside, which means in between the attire and the skin, the user's skin might not be isolated from the SMA wire. We acknowledge not having a proper temperature isolation mechanism with the current set up. In the future, this can be overcome by having a thin, flexible isolation coating around the 3D printed substrate.

Diverse actuation levels: The current proposed fabrication mechanism generates different levels of displacements for distinct cloth actuators. Those are based on different levels of stuffiness in the support base layer or different lengths of the anchor points. When it comes to a single cloth actuator, which requires to have multiple levels of displacements over time, varying the current passing through the SMA wire is the only potential solution with our proposed method. Also, surpassing the standard drive current of the SMA wire (340mA) might reduce the life-span of it. Nonetheless, this matter might be resolved by using actively-controllable real-time mechanical locks and 3D printed elements with the cloth actuator.

Extending to a fully functional toolkit: While we were conducting the user feedback session with two stages, most of the participants were excited about this technique and requested to carry out the third stage of the study to do more modifications such as adding more actuators, adjusting intensity, and changing locations of the cloth actuator. Even though this fact demonstrates the interest of the participants towards engaging with our fabrication method, it is clear that having a software toolkit for designing cloth actuators would improve the overall outcome. A toolkit which accurately predicts and visualizes the cloth deformations based on the designed 3D printed shape and the SMA wire arrangement, would be an effective add-on for designers who follow our method. To extend ClothTiles into a fully functional toolkit, still, there are additional steps to be taken, such as developing a programmable power supply to dynamically control the cloth actuators and integrate them in different interfaces. It is also essential to overcome the safety issues that could happen due to uninsulated SMA wires, and applying an insulating coating around the wires could potentially solve this concern. Furthermore, a fully functional toolkit should inform the designers about the wear-off durability (i.e., effects of washing, sunlight, and deformations), depending on the chosen materials' physical and mechanical properties.

Envisioned future interfaces: We envision future interfaces associated with ClothTiles to enable actuation beyond clothes, accessories, and wearable interfaces. For example, ClothTiles could be further extended towards day-to-day furniture such as sofas or chairs [31], beds [22], and car seats [14] to provide discreet haptic feedback to the users. Our technique could facilitate bridging rapid-prototyping and printable robotics [27, 61] to easily develop robotics structures. Future ClothTiles also could function as I/O interfaces [59] that can sense the context around the user by sensing several activities such as the touches, stretches, or movements through the SMA wire itself while generating haptic clues at the same time.

7 CONCLUSION

In this paper, we present ClothTiles and its novel prototyping technique for enabling actuation of on-textile interfaces. It leverages flexible 3D-printing and Shape-Memory Alloys (SMAs) alongside new parametric actuation designs. We demonstrate the concept of clothing actuation using a base element, and then systematically explore the ways of aggregating, scaling, and orienting the prospects to enable an extended actuation in clothing. Our technique is versatile and easily customizable, enabling various actuation types with different clothes as demonstrated in a user study. Users found two application scenarios to be useful, mentioning aesthetics and functional aspects. We conclude with a number of insights for the Do-It-Yourself community on how to employ 3D-printing with SMAs to enable actuation on clothes.

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REFERENCES

[1] Roland Aigner, Andreas Pointner, Thomas Preindl, Patrick Parzer, and Michael Haller. 2020. Embroidered Resistive Pressure Sensors: A Novel Approach for Textile Interfaces. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376305

[2] Lea Albaugh, Scott Hudson, and Lining Yao. 2019. Digital Fabrication of Soft Actuated Objects by Machine Knitting. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland UK) *(CHI EA '19)*. Association for Computing Machinery, New York, NY, USA, 1–4. https://doi.org/10.1145/3290607.3313270

[3] Guido Belforte, Gabriella Eula, Alexandre Ivanov, and Silvia Sirolli. 2014. Soft pneumatic actuators for rehabilitation. *Actuators* 3, 2 (2014), 84–106.

[4] Matthias Berning, Florian Braun, Till Riedel, and Michael Beigl. 2015. ProximityHat: A Head-Worn System for Subtle Sensory Augmentation with Tactile Stimulation. In *Proceedings of the 2015 ACM International Symposium on Wearable Computers* (Osaka, Japan) *(ISWC '15)*. Association for Computing Machinery, New York, NY, USA, 31–38. https://doi.org/10.1145/2802083.2802088

[5] Leonardo Cappello, Kevin C Galloway, Siddharth Sanan, Diana A Wagner, Rachael Granberry, Sven Engelhardt, Florian L Haufe, Jeffrey D Peisner, and Conor J Walsh. 2018. Exploiting textile mechanical anisotropy for fabric-based pneumatic actuators. *Soft robotics* 5, 5 (2018), 662–674.

[6] George Chernyshov, Benjamin Tag, Cedric Caremel, Feier Cao, Gemma Liu, and Kai Kunze. 2018. Shape Memory Alloy Wire Actuators for Soft, Wearable Haptic Devices. In *Proceedings of the 2018 ACM International Symposium on Wearable Computers* (Singapore, Singapore) *(ISWC '18)*. Association for Computing Machinery, New York, NY, USA, 112–119. https://doi.org/10.1145/3267242.3267257

[7] Marcelo Coelho and Pattie Maes. 2008. Sprout I/O: A Texturally Rich Interface. In *Proceedings of the 2nd International Conference on Tangible and Embedded Interaction* (Bonn, Germany) *(TEI '08)*. Association for Computing Machinery, New York, NY, USA, 221–222. https://doi.org/10.1145/1347390.1347440

[8] Artem Dementyev, Tomás Vega Gálvez, and Alex Olwal. 2019. SensorSnaps: Integrating Wireless Sensor Nodes into Fabric Snap Fasteners for Textile Interfaces. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 17–28. https://doi.org/10.1145/3332165.3347913

[9] Jiachun Du, Panos Markopoulos, Qi Wang, Marina Toeters, and Ting Gong. 2018. ShapeTex: Implementing Shape-Changing Structures in Fabric for Wearable Actuation. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 166–176. https://doi.org/10.1145/3173225.3173245

[10] Don Samitha Elvitigala, Denys J.C. Matthies, Löic David, Chamod Weerasinghe, and Suranga Nanayakkara. 2019. GymSoles: Improving Squats and Dead-Lifts by Visualizing the User's Center of Pressure. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300404

[11] Jack Forman, Taylor Tabb, Youngwook Do, Meng-Han Yeh, Adrian Galvin, and Lining Yao. 2019. ModiFiber: Two-Way Morphing Soft Thread Actuators for Tangible Interaction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3290605.3300890

[12] FreeCAD. 2020. *Open source 3D parametric modeler*. FreeCAD. https://www.freecadweb.org/

[13] Maas Goudswaard, Abel Abraham, Bruna Goveia da Rocha, Kristina Andersen, and Rong-Hao Liang. 2020. FabriClick: Interweaving Pushbuttons into Fabrics Using 3D Printing and Digital Embroidery. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 379–393. https://doi.org/10.1145/3357236.3395569

[14] Thomas Grah, Felix Epp, Martin Wuchse, Alexander Meschtscherjakov, Frank Gabler, Arnd Steinmetz, and Manfred Tscheligi. 2015. Dorsal Haptic Display: A Shape-Changing Car Seat for Sensory Augmentation of Rear Obstacles. In *Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Nottingham, United Kingdom) *(AutomotiveUI '15)*. Association for Computing Machinery, New York, NY, USA, 305–312. https://doi.org/10.1145/2799250.2799281

[15] Jianglong Guo, Chaoqun Xiang, Tim Helps, Majid Taghavi, and Jonathan Rossiter. 2018. Electroactive textile actuators for wearable and soft robots. In *2018 IEEE International Conference on Soft Robotics (RoboSoft)*. IEEE, Livorno, Italy, 339–343.

[16] Aakar Gupta, Antony Albert Raj Irudayaraj, and Ravin Balakrishnan. 2017. HapticClench: Investigating Squeeze Sensations Using Memory Alloys. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 109–117. https://doi.org/10.1145/3126594.3126598

[17] Nur Al-huda Hamdan, Adrian Wagner, Simon Voelker, Jürgen Steimle, and Jan Borchers. 2019. Springlets: Expressive, Flexible and Silent On-Skin Tactile Interfaces. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3290605.3300718

[18] Cedric Honnet, Hannah Perner-Wilson, Marc Teyssier, Bruno Fruchard, Jürgen Steimle, Ana C. Baptista, and Paul Strohmeier. 2020. PolySense: Augmenting Textiles with Electrical Functionality Using In-Situ Polymerization. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376841

[19] Mohammad Mahdi Kheirikhah, Samaneh Rabiee, and Mohammad Ehsan Edalat. 2010. A review of shape memory alloy actuators in robotics. In *Robot Soccer World Cup*. Springer, Berlin, Heidelberg, 206–217.

[20] Ali Kiaghadi, Morgan Baima, Jeremy Gummeson, Trisha Andrew, and Deepak Ganesan. 2018. Fabric as a Sensor: Towards Unobtrusive Sensing of Human Behavior with Triboelectric Textiles. In *Proceedings of the 16th ACM Conference on Embedded Networked Sensor Systems* (Shenzhen, China) *(SenSys '18)*. Association for Computing Machinery, New York, NY, USA, 199–210. https://doi.org/10.1145/3274783.3274845

[21] Espen Knoop and Jonathan Rossiter. 2015. The Tickler: A Compliant Wearable Tactile Display for Stroking and Tickling. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI EA '15)*. Association for Computing Machinery, New York, NY, USA, 1133–1138. https://doi.org/10.1145/2702613.2732749

[22] Masahiro Koge, Daichi Ogawa, Seiya Takei, Yuriko Nakai, Taira Nakamura, Takuto Nakamura, Ryuta Okazaki, Taku Hachisu, Michi Sato, and Hiroyuki Kajimoto. 2014. Haptic Bed: Bed-Style Haptic Display for Providing Weight Sensation. In *Proceedings of the 11th Conference on Advances in Computer Entertainment Technology* (Funchal, Portugal) *(ACE '14)*. Association for Computing Machinery, New York, NY, USA, Article 47, 4 pages. https://doi.org/10.1145/2663806.2663861

[23] Michael Korger, Alexandra Glogowsky, Silke Sanduloff, Christine Steinem, Sofie Huysman, Bettina Horn, Michael Ernst, and Maike Rabe. 2020. Testing thermoplastic elastomers selected as flexible three-dimensional printing materials for functional garment and technical textile applications. *Journal of Engineered Fibers and Fabrics* 15 (2020), 1558925020924599.

[24] Peter Krulevitch, Abraham P Lee, Philip B Ramsey, James C Trevino, Julie Hamilton, and M Allen Northrup. 1996. Thin film shape memory alloy microactuators. *Journal of microelectromechanical systems* 5, 4 (1996), 270–282.

[25] Kristi Kuusk, Aleksander Väljamäe, and Ana Tajadura-Jiménez. 2018. Magic Lining: An Exploration of Smart Textiles Altering People's Self-Perception. In *Proceedings of the 5th International Conference on Movement and Computing* (Genoa, Italy) *(MOCO '18)*. Association for Computing Machinery, New York, NY, USA, Article 47, 6 pages. https://doi.org/10.1145/3212721.3212893

[26] JH Low, N Cheng, PM Khin, Nitish V Thakor, Sunil L Kukreja, HL Ren, and Chen-Hua Yeow. 2017. A bidirectional soft pneumatic fabric-based actuator for grasping applications. In *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, Vancouver, BC, Canada, 1180–1186.

[27] Robert MacCurdy, Robert Katzschmann, Youbin Kim, and Daniela Rus. 2016. Printable hydraulics: A method for fabricating robots by 3D co-printing solids and liquids. In *2016 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, Stockholm, Sweden, 3878–3885.

[28] David J Miller, Larry A Fahnestock, and Matthew R Eatherton. 2012. Development and experimental validation of a nickel–titanium shape memory alloy self-centering buckling-restrained brace. *Engineering Structures* 40 (2012), 288–298.

[29] Sachith Muthukumarana, Don Samitha Elvitigala, Juan Pablo Forero Cortes, Denys J.C. Matthies, and Suranga Nanayakkara. 2020. Touch Me Gently: Recreating the Perception of Touch Using a Shape-Memory Alloy Matrix. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376491

[30] Sara Nabil, Jan Kučera, Nikoletta Karastathi, David S. Kirk, and Peter Wright. 2019. Seamless Seams: Crafting Techniques for Embedding Fabrics with Interactive Actuation. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 987–999. https://doi.org/10.1145/3322276.3322369

[31] Suranga Nanayakkara, Lonce Wyse, and Elizabeth A. Taylor. 2012. Effectiveness of the Haptic Chair in Speech Training. In *Proceedings of the 14th International ACM SIGACCESS Conference on Computers and Accessibility* (Boulder, Colorado, USA) *(ASSETS '12)*. Association for Computing Machinery, New York, NY, USA, 235–236. https://doi.org/10.1145/2384916.2384970

[32] Simon Olberding, Sergio Soto Ortega, Klaus Hildebrandt, and Jürgen Steimle. 2015. Foldio. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology - UIST '15*. ACM Press, Charlotte, NC, USA, 223—-232. https://doi.org/10.1145/2807442.2807494

[33] Patrick Parzer, Florian Perteneder, Kathrin Probst, Christian Rendl, Joanne Leong, Sarah Schuetz, Anita Vogl, Reinhard Schwoediauer, Martin Kaltenbrunner, Siegfried Bauer, and Michael Haller. 2018. RESi: A Highly Flexible, Pressure-Sensitive, Imperceptible Textile Interface Based on Resistive Yarns. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 745–756. https://doi.org/10.1145/3242587.3242664

[34] Andreas Peetz, Konstantin Klamka, and Raimund Dachselt. 2019. BodyHub: A Reconfigurable Wearable System for Clothing. In *The Adjunct Publication of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 39–41. https://doi.org/10.1145/3332167.3357108

[35] Eujin Pei, Jinsong Shen, and Jennifer Watling. 2015. Direct 3D printing of polymers onto textiles: experimental studies and applications. *Rapid Prototyping Journal* 21, 5 (aug 2015), 556–571. https://doi.org/10.1108/rpj-09-2014-0126

[36] Jesús Pérez, Miguel A. Otaduy, and Bernhard Thomaszewski. 2017. Computational Design and Automated Fabrication of Kirchhoff-Plateau Surfaces. *ACM Trans. Graph.* 36, 4, Article 62 (July 2017), 12 pages. https://doi.org/10.1145/3072959.3073695

[37] Nils-Krister Persson, Jose G. Martinez, Yong Zhong, Ali Maziz, and Edwin W. H. Jager. 2018. Actuating Textiles: Next Generation of Smart Textiles. *Advanced Materials Technologies* 3, 10 (jul 2018), 1700397. https://doi.org/10.1002/admt.201700397

[38] Michael L. Rivera, Jack Forman, Scott E. Hudson, and Lining Yao. 2020. Hydrogel-Textile Composites: Actuators for Shape-Changing Interfaces. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/3334480.3382788

[39] Michael L. Rivera and Scott E. Hudson. 2019. Desktop Electrospinning: A Single Extruder 3D Printer for Producing Rigid Plastic and Electrospun Textiles. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300434

[40] Michael L. Rivera, Melissa Moukperian, Daniel Ashbrook, Jennifer Mankoff, and Scott E. Hudson. 2017. Stretching the Bounds of 3D Printing with Embedded Textiles. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 497–508. https://doi.org/10.1145/3025453.3025460

[41] Hugo Rodrigue, Wei Wang, Min-Woo Han, Thomas JY Kim, and Sung-Hoon Ahn. 2017. An overview of shape memory alloy-coupled actuators and robots. *Soft robotics* 4, 1 (2017), 3–15.

[42] Razieh Hashemi Sanatgar, Christine Campagne, and Vincent Nierstrasz. 2017. Investigation of the adhesion properties of direct 3D printing of polymers and nanocomposites on textiles: Effect of FDM printing process parameters. *Applied Surface Science* 403 (2017), 551–563.

[43] Vanessa Sanchez, Christopher J. Payne, Daniel J. Preston, Jonathan T. Alvarez, James C. Weaver, Asli T. Atalay, Mustafa Boyvat, Daniel M. Vogt, Robert J. Wood, George M. Whitesides, and Conor J. Walsh. 2020. Smart Thermally Actuating Textiles. *Advanced Materials Technologies* 5, 8 (jul 2020), 2000383. https://doi.org/10.1002/admt.202000383

[44] Elizabeth B-N Sanders and Pieter Jan Stappers. 2008. Co-creation and the new landscapes of design. *Co-design* 4, 1 (2008), 5–18.

[45] Robert Scheibe, Mathias Moehring, and Bernd Froehlich. 2007. Tactile feedback at the finger tips for improved direct interaction in immersive environments. In *2007 IEEE Symposium on 3D User Interfaces*. IEEE, Charlotte, North Carolina, USA, 125–132.

[46] Roshan L Shishoo. 1995. Importance of mechanical and physical properties of fabrics in the clothing manufacturing process. *International Journal of Clothing Science and Technology* 7, 2-1 (1995), 35–42.

[47] Melanie F. Simons, Alice C. Haynes, Yan Gao, Yihua Zhu, and Jonathan Rossiter. 2020. In Contact: Pinching, Squeezing and Twisting for Mediated Social Touch. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/3334480.3382798

[48] Massimiliano Solazzi, William R Provancher, Antonio Frisoli, and Massimo Bergamasco. 2011. Design of a SMA actuated 2-DoF tactile device for displaying tangential skin displacement. In *2011 IEEE World Haptics Conference*. IEEE, Istanbul, Turkey, 31–36.

[49] T Spahiu, N Grimmelsmann, A Ehrmann, E Piperi, and E Shehi. 2017. Effect of 3D printing on textile fabric. *Engineering and Entrepreneurship* 1, 1 (2017), 1–7.

[50] Tatjana Spahiu, Erald Piperi, Andrea Ehrmann, Ermira Shehi, and Dudina Rama. 2019. 3D printed geometries on textile fabric for garment production. In *International Conference of Progress in Digital and Physical Manufacturing*. Springer, Leiria, Portugal, 271–276.

[51] Scott E Stapleton, Dorit Kaufmann, Helga Krieger, Jan Schenk, Thomas Gries, and David Schmelzeisen. 2019. Finite element modeling to predict the steady-state structural behavior of 4D textiles. *Textile Research Journal* 89, 17 (2019), 3484–3498.

[52] Katja Suhonen, Kaisa Väänänen-Vainio-Mattila, and Kalle Mäkelä. 2012. User experiences and expectations of vibrotactile, thermal and squeeze feedback in interpersonal communication. In *The 26th BCS Conference on Human Computer Interaction*. BISL, 26, 205–214.

[53] Ruojia Sun, Ryosuke Onose, Margaret Dunne, Andrea Ling, Amanda Denham, and Hsin-Liu (Cindy) Kao. 2020. Weaving a Second Skin: Exploring Opportunities for Crafting On-Skin Interfaces Through Weaving. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 365–377. https://doi.org/10.1145/3357236.3395548

[54] Guanyun Wang, Tingyu Cheng, Youngwook Do, Humphrey Yang, Ye Tao, Jianzhe Gu, Byoungkwon An, and Lining Yao. 2018. Printed Paper Actuator: A Low-Cost Reversible Actuation and Sensing Method for Shape Changing Interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3174143

[55] Guanyun Wang, Ye Tao, Ozguc Bertug Capunaman, Humphrey Yang, and Lining Yao. 2019. A-Line: 4D Printing Morphing Linear Composite Structures. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300656

[56] Guanyun Wang, Humphrey Yang, Zeyu Yan, Nurcan Gecer Ulu, Ye Tao, Jianzhe Gu, Levent Burak Kara, and Lining Yao. 2018. 4DMesh: 4D Printing Morphing Non-Developable Mesh Surfaces. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 623–635. https://doi.org/10.1145/3242587.3242625

[57] Wen Wang, Lining Yao, Teng Zhang, Chin-Yi Cheng, Daniel Levine, and Hiroshi Ishii. 2017. Transformative Appetite: Shape-Changing Food Transforms from 2D to 3D by Water Interaction through Cooking. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 6123–6132. https://doi.org/10.1145/3025453.3026019

[58] Chaoqun Xiang, Jianglong Guo, Rujie Sun, Andrew Hinitt, Tim Helps, Majid Taghavi, and Jonathan Rossiter. 2019. Electroactive textile actuators for breathability control and thermal regulation devices. *Polymers* 11, 7 (2019), 1199.

[59] Sang Ho Yoon, Siyuan Ma, Woo Suk Lee, Shantanu Thakurdesai, Di Sun, Flávio P. Ribeiro, and James D. Holbery. 2019. HapSense: A Soft Haptic I/O Device with Uninterrupted Dual Functionalities of Force Sensing and Vibrotactile Actuation. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 949–961. https://doi.org/10.1145/3332165.3347888

[60] Mengjia Zhu, Amirhossein H. Memar, Aakar Gupta, Majed Samad, Priyanshu Agarwal, Yon Visell, Sean J. Keller, and Nicholas Colonnese. 2020. PneuSleeve: In-Fabric Multimodal Actuation and Sensing in a Soft, Compact, and Expressive Haptic Sleeve. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376333

[61] Ali Zolfagharian, Akif Kaynak, and Abbas Kouzani. 2020. Closed-loop 4D-printed soft robots. *Materials & Design* 188 (2020), 108411.