*Flex*tiles: Designing Customisable Shape-Change in Textiles with SMA-Actuated Smocking Patterns

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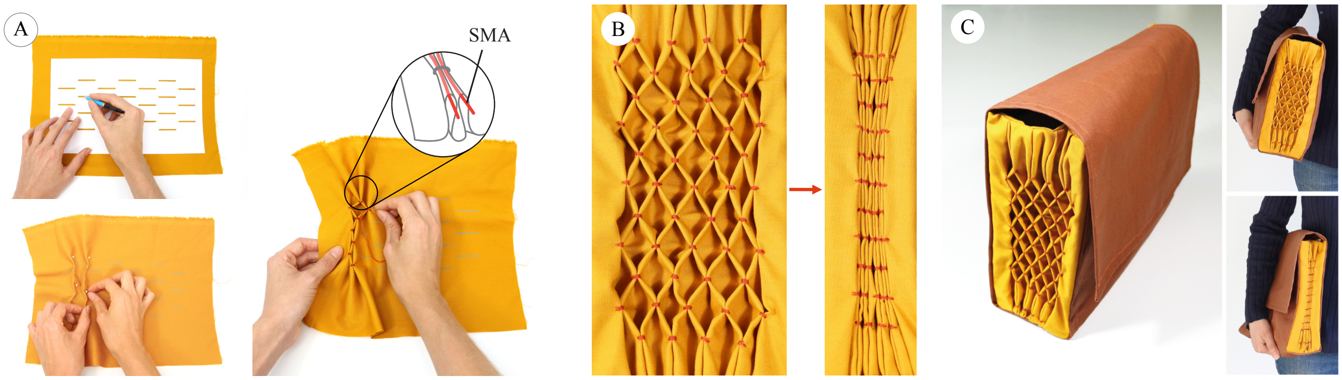

Figure 1: *Flex*tiles are a customisable design schema for augmenting textiles with shape-change, founded on the traditional textile technique of smocking. (A) Based on a software-generated template, the customised structure is fabricated with simple tools. (B) The SMA wires hidden in the smocking folds produce planar contraction of the structure when activated, (C) enabling designers to seamlessly integrate dynamic shape-change into their textile projects.

ABSTRACT

Shape Memory Alloys (SMAs) afford the seamless integration of shape-changing behaviour into textiles, enabling designers to augment apparel with dynamic shaping and styling. However, existing works fall short of providing versatile methods adaptable to varying scales, materials, and applications, curtailing designers' capacity to prototype customised solutions. To address this, we introduce *Flex*tiles, parameterised SMA design schema that leverage the traditional craft of smocking to integrate planar shape-change seamlessly into diverse textile projects. The conception of *Flex*tiles stems from material experimentation and consultative dialogues with designers, whose insights inspired strategies for customising scale, elasticity, geometry, and actuation of *Flex*tiles. To support the practical implementation of *Flex*tiles, we provide a design tool and experimentally characterise their material properties. Lastly, through a workshop with practitioners, we explore the multifaceted applications and perspectives surrounding *Flex*tiles, and subsequently realise four scenarios that illustrate the creative potential of these modular, customisable patterns.

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CCS CONCEPTS

• **Human-centered computing** → **HCI design and evaluation methods**; • **Hardware** → **Emerging interfaces**;

KEYWORDS

Actuated Textiles, Shape Memory Alloys, Fabrication

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1 INTRODUCTION

A recent advancement in textile technologies is to actuate fabrics with shape-changing behaviour. This move from passive to active fabrics opens up a new arena of textile design, broadening the scope for novel aesthetics, e.g. dynamically changing shape and style [4], and novel functionality, e.g. dynamically altering fit [36], within garments and accessories. Shape Memory Alloy (SMA) wires are increasingly being used to drive such actuation as they afford silent, controllable actuation with a high force-to-weight ratio [41]. Additionally, the fibre-like form factor of SMA enables them to be embedded seamlessly into textiles with minimal disruption to the aesthetic and material properties of the fabric.

In this paper, we focus on generating *planar shape-change* in textiles with SMA; structural changes in shape that remain in the textile plane. This enables transformations of the geometric shape, fit and style of fabric artefacts, affording diverse opportunities for designers to explore interactive and responsive apparel and furnishings. However, leveraging the actuation force of SMA for planar shape change is non-trivial which can be a barrier to use. Existing works typically achieve this by incorporating SMA wires into the body of the textile during production via weaving [6, 14, 30, 31], felting [4], and knitting [19]. Projects that integrate the SMA into textiles post-production focus on localised contraction [28, 36, 39] or generate global shape change, but require a specific type of fabric to function [10, 33]. These projects demonstrate the efficacy of SMA with a variety of patterns, textile techniques, and use cases but offer limited customisation options for adapting the proposed designs to different fabrics, scales, functionalities, and applications. This limits the ability of designers to prototype with and explore this technology in their own work. Further to this, little is known about which properties, behaviours and applications of SMA-driven shape-change in textiles are most desirable to designers. As has been initiated in other areas such as visual displays in textiles [11], it is invaluable to include designers in the development of these new technologies.

We address this open issue with *Flex*tiles: parameterised SMA design schema that leverage the traditional textile technique of smocking to produce *planar shape-change* in textiles. *Flex*tiles can be *seamlessly integrated into off-the-shelf fabrics* and embedded into the garment design and production process, thereby making them *accessible* for designers to experiment with. Designers and practitioners were consulted throughout the development of *Flex*tiles designs, and their perspectives inform the design of *Flex*tiles and provide valuable insights for future research directions in SMA-actuated textiles.

In this paper, we thus introduce *Flex*tiles designs and the simple fabrication methods and tools required for creating them. *Flex*tiles designs arose out of material explorations combining SMA wire and traditional textile techniques. We present findings from interviews with 5 expert designers who were consulted during the early-stage development of *Flex*tiles. The consultations identified promising directions for techniques to use and focus areas that guided the design parameters and customisation strategies of *Flex*tiles. We detail the parameterised design schema developed in response to the interviews, detailing how the modular structure of the smocking pattern affords *customisation of scale, stretchability, geometry, actuation location, and direction*, providing a broad design space of actuation. We extend this design space further with *visual customisation* through the use of different fabrics, colour patterns, embellishments and selective actuation. To support the implementation of *Flex*tiles, we provide a design tool for generating smocking templates and visualising actuation prior to fabrication. We additionally characterise the foundational properties and behaviours of the proposed actuation schemes to assist designers in making informed choices on the materials and patterns to use for their desired applications. To explore possible application areas of SMA-driven shape-changing textiles, we report on a workshop conducted with 4 practitioners in which we used *Flex*tiles as a probe for generating and investigating possible application areas. We present four application cases of *Flex*tiles designs inspired by discussions during the workshop that illustrate varied scenarios for the afforded shape change in textiles.

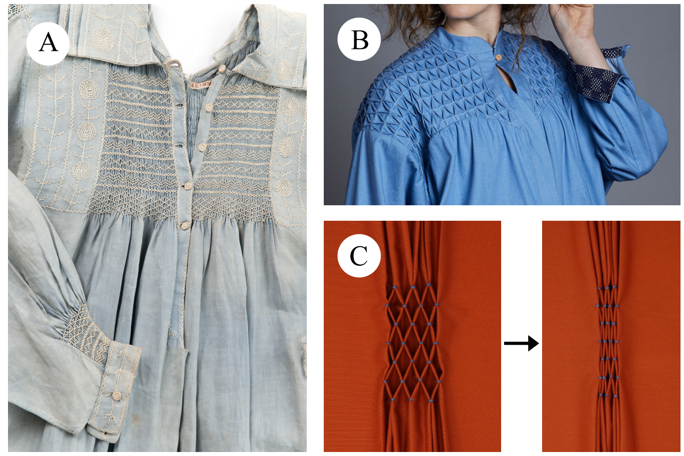

Figure 2: (A) Smocking on the body and sleeves of an early 20th-century dress made in Dorset, UK.[1] (B) Decorative honeycomb smocking in a contemporary garment.[2] (C) A *Flex*tile sample in its expanded (left) and contracted (right) states.

2 RELATED WORK

Our work draws from traditional textile techniques and recent research in SMA-actuation of textiles. Our approach is inspired by research that has included perspectives of designers and reflective practices throughout the development of new textile technologies.

2.1 Textile Techniques for Shape-Change

To develop a means of actuating planar shape change in fabric that would be compatible with varied textiles and accessible for designers to implement, we looked at existing textile techniques for changing textile shape and fit that could be leveraged with SMA. Changes in shape or fit can be achieved passively with elasticity (e.g. knitted fabrics [24]), or with textile techniques such as gathering, pleating, shirring, ruching, and smocking [8, 48]. Recent methods include 3D printing onto stretch fabric [52] and heat-setting origami folds into non-stretch fabric [61].

Smocking. We selected a traditional craft technique called Honeycomb Smocking for *Flex*tiles, as shown in Figure 2[12]. Smocking techniques are diverse and present in the craft heritage of many cultures across the world, for example, the Ghanaian smock is a traditional dress still worn today in Ghana [15]. As far as we are aware, honeycomb smocking was one of a selection of smocking techniques first developed in the 18th century in England and Wales [51] to add elasticity and shaping to the thick cotton fabric of labourers clothes [32]. The techniques are based on gathering and embroidering folds in the fabric, enabling the rectangular pieces of cloth from the weaving mill to be shaped without wasting fabric. [45] The embroidered stitches can be customised, which became a basis for decorative embellishment and personalisation of garments, as seen in the dress from the early 1900s in Figure 2A. This

[1]Image A used with permission from The Museum of English Rural Life, University of Reading. Collection number 63/283.
[2]Image B used with permission from The Smockworks, UK, (photo credits: ©Marec Puc)

style of smocking has a varied social history from use in labourer's clothing to eventually being seen in the fashion pages of Vogue magazine [53]. Nowadays, it is primarily used as a decorative feature of everyday garments, for example, in the modern dress shown in Figure 2B, but it can also add bold texture and shaping in fashion design [34]. Not all smocking allows for planar shape change; we selected honeycomb smocking due to its unique expandable structure based on regular folds (see Figure 2C). The technique of honeycomb smocking was first introduced to the field of HCI by the Hybrid Bricolage [12]. Their in-depth exploration of the technique for static (non-actuated) projects includes a pattern catalogue for modifying the parameters of the smocking pattern to generate varied visual and textural effects and design software for creating templates. These provided inspiration for *Flex*tiles with details on designing with this textile technique.

2.2 Active Shape-Change in Textiles

Shape-changing interfaces and displays have emerged in HCI and beyond, affording a diverse range of interactions [3]. Existing works that focus on shape-change in fabrics have achieved this with multiple actuation technologies, for example; fluidics [9, 18, 27, 29, 40, 42, 44], motors and/or tendons [2, 59], shape memory polymers [56], eleactroactive actuators [20, 58], shape memory alloys (see next section), and even with organic actuation such as biofilms [60] and humidity-responsive yarns [47]. We have seen one example of combining actuation with honeycomb smocking; Albaugh's playful smocked collar [1] is actuated with tendons to show or hide the wearer's face in different social scenarios. The actuation of the collar bends the smocking out of plane, but we are interested in shape-change within the plane of the textile. Of the existing actuation methods, multiple afford some degree of planar shape-change in textiles [4, 14, 19, 27, 29, 31, 33, 43, 44, 56]. We selected SMA actuation since it allows for seamless integration into fabrics [14], DIY fabrication [39] and simple control (or even environmental activation [63]).

SMA-actuation of Textiles. SMA-actuated textiles projects started appearing two decades ago with works such as the Vilkas dress with rising hem line [4] and the Oricalco un-crumpling shirt [14]. They have since increased in number exponentially, with the majority presented in the last 5 years (e.g. [19, 28, 30, 36–39, 50]). SMAs can generate a wide variety of movement behaviours in textiles, for example, modifying local topology and actuating small elements to bend, roll or lift [5, 21, 30, 37–39, 55], changing global texture [6, 10, 38, 56, 57] or stiffness [7], and generating in-plane shape-change such as contraction and expansion [4, 19, 31, 33]. We have seen one example of SMA-actuation in smocking; KOBAKANT provide a short tutorial[22] for actuating a diagonal smocking pattern with SMA springs.

Of these, some of the proposed methods present barriers to use for designers looking to incorporate them in their projects, such as requiring specialised tools or equipment [14, 19, 28], or being incompatible with off-the-shelf fabrics [4, 6, 14, 19, 28, 31]. Most importantly, only a few provide a broader design space and characterisation of techniques for integrating SMA-actuation into fabrics [30, 37, 39]. Patch-O [30] present a technique for fabricating morphable patches with weaving, providing a parameterised technique for creating small patches that can bend, open and scrunch. ClothTiles [37] present a design space for 3D printing actuatable elements onto clothing for localised deformation. And, Seamless Seams [39] provide accessible techniques for actuating small fabric elements with bending, curling and creasing behaviours. In this work, we extend this design space of SMA-actuation in textiles to provide a parameterised technique for scalable planar shape-change. By using a traditional textile technique as our basis, we can incorporate the SMA wire aesthetically into diverse fabrics.

2.3 Including Designers in the Design Process

Designers play a vital role in bringing new technologies into the public domain. They have unique expertise in fabrication and design processes combined with an understanding of end-user needs and the state-of-the-art in their field. This expertise and tacit knowledge are of great value when developing new technologies. Prior research introducing novel textile technologies has demonstrated this by involving designers in e.g. evaluating novel interfaces [11, 25, 30], fabrication processes [30], technology samples to aid design [54], and in developing design recommendations for other designers [16]. These works gather data through interviews (primarily semi-structured) and workshops with designers in which the designers see or interact with the materials and interfaces, and findings are drawn from the transcribed data using qualitative analysis methods such as grounded theory [11, 25, 30] and descriptive coding [54]. The projects drew valuable insights from working with the designers that guide future technology directions. For example, the sessions conducted by Devendorf and colleagues with fashion designers and wearers revealed essential factors that distinguish the desired behaviour of Ebb, a textile-integrated visual display, from screen-based devices, reframing typical visual display heuristics such as speed and resolution [11].

Inspired by these works, we consulted with designers and practitioners throughout the development of *Flex*tiles to identify the fabrication methods and possible application spaces of the techniques that are of value to designers.

3 FLEXTILES PRINCIPLE

The working principle of *Flex*tiles is to leverage the expandable lattice structure of honeycomb smocking for actuation with SMA wire. This technique was developed during a process of hands-on material and fabrication exploration and subsequently developed further through consultations with designers. We first detail the simple fabrication method and materials foundational to implementing a *Flex*tile design.

3.1 Fabrication

Figure 3 details the steps for fabricating a *Flex*tile swatch using a 3 by 3 regular array as an example. A unit cell template is first selected (Figure 3A1) and multiplied to form an array (A2). The lines in the template indicate where embroidery stitches should be made; a unit cell consists of four lines to be stitched together, pulling folds of the fabric together to form a diamond in the structure. Through a process of drawing the smocking template onto the fabric (B1), pinning or sewing the SMA into folds along the vertices of the stitch lines (B2), stitching the folds together (B3) and continuing this process until the array is complete (B4), the *Flex*tile swatch is fabricated.

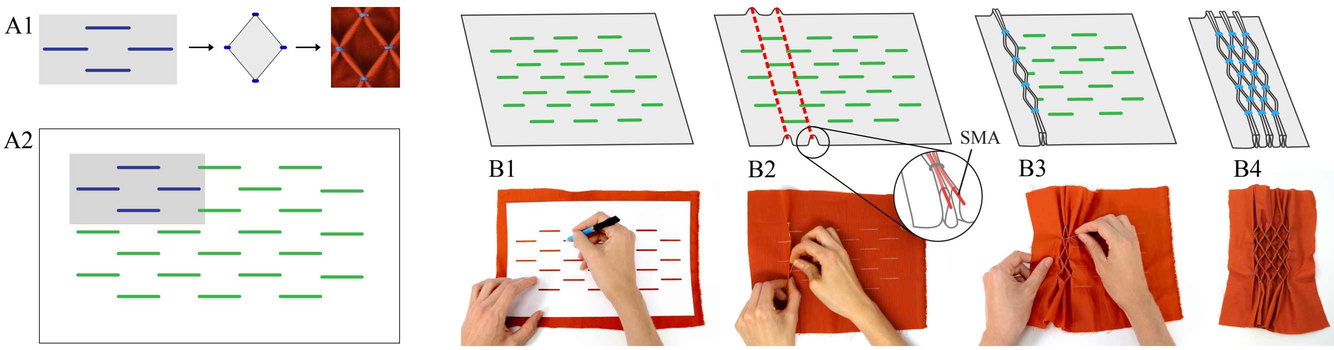

Figure 3: *Flex*tile fabrication steps: A) The smocking pattern consists of unit cells (A1) in an array (A2). B) To fabricate *Flex*tiles, the smocking pattern is drawn onto the fabric using a template (B1) that can generated by our design tool. Folds containing the SMA wire are pinned or stitched along the vertices of the marked lines (B2) and stitches are made at each marked line while ensuring the SMA is encased within the resulting fold (B3). Stitches are continued to complete the pattern (B4) resulting in a diamond structure with SMA embedded inside.

This technique produces a stretchable structure, with the SMA wire concealed inside. The SMA wire used straightens when heated above its transition temperature, causing the open diamonds of the smocking structure to close (as seen in Figure 1B). According to the counter-force of the desired application, the structure will open again or remain closed.

Depending on the application, silver jewellery crimps can be used to secure the SMA wire in place by crimping a loop at the end of each SMA wire that can be sewn to the fabric. In cases where electrical current is used to heat the SMA wire, the silver crimps are also used to connect the electrical wires to the SMA wire since SMA is incompatible with solder. The jewellery crimps are affordable and only require a pair of pliers to attach.

3.2 Materials

*Flex*tiles are implemented with off-the-shelf fabrics, embroidery thread and SMA wire. The SMA wire used here is nitinol, a Nickel Titanium alloy that is pseudoplastic when in its 'martensite' state at temperatures below the transition temperature M_F, and becomes superelastic (returning to a pre-trained form) in its 'austenite' state at temperatures above the transition temperature A_F. The austenite form can be trained by heating the alloy to temperatures between 400°C and 500°C in the desired shape and then rapidly cooling the alloy. In this paper, we use an affordable off-the-shelf nitinol wire already trained straight so that no training of the wire is required. We purchased 0.25mm (A_F = 55°C) and 0.5mm (A_F = 45°C, and 20°C) diameter wires at an affordable cost on ebay from Heiko Engelhardt [13] who provide shipping to many countries. However, *Flex*tiles are also compatible with any source of straightening SMA wire, which can be bought cheaply under the name of 'memory wire' used in magic tricks. We chose the aforementioned wires based on their low activation temperatures (compared to the SMA often seen in textile projects, such as Flexinol, BMX and BMF which have A_F = 70°C or 90°C), low cost and straightening rather than contracting behaviour (contraction can require constant activation, raising concerns over power usage and temperature for wearable projects, and potentially requiring specialised control e.g. [36]).

4 DESIGNING FLEXTILES

Figure 4 illustrates the timeline of *Flex*tiles development. The foundational *Flex*tile principle described above was developed via a process of hands-on material and fabrication exploration (a in Figure 4). During this phase, we explored varied textile techniques such as pleating (folding or gathering fabric) and embroidery (stitching onto fabric, including styles such as cutwork and smocking). We then interviewed designers (b) to explore their perspectives on these methods, identify the most promising technique, and discuss ways to develop the designs further. In response to these consultations, we selected the smocking principle as a basis for *Flex*tiles and developed customisation strategies and a design tool to support designers (c). We conducted a workshop with practitioners with practitioners to explore the application space for *Flex*tiles (d), and subsequently fabricated four application cases to evaluate the feasibility of some of the proposed ideas (e). We document our key findings from this process in the rest of this paper.

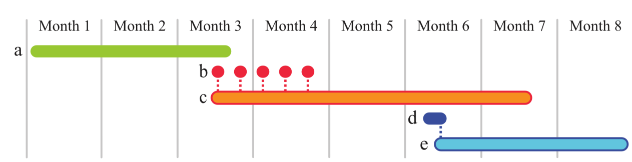

Figure 4: Timeline of *Flex*tiles development and designer involvement; a) initial material and fabrication exploration, *Flex*tiles foundational principle developed, b) consultations with designers, c) conceptual and practical development of customisation strategies, d) workshop with practitioners, e) fabricating application examples.

4.1 Consultations with Designers

In our material and fabrication exploration phase, existing textile techniques were explored for multiple reasons. First, they offer high compatibility with off-the-shelf fabrics and do not require expensive tools. Second, they are familiar to designers with textile or fashion expertise, and free guides are available to support novices. Third, the first author–a crafts practitioner themselves–was interested in the long history of these practices and in enabling new functionality to encourage their continued use. We consulted textile, e-textile and product design experts to probe their perspectives on the techniques and understand the requirements and opportunities for designers to use them. We detail the findings from these consultations, which informed the customisation strategies and tools presented in the following sections.

4.1.1 Participants. The interviewees were 5 designers (D1-D5) with significant textile, e-textile and product design expertise. D1 is a fashion designer and founder of a clothing company producing luxury smocked garments. D2 is a freelance textile designer working in a weaving mill producing functional stretch fabrics. D3 is an e-textiles designer and founder of a company producing therapeutic e-textile cushions. D4 is a lecturer in textiles design with experience in actuated textiles and structures. D5 is a product designer specialising in wearable and medical devices, working for a large design consultancy. All interviewees gave informed consent to use their data in this project.

4.1.2 Interview Method. The consultations were conducted as semi-structured interviews by the first author via online video calls (approx. 1 hour). Prior to the interviews, the designers were sent a short video introducing the project and materials, and showcasing the shape-changing textile techniques being explored, which included an actuated honeycomb smocking swatch like the sample shown in Figure 1B. We asked the designers their (a) suggestions for further patterns or customisation of the techniques to investigate, and (b) perspectives on the concept of shape-changing textiles as exampled by the techniques. The first author analysed the session transcripts using a qualitative content analysis approach [46] to collate all suggestions and reflections of the designers that directly related to the design and possible modifications of *Flex*tiles. They then identified suggestions that could be feasible from this list, drawing from their expertise with the materials and techniques.

4.1.3 Findings. The interview data confirmed that the textile techniques presented could be of value to designers and prompted us to employ and further develop the honeycomb smocking technique for *Flex*tiles. Below we summmarise the designers' responses that directly informed this decision.

Value of employing traditional textile techniques. All of the designers found value in the use of these traditional craft techniques to incorporate shape-change into fabrics. Where the value lay varied between interviewees. Smocking expert D1 drew parallels with their own approach of combining traditional smocking patterns with modern "silhouettes" and fabrics, seeing this introduction of novel functionality (by incorporating SMA) as a natural further step in this progression. They discussed the "juxtaposition of taking a tradition which to be fair if nobody uses it it's just gonna die [...] and us[ing] this technique within designs [with criteria of] being sellable and desirable to people, and great, functional garments." They and textile designer D2 highlighted the value of modernising techniques such as smocking in keeping traditional crafts alive. D4 found value in using textile techniques from a fabrication and design perspective, viewing them as "really fantastic tools to use with textiles designers as [the techniques] are still very open in terms of aesthetics but still you're providing very straightforward structures and behaviour that [textile designers] would understand. And they would appeal also because you're using tools or techniques that are part of this textiles vocabulary." For product designer D5, the textile techniques' value was in seamlessly embedding functionality into clothing without needing bulky electronics or materials (such as those often used in the medical devices they work with), affording comfort and discretion.

Aesthetics of Flextiles. Aesthetics were mentioned frequently in the interviews. For D1, the aesthetic quality of the smocking is a benefit that supports the adoption of such technologies; they commented "I did loads of research on wearable technology [..] probably 20 years ago, and I still feel that I know the technologies there but it's never really come into the field. [...] I think fashion and tech almost need to come closer together because what I see is when you see technology companies doing wearable textiles it's often quite clumsy. It doesn't have that style or aesthetic that it needs to be adopted. [...I] always think that's like a massive gap that hasn't been sort of filled." For D3, they were interested in the experiential or sensory potential of the smocking structures and slow, gentle movement. They imagined incorporating *Flex*tiles into the large cushions they were designing, so that "you could be comforted by it and it gently moves and rocks you and gently undulates," "some bits could move and some bits are harder or softer, and [have] different shapes." D1 also commented on the sensory aspects of smocking, describing smocking as "such a beautiful texture, and when people see the garments they automatically want to touch it" and "look[ing] like a work of art to me, really sculptural."

Opportunities and limitations of Flextiles. A primary contribution of the interviews to the development of *Flex*tiles were suggestions for ways to customise the structures. As D1 commented, there is "creativity with smocking of playing with the designs and structure and pattern". The designers proposed customisation strategies such as adapting actuation, scale and aesthetics. These are detailed in Section 5. Limitations of the smocking technique were also discussed, including the time-consuming trial-and-error phase of developing smocking templates and the difficulty in predicting the outcome of a design. We aim to address these with our design tool and material characterisation, presented in Sections 6 and 7.

5 CUSTOMISATION STRATEGIES

Modifying the materials and properties of the *Flex*tiles primitives opens up a broad design space. We outline these possibilities below, which arose from the consultations with designers and from experimentation with *Flex*tile structures.

5.1 Actuation

The designers were interested in the range of actuation possibilities available with *Flex*tiles, such as responding to the body (D2, D3), the environment (D3, D4) or programmatically from other stimuli (D4, D5). Varied options enable versatility; as D4 commented "as a designer the question is what is the stimulus? what is the input like?" Designer D4, who has explored SMA-actuation in their own work, also highlighted the temporal properties of the actuation; "because [shape-changing materials] respond to time in a very different manner than most common materials that designers are working with, they bring this sense of time in a very physical way." This led us to explore methods of customising *Flex*tiles actuation:

5.1.1 Actuation techniques. *Flex*tiles are activated once their temperature exceeds the transition temperature A_F. Therefore, we provide multiple techniques for triggering actuation by selecting the SMA accordingly. Lower transition temperature SMA (e.g. A_F = 20°C) can be responsive to body temperature or the ambient air temperature, for example, when transitioning from inside an air-conditioned building to outdoors in a hot climate. Higher temperature SMA (e.g. A_F = 45°C or 55°C) can be activated with a standard hairdryer or iron, suitable for certain applications and enabling the designer to test actuation output while prototyping. The SMA can also be connected to power and activated by ohmic heating, allowing human input or sensor data to trigger activation. For ohmic heating in wearable projects, it is recommended that the SMA is sewn into channels in the fabric before smocking to prevent skin contact and power is limited to minimise risk of high temperatures (see Section 9). These actuation techniques afford different time scales for actuation, but we can also customise this in the smocking structure.

5.1.2 Spatial and Temporal Customisation. For all actuation techniques, *Flex*tiles can be implemented with global activation (i.e. all cells activate, as in Figure 5A3). When activating the SMA with a controllable power or heat source, actuation can be customised by activating cells, in turn, to provide temporal actuation patterns or actuating specific cells or sections of SMA within the structure to provide spatial actuation patterns. These spatial actuation patterns are best afforded by actuating whole columns of the array, as shown in Figure 5A, since the columns align with the folds of the fabric containing the SMA wire. Each entire column can be activated by a continuous length of SMA wire and connected to power at one end of the column. Alternatively, power can be connected to segments of the SMA wire by connecting to the SMA at the vertices of selected cells (Figure 5B1). When many cells are connected individually in one column this method increases the complexity of the prototype to control the current drawn by each segment, and the power wires can no longer be hidden within the structure. A solution to this when individual cell activation is desired, is only to place SMA in the desired cells (Figure 5B2) and activate the SMA globally.

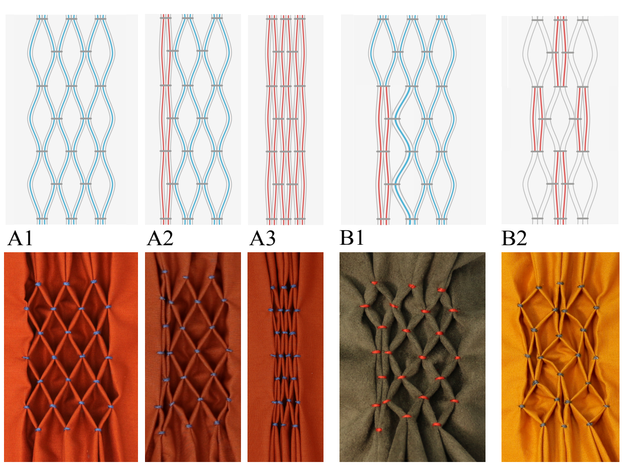

Figure 5: Ohmic heating enables selective actuation of the structure by actuating columns sequentially (A1 to A3), activating partial segments of SMA locally to actuate individual cells (B1) or placing SMA in individual cells and globally activating the SMA (B2).

5.2 Geometry

Spatial customisation is not limited to the actuation schemes used. Designers D1 and D2 both highlighted the geometric properties of the repeated structures themselves. This prompted us to explore further customisation of *Flex*tiles by modifying the cell geometries of the smocking template to generate different geometries of global shape change in the structure. Table 1 demonstrates three examples: the traditional rectangular honeycomb smocking pattern which allows for 1D planar contraction and expansion; adding asymmetry to the cell geometry to generate shearing by converting the diamonds to rhomboids; adding asymmetric scaling to the cell geometry to generate a fanning effect by linearly increasing the diamond size along the fold lines of the smocking pattern. These patterns can be used alone or in combination and their behaviour also depends on the properties of the template used.

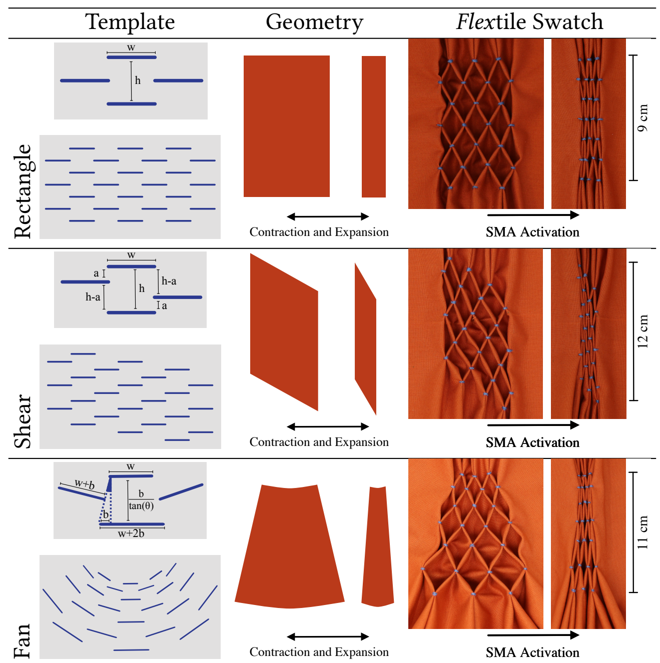

Table 1: Geometric customisation of *Flex*tiles actuation is achieved by manipulating the physical parameters of the smocking template. Left: unit cell (top) with width w and height h, and 3 by 3 array (bottom). For Shear, the degree of shearing relates to the ratio a:(h-a). For Fan, the degree of fanning relates to θ the opening angle. Middle: The afforded change in geometry. Right: Example actuation in *Flex*tile swatches made with the 3 by 3 templates shown.

5.3 Scale

In the interviews, D1, D2 and D4 all highlighted that a benefit of smocking is the ability to play with scale, for example, small smocking details on a sleeve or larger smocking structures on furnishings. D4 discussed the range of size available, from the "scale of the habitat" to the "scale of the body". And D2 described the smocking as this "very modular thing that you can, if you need it, you can make it big and, if you don't, then it's closed." By treating the smocking pattern as a modular array of cells, we can scale *Flex*tiles by modifying the cell and array sizes.

5.3.1 Cell Size. The cell size of the smocking pattern can be modified to scale the pattern to different application cases; for example, a small scale (e.g. $w = h = 20mm$) to integrate into the cuff of a sleeve, or a large scale (e.g. $w = h = 60mm$) to integrate into an item of furniture. Cell size influences actuation behaviour according to the thickness and stiffness of the fabric and the diameter of SMA wire used (see Characterisation section). The general rule is to maintain a suitable ratio between the structure's elasticity and actuation strength; small cells function best with thinner SMA and fabric (e.g 0.25 mm diameter SMA, 60 g/m^2 weight fabric), and large cells require thicker SMA and fabric (e.g. 0.5 mm SMA, 200 g/m^2 weight fabric).

5.3.2 Array size. Altering the number of cell rows and columns enables a change of scale while preserving the material properties of each cell. This is a simple technique for predictably extending the afforded actuation; for example, extending a *Flex*tiles swatch from 3 to 6 cell columns will double the actuation displacement. In practice, there are several trade-offs to be made here. Increasing the array size increases the fabrication time since fabrication time is based on the number of cells to be sewn and the number of SMA wires to be connected - these remain the same in the case of modifying cell size. Additionally, increasing array size requires more SMA, which requires more power in the case of ohmic heating.

5.3.3 Scaling with Power. For projects using ohmic heating to activate the SMA wire, power is the main limitation for scaling up a project. In particular, when considering wearable projects where safety and the wearability of the power supply are key factors. We made a calculation of, and then verified experimentally, the approximate voltage required based on typical resistivity of nitinol in austenite state ($82 \times 10^{-6}\Omega cm$), from which we calculate voltage per cm ($E = 0.104V/cm$). Therefore, for a design with constant diamond height h in cm (see Figure 6), number of actuated cells N_a and number of SMA wires N_c (we add 2cm per wire for the connecting each end), the total voltage is $V = 2(N_a h + N_c)E$. We verified this experimentally; for the example swatch in Figure 5A, 9.4 V was drawn for 1A current in SMA of length 66 cm, diameter 0.5 mm ($E = 0.14V/cm$). Therefore, it is possible to power this swatch with a 9V battery (with minor performance loss). With 1Ah capacity, this could provide approximately 60-120 activations of 30-60 seconds duration depending on the counter-force acting on the patch (see Characterisation section). 6 AA batteries of 1.5 V and 2 Ah capacity could provide approximately 120-240 activations of 30-60 seconds.

5.4 Stretchability

Smocking expert D1 discussed how in their own practice they had been "playing around with different variations [of smocking patterns] using different ratios and different use of space," which they described as changing the structure and rigidity of the smock. We explored such variations with the *Flex*tiles patterns.

*Flex*tiles actuation patterns require an expandable structure which is determined by the ratio ($r = \frac{h}{w}$) of height (h) to width (w) of the diamond cells in the smocking template. As exampled in

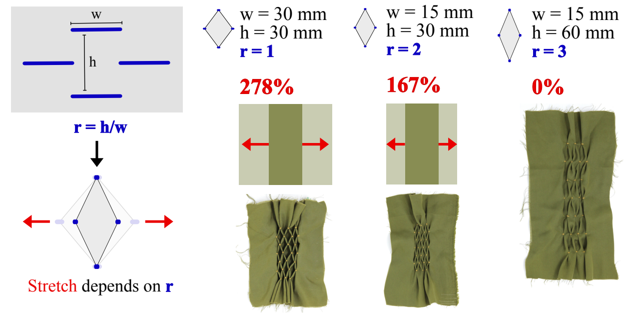

Figure 6: The width (w) and height (h) of the lines in the smocking template determine the properties of each diamond cell. Example swatches with $h : w$ ratios of 1, 2 and 3 (left to right), and their elasticity (inset graph). The fabric is Tencel, weight 150 g/m^2.

Figure 6, if $r >= 2$, there is minimal or no expansion in the structure. As the ratio decreases ($r < 2$), the structure starts to gain stretchability, capable of reaching nearly 280% of its relaxed width at $r = 1$. As the ratio decreases further ($r < 1$) the stretchability no longer increases, but more fabric is used and the cells become deeper. A highly expandable structure is best for generating maximum contractile and expansive displacements. However, the trade-off here is the amount of fabric used and the depth of the folds which may add bulk to the project, especially for heavy-weight fabrics.

5.5 Aesthetics

A key benefit of *Flex*tiles that was highlighted during the interviews is their aesthetic qualities. We developed multiple methods for customising the visual appearance of *Flex*tiles as demonstrated in Figure 7. These swatches example different fabrics (tencel 7A1 and A2, cotton 7B, felt 7C and 7E, vegan suede and cotton combined 7D and linen 7F). They highlight the following customisation options.

Inspired by designer D1's discussion on the texture of smocking, we observed that the smocking pattern can be presented on the reverse side, to produce a textured effect (shown in Figure 7A1 in its stretched form and in A2 in its contracted form - this technique works best when the SMA is fully sewn into channels to hide the embroidery and wire from view), which can be further customised with two-sided fabrics. D1 also commented that they had experimented with pattern structures and pattern layouts, for example, using "a similar technique but sometimes going diagonally and playing around with the space." Inspired by this, we modify the diamond smocking pattern to hexagon-variations (Figure 7B) and demonstrate a distributed layout of diamonds for visual effect (Figure 7F). Discussing apertures that could open and close within structures with product designer D5 prompted us to explore removing the fabric inside the cells to allow airflow or light through the structure (Figure 7C). D2 was interested in combining the smocking with "a printed fabric like when you have a screen print", such that the structure opening and closing would hide different areas of colour or change an image. We example this with adding a contrasting colour inside the cells (Figure 7D).

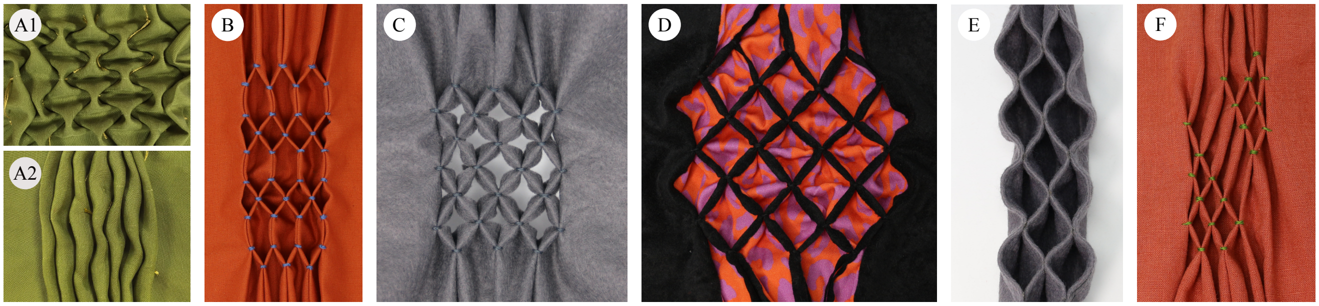

Figure 7: *Flex*tile swatches exampling visual customisation strategies: (A1) and (A2) Reverse side of smocking for texture change; (B) hexagon smocking pattern; (C) porous array allowing airflow or light; (D) hiding or revealing contrasting colour; (E) exaggerating depth of cells to create structure; (F) distributed smocking pattern.

5.6 Disassembly and Reuse

Designers D3 and D4 highlighted the importance of sustainability of the materials and power supply used for shape-changing textiles. Further to using non-electronic heat sources for powering projects, D4 suggested that the *Flex*tile structures could allow for disassembly and reuse of materials. With our method, the SMA wires are primarily held within the folds of the smocking pattern and we use jewellery crimps to connect to the SMA wires or fasten them in the fabric. Therefore, when a prototype or its shape-changing behaviour is no longer needed, the crimps can be simply removed and the wires pulled out of the structure for reuse. This process does not damage the smocking pattern, meaning that the SMA wires can be removed from a final garment or furnishing, leaving the artifact intact for continued use.

6 DESIGN TOOL

Further to contributing customisation strategies, the interviews with designers raised some challenges of using the smocking technique which we aim to address in this and the following section. One factor discussed with smocking expert D1 is the challenge of predicting both the fabric size needed for a smocking panel and the expected outcome. In their practice, D1 uses a toile (mock-up) of a piece first and works out the optimum size and pattern from trial and error. This time-consuming process could be a barrier for designers looking to create *Flex*tile designs. Therefore, we developed a design tool (Figure 8) to reduce the trial and error phase of creating a new smocking design.

6.1 Implementation

Our design tool [4] is implemented in html and freely available for online and offline use. The template and animation are generated from mathematical calculations based on the known properties of the different patterns discussed in the previous section and data inputted by the user. As such, the animation provides a 2D approximation of the fabricated outcome for a given smocking pattern and the amount of fabric required.

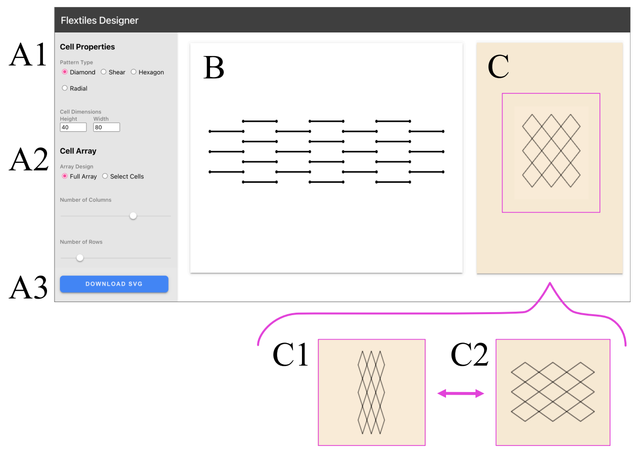

Figure 8: Our dedicated design tool allows designers to specify cell properties (A1) and array properties (A2) of their desired smocking pattern and download the template as an SVG (A3). The canvas (B) displays the smocking template and the preview panel (C) illustrates the expected fabricated outcome in its contracted (C1) and expanded (C2) states.

6.2 Functionality

The design tool allows for customised designs as detailed in Section 5. First, it allows users to select a canvas size, enabling the design of projects at different scales. Next, the user can customise the smocking pattern style they wish to use (A1). The tool provides four options for geometric patterns: the three diamond cell geometries - rectangle, shear and fan - shown in Table 1, and a hexagon cell pattern as shown in Figure 7B. For each, the designer can choose the height and width of the cell template as illustrated in Table 1, with options to customise the shear constant and radial angle for the shear and fan patterns respectively. Having chosen a pattern style, the user can then automatically generate an n by m grid of cells, or select individual cells within a grid (A2). The tool generates a smocking template (B) and provides a 2D visualisation (C) of the final smocking pattern to give designers an idea of the fabricated outcome. The visualisation can be animated to view the pattern structure when closed (C1) or expanded (C2). This

[4]Accessible here: https://flextiles.github.io/ (note: not compatible with small screens)

animation provides information about the expected expandability of the structure according to the findings in Section 5.4. Finally, the designer can export an svg file (A3) of their custom smocking pattern, which consists of lines indicating where sewing stitches should be made in the fabric. The template can be printed onto textile transfer paper or lasercut on card as a stencil.

7 CHARACTERISATION

The design tool provides a template and information on the visual structure of the designed smocking pattern. However, the behaviour of the fabricated swatch depends on multiple factors, such as the fabric and SMA wires used, the counter-force acting on the swatch and the cell scale. Therefore, we characterise the performance of *Flex*tiles with varied fabrics, SMAs and properties to support designers in making informed choices regarding materials and design.

7.1 Method

In the following sections, 'under load' refers to applying a counter-force to contraction of the *Flex*tile patches as illustrated in Figure 9B. The patches are stretched to full expansion, rotated and clamped from the upper side, with a mass m attached to the lower side exerting a force that acts to open the diamond structure. The force is calculated ($F = mg$) based on the mass and doesn't include the added mass of the fabric's own weight under gravity. For each mass, we undertook the following process for collecting data; the *Flex*tile patch is stretched to its maximum width L, then the SMA is activated to contract the patch and the motion captured on video, once the SMA has reached maximum contraction the power is switched off and the expansion of the patch recorded as the SMA cools down. We report the final contraction of the patch ($\Delta L/L$) reached with SMA activated (solid lines in Figure 9, plots A1 to A3) and then after the SMA is de-activated and has settled (dashed lines in plots A1 to A3). All characterisations are conducted using a 3 by 3 array of regular diamond cells ($w = h = 3cm$).

7.2 Results

SMA. Larger diameter SMAs supply greater actuating forces, but add stiffness to the fabric and require a larger current to actuate (in the case of ohmic heating). Figure 9A1 compares the actuation under load of a cotton *Flex*tile patch for three SMA wire types; (S1) 0.25mm diameter wire ($A_f = 55°C$, I = 0.35A), (S2) two 0.25mm wires in parallel ($A_f = 55°C$, I = 0.7A) and (S3) 0.5mm wire ($A_f = 45°C$, I = 1A). The single 0.25mm SMA (S1) was not strong enough to actuate the structure. The 0.5mm SMA wire (S3) performs significantly better under higher counter-forces, but, where counter-forces are low and passive expansion is desired, the two 0.25mm wires in parallel (S2) perform better and these add less stiffness to the fabric.

Fabrics. The actuation behaviour of *Flex*tiles can be customised by selecting different fabrics. Figure 9A2 shows the actuation behaviour under load of *Flex*tile swatches made with four different weights of fabric; (F1) light-weight vegan silk (75% triacetat, 25% polyamid, 70 g/m^2), (F2) standard-weight cotton (160 g/m^2), (F3) medium-weight canvas (100% cotton, dry waxed, 227 g/m^2), and (F4) heavy-weight denim (330 g/m^2). The shaded regions of the graphs indicate that lighter-weight fabrics are better for leveraging counter-force into passive expansion (F1 and F2). Heavier-weight fabrics perform better for retaining contraction under load when the SMA is de-activated (F3 and F4). Cotton (F2) performed best in terms of high percentage contraction and expansion under load.

Cell Scale. The scale of the cells in the *Flex*tile smocking structure influence the elasticity for the given fabric and SMA type. Figure 9A3 shows the contraction of 3 different cell sizes under load (C1) $w = h = 60mm$, (C2) $w = h = 30mm$, (C3) $w = h = 15mm$ (Note: these were 1 by 3 cell arrays in cotton fabric, with SMA S2, I = 1A). A larger cell size affords greater overall displacement as well as percentage expansion but performs less well under load.

Temporal Behaviour. These tests were carried out on the cotton *Flex*tile swatch (SMA 0.5mm, $A_f = 45°C$, I = 1A):

Time Response: Figure 9A4 shows the displacement over time when actuating the patch to maximum contraction under different loads. In all cases the actuation is slow for the first 5 seconds as the SMA raises in temperature. The results indicate that counter-forces have a significant impact on the rate of contraction.

Starting Displacement: Starting at 5 different expansion distances, the structure consistently contracted to 25% total width (std 0.81) for $F = 0$, and 37% (std 1.1) for $F = 1.4N$. This indicates that the final contraction is consistent regardless of the initial width of the structure.

Consistency: Repeating 5 trials each with forces $F = 0$, $1.4N$ and $2.6N$ gave a mean standard deviation for the percentage contraction of 1.2 for contracted state and 2.36 for relaxed state post-contraction. This indicates a level of consistency in actuation behaviour that is sufficient for most textile projects.

Sequential Actuation: Actuating individual columns (for 3 by 3 array) in all order permutations (SMA 0.5mm, $A_f = 45°C$, I = 1A, $F = 0$) produced a contraction (as percentage of maximum width) of mean 23.0% (std 6.2) per row.

Material Fatigue: To understand how *Flex*tile designs perform with repeated use, we conducted fatigue tests on the fabric swatches F1-F4 in Figure 9C. New SMA wires were inserted in each swatch before testing. To simulate extreme conditions, we selected a load equating to the largest displacement recorded in Figure 9A2, and continuously cycled actuation for up to 1000 cycles with high current. Activation parameters and results are shown in Table 2. We noted a marked performance deterioration for F2 compared to F3 and F4, despite similar load. This may be due to F2's larger displacement in each cycle or larger SMA deformation angle at maximum expansion due to being a less stiff fabric. We additionally tested an F2 swatch with a lower load, which performed consistently for 1000 cycles.

Temperature. Temperature is an important factor in powered SMA projects and raises safety considerations for projects that may be worn or touched. The temperature reached by a powered *Flex*tile swatch depends on the SMA, current, activation duration, and the heat dissipation rate through the fabric. We activated each swatch F1-F4 and took videos of the front and back with a thermal imaging camera (Flir One Pro). The peak temperature and a 3-point average were collected across the smocked area after 30 seconds of activation at $I = 0.7A$ (F1) and $I = 1A$ (F2-F4). Peak point temperature was $60°C$ for F1, $45°C$ for F2, $44°C$ for F3, and $38°C$ for F4. The 3-point average was $54°C$ for F1, $36°C$ for F2, $36°C$ for F3, and $31°C$ for F4. While the peak temperatures are high, especially for

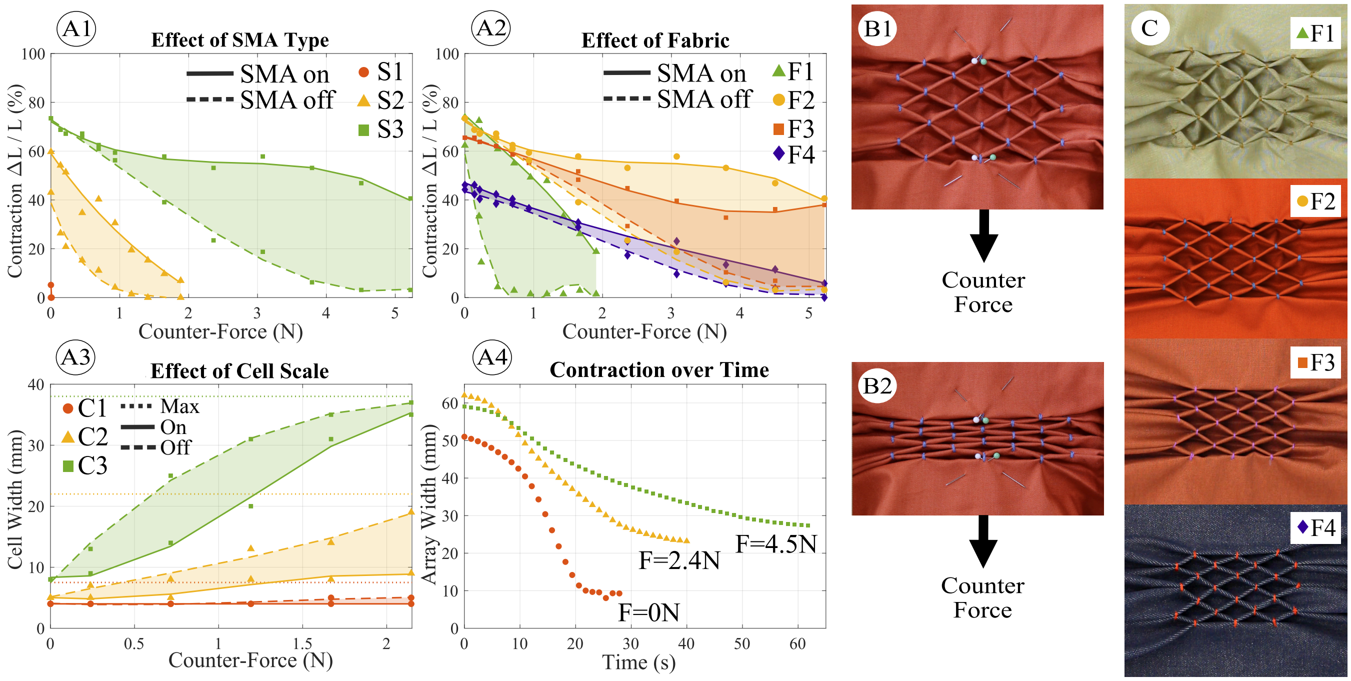

Figure 9: Characterisation of *Flex*tiles. Plots A1-A2) Contraction ratio against a counter-force for a cotton patch with SMA in activated austenite state (solid lines) and de-activated martensite state (dashed lines) for; A1) varied SMA S1, S2 and S3, and A2) varied fabrics (pictured right in C) F1 (silk, with SMA S2), F2 (cotton, S3), F3 (canvas, S3) and F4 (denim, S3). A3) Change in cell width under load for the cotton patch with varied cell scales C1, C2 and C3. A4) The time response for the cotton patch when contracting under three counter-forces. B) The setup for applying counter-forces to the swatches, with B1) no activation and B2) SMA activated.

						% Contraction at Cycle				
F	SMA	Load (N)	I (A)	On (s)	Off (s)	10	250	500	750	1000
F1	S2	0.9	0.7	25	40	100	82	68	68	66
F2	S3	4.0	1.2	30	80	100	74	50	-	-
F3	S3	4.5	1.2	30	80	100	82	80	72	71
F4	S3	3.8	1.2	30	80	100	100	95	89	84
F2	S3	2.1	1.2	15	80	100	100	100	100	100

Table 2: Fatigue test results for swatches with fabric (F). Swatches were activated in on/off cycles for up to 1000 cycles with current (I). Performance reported as % of contraction displacement at cycle 10.

the thinnest fabric F1 (silk), the surface felt warm to the touch but not uncomfortably so. Heat transfer to the skin depends on many factors, such as the object mass, geometry, fabric thickness and material, and contact time [62]. All swatches were safe to touch on both sides even after 30s of continuous activation. However, if worn tightly on the body, we recommend that designers use thicker fabrics or add an insulating fabric layer underneath and sew the SMA into channels to avoid direct contact with the skin. We advise minimising the activation time for powered projects and incorporating a minimum cooling period (Table 2 shows our minimum cooling periods for reference) after every activation to prevent the risk of overheating.

8 EXPLORING APPLICATION OPPORTUNITIES

Thus far, we have presented tools and methods for fabricating customised *Flex*tile designs. But what might these designs be used for and in what contexts are they valuable? We conducted a workshop to envision possible use cases for *Flex*tiles and subsequently realised four applications to explore the feasibility of the ideas that arose.

8.1 Workshop with Practitioners

The workshop was an exploratory in-person session with four local practitioners. The participants were: P1 (m, 31), an engineer with expertise in SMA wire; P2 (f, 27), a researcher with experience in wearable technologies and E-textiles; P3 (f, 33), an artist experienced with techniques such as weaving; and P4 (f, 30), an artist with experience in sewing and costume production. The first author, as facilitator, also contributed to the discussions, with expertise in SMA-actuation and *Flex*tiles designs. All participants gave informed consent to use their data in this project.

The workshop was 2 hours with 4 phases: (1) Introduction to SMA-actuated textiles, including demonstrations of SMA wire and *Flex*tile primitives. (2) Ideation of application ideas within six themes (changing the style or function of clothing, responsive

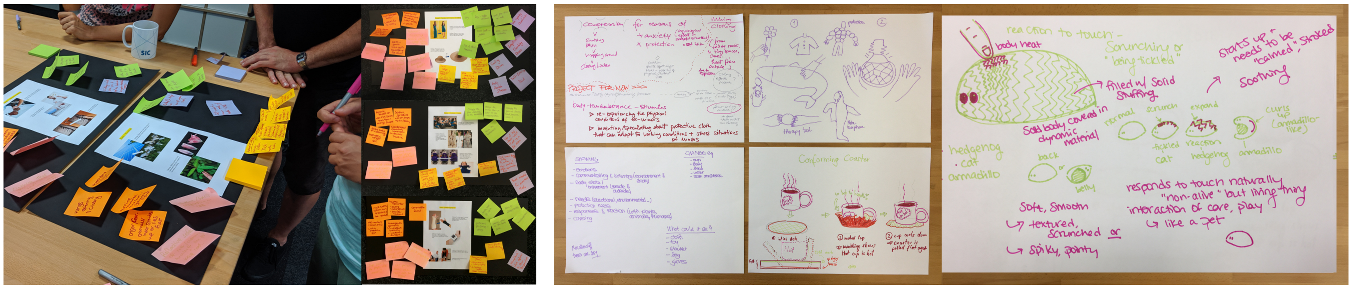

Figure 10: Photos from the workshop with practitioners. Left: Post-it note collations from the generative ideation phase. Right: Sketches made by participants in the idea refinement phase.

furnishings, costume and fashion, medical and health, interactive clothing, and biomimicry). For each, participants had 2 minutes to generate ideas and add them to a collective board (Figure 10, left), then the group discussed the ideas that arose. (3) Individual reflection and exploration of materials provided for inspiration. (4) Participants individually developed one or two ideas further, making sketches of possible prototype designs (Figure 10, right), which were then shared and discussed as a group. The first author transcribed audio recordings and coded the data in two passes using an open coding approach [49].

8.1.1 Findings. The ideas generated during the workshop (see full list in Appendix) span various behaviours, material properties, activation strategies and contexts, which support and extend the suggestions made by designers in Section 4. We briefly present recurrent global findings before discussing more specific findings that informed our application cases in the next section.

Participants' discussions indicated that they found the planar shape-change inspiring for clothing or furnishing that could *adapt to their needs* and several concepts recurred: (a) having one adaptable item in place of many items (P1-P4), e.g. a bag that expands to become a suitcase to carry more items (P4); (b) enabling personalised interactions tailored to the user (P1-P4), e.g. clothing that changes shape to fit the individual (P1, P2); (c) responding in a dynamic and context-aware manner (P1-P4), e.g. clothing adapting to provide protection (P2, P3, P4); and (d) not detracting or distracting from the user's current activity or focus (P1-P4), e.g. clothing adapting as needed during sports without interrupting the activity (P2, P4).

The aesthetic material and behavioural qualities of *Flex*tiles, such as being made of soft, familiar fabrics and exhibiting "quiet" (P1) and "organic" (P1) motion, were described as positive attributes and participants discussed the concept of embedding these interfaces into the *textiles of daily life* (P1-P4) to provide *ambient* (P1, P2, P4) interactions. The participants also explored applications inspired by a *life-like* quality of the SMA-driven movement, for example, fabric devices that react to touch (P2, P3), e.g. a toy that curls up when held (P2), and engage with the body (P1-P4), e.g. clothing that pokes you to encourage different behaviour (P1) or squeezes you to convey a hug from a remote loved one (P2, P3, P4). Tangential to this was fabric responding to environmental factors, e.g., responding to ambient temperature (P1-P4) and changing shape or texture to allow more light, air or heat through. All participants were interested in using alternative sources of heat to activate the SMA wire so as not to "waste energy" (P3), e.g. sunlight (P1, P2, P4), a hot water bottle (P1) or hot dishes (P2).

8.2 Applications

The workshop proposed broad application possibilities but without discussing the feasibility of realising functional prototypes with *Flex*tile techniques. We explored this after the workshop by fabricating four application cases informed by the session findings and participant ideas. The application cases showcase *Flex*tile designs and actuation schemes with varied scales, responsivity and functionality. They all use templates generated by our design tool.

8.2.1 The top fit for a life-time. The participants discussed clothing adapting to the user's needs, e.g. clothes "conform[ing] to the shape of bodies rather than coming in standard size" and "adapt[ing] to the change in shape of the body through the day, [...] maybe through life as well like for children growing or maternity clothes" (P2). Inspired by this discussion, we designed the top 'fit for a lifetime'. The top, shown in Figure 11A, contains two *Flex*tile panels in contrasting colour that change the shape of the top from being loose to fitted around the waist. We explored using an available heat-source - a hairdryer - one of the heat sources discussed in the workshop; when the wearer puts the top on in the morning, they can heat it to create a figure-hugging fit which will remain throughout the day until they choose to stretch the pattern for a looser fit. The force required to open the pattern is approximately 3-4N. We tested the top in different activities to investigate whether this was sufficient to maintain closure. The top maintained closure for an entire day during typical office wear and when worn during a yoga class (23mm fully contracted width, 30mm at end of day, 28mm after yoga session, 55mm fully expanded width). Our experimentation suggests that designs like this would function best on areas of the body without high flexion (e.g. upper/lower arm, torso, thigh, calf) and would be unlikely to maintain closure on joints (e.g. elbows, knees, shoulders, or hips). *Flextiles specs: shearing pattern, mid-scale cells, light-weight fabric, 0.5 mm diameter SMA, A_f=45°C.*

8.2.2 The environmentally responsive scarf. During discussions on environmentally-responsive clothing, P2 commented on the changes in temperature inside and outside buildings; "we move around through lots of artificial environments, [..a coat] works when you're outside because it's cold but then you move into a

Figure 11: Application examples; A) the *top fit for a lifetime*, for garments that fit perfectly even as our body changes (A1 expanded, A2 contracted), B) the *environmentally responsive scarf*, for style that draws awareness to our environment by activating with ambient temperature (B1 textured when cold, B2 smooth when warm), and C) the *ticklish hedgehog*, that curls in response to touch (C1 expanded state, C2 curled state in response to touch detected by embroidered capacitive touch sensors).

building and you're sweating and pulling all of your clothes off" (P2). P1 and P2 discussed the idea of temperature-responsive clothing in this context, not just for temperature regulation, but also "to show different visual cue[s]" (P1), taking inspiration from nature, "like when birds kind of ruffle their feathers, that kind of texture change" (P2). Inspired by this, we developed 'the environmentally responsive scarf'. The scarf, shown in Figure 11B, uses low-temperature SMA wire that responds to ambient temperature changes. Outside in cold weather, the wearer can scrunch the scarf around their neck for warmth. The design incorporates a large diamond *Flex*tile array with a reverse smocking pattern within the lightweight weave of the scarf to produce a textured effect, inspired by the idea of ruffled-up feathers for warmth (P1, P2). Upon entering a heated building of 22+°C, the scarf straightens, loosening away from the neck and becoming smooth. The scarf supports the wearer in regulating their temperature while also bringing their awareness to these transitions throughout their day. We found the scarf to function successfully on entering the building from a cold environment, but this method of activation is slow in comparison to other methods (transition time ~1-3 minutes). *Flextiles specs: rectangular pattern reversed, large-scale cells, light-weight fabric, 0.5 mm diameter SMA,* A_f*=20°C.*

8.2.3 The ticklish hedgehog.

Participants mentioned the 'life-like' qualities of *Flex*tiles in various contexts, such as an "opening and closing" movement of breath (P3), "growing" with the sun (P4) and "raising hair" like a cat (P1). P2 sketched ideas for a toy creature (Figure 10, far right), presenting behaviours - inspired by hedgehogs, cats and armadillos - such as curling up or raising spikes when touched. She was interested in the idea that "when you touch [the creature] it somehow squishes and responds to you in some way, some thing to play with and make that emotional connection to something non-living". Inspired by this, we created a hedgehog toy (Figure 11C) that curls up in a ball when tickled. In P2's design, the creature would respond to the warmth of the hands, but we found that the lower temperature SMA (A_f=20°C) did not work for this, as it was already semi-activated at room temperature. Therefore, we fabricated capacitive touch sensors on the belly of the hedgehog by embroidering the smocking pattern first with conductive thread, which becomes hidden seamlessly in the pattern. The conductive thread is connected to a micro-controller (Arduino Nano) inside the toy and touches are detected using the Arduino 'CapSense' (capacitive sensing) library. On detecting a touch, the SMA wires (A_f=45°C) are activated via battery power. *Flextiles specs: rectangular pattern, heavy-weight fabric, 0.5 mm diameter SMA,* A_f*=45°C.*

8.2.4 The "Mary Poppins" luggage.

At multiple instances, participants discussed replacing multiple items with one adaptable item, such as bedding that adapts to the seasons (P2) or a chair adapting to different people (P3). We found some of the suggestions to be beyond the capacity of current *Flex*tiles designs; for example, P4's suitcase-to-bag conversion is of a scale that would be very power-hungry. We developed a smaller example of adaptive luggage to explore the use of *Flex*tiles for dynamic size adjustment. Typical methods for adjusting bag size, such as drawstrings, straps and buckles, can be fiddly to use and come with their own aesthetic. The satchel, shown in Figure 1C, incorporates *Flex*tiles into the side panels of the bag. Sequential array activation of the side panels enables the bag to seamlessly adapt to the size of the bag's contents, for example, when the bag is empty the sides can collapse for a streamlined look and reduced size. An internal battery pack powers the actuation. Future implementations could employ sensing to automatically close according to the bag's contents so that the user can use it hands-free. *Flextiles specs: rectangular pattern, mid-scale cells, medium-weight fabric, 0.5 mm diameter SMA,* A_f*=45°C.*

9 DISCUSSION, LIMITATIONS AND FUTURE WORK

We began this work interested in combining SMA materials and textile craft techniques to enable designers to incorporate dynamic planar shape-change into their projects. This became a journey of discovery with the materials and craft of smocking, revealing opportunities for customization and meaningful applications. Engaging in dialogues with designers and the materials throughout the process enriched the designs and echoes the long history of sharing and developing textile techniques by hand and word-of-mouth. Reflecting on this journey, we discuss the limitations of this work and identify future directions for *Flex*tiles:

Prototyping with designers: We have included designers throughout the development of *Flex*tiles through interviews and a group workshop. However, we did not engage designers in fabricating *Flex*tile patterns themselves. This is an important next step for ensuring the techniques and tools are accessible and identifying any barriers to use. In engaging more deeply with the materials and processes, the designers will be enabled to 'follow the materials' [23] and develop their own dialogue with *Flex*tiles. This was mentioned by participants, for example, designer D3 commented that their suggestions were limited by not having hands-on experience with the materials. We are interested in exploring not only how designers engage with the fabrication process but also in the shape-changing artefacts they create.

Diversifying textile techniques: Our discussions with designers and experiences with *Flex*tiles designs highlighted the value of using traditional textile techniques for generating shape-change due to their compatibility with diverse fabrics and seamless integration in textile projects. In this work, we have showcased honeycomb smocking for generating in-plane shape change. However, we envision this as one of many textile manipulation techniques that can afford varied shape-changing behaviours to complement existing methods such as integrating SMA into weaving and knitting. Future work will explore further craft techniques and shape-changing possibilities.

Incorporating feedback control: *Flex*tiles do not currently employ feedback control for actuation and are not force- or displacement-aware. This limits the possibility of fine-tuning the rate of shape change with *Flex*tiles since SMAs have a nonlinear behaviour that is influenced by external factors such as ambient temperature and counter-force. Moreover, many applications proposed by participants in the workshop require sensing to function as desired. Future work could explore implementing techniques such as neural networks, which have been demonstrated for providing position control with SMA [35]. Temperature is another key factor to consider in powered projects; designers need to ensure that they set an upper limit on the activation duration and a lower limit on the time between activations to allow for cooling based on the expected context of use (e.g. type of fabric, proximity to the skin, etc). Incorporating a temperature sensing system could enable greater diversity of body-based applications while ensuring safety.

Optimizing activation strategies: Powering SMA projects is always a topic of concern due to the high current requirements and possibility of high temperatures. *Flex*tiles can be actuated sequentially to reduce power requirements and their surface temperature during ohmic heating ranged from 30-40°C, indicating that the folds of fabric successfully protect the user from heat. However, for scaling up *Flex*tiles in powered projects, we recognise that optimisation strategies are needed for supplying distributed power and embedding wires through the garment's seams.

In future work, we are particularly interested in the opportunity to make further use of alternative heat sources, such as ambient temperature or body heat, which were heavily discussed in the workshop. These techniques address the power concern and the sustainability issues raised in powering e-Textiles projects [17]. Additionally, as highlighted in participant discussions, a unique affordance of these materials is the aesthetic and embodied dialogue with the body or environment they can elicit. We demonstrated one use case for ambient temperature activation with the scarf. However, we recognise that further experimentation is needed to understand the behaviour of *Flex*tiles at different temperatures to inform the design of these interfaces.

Automatising design and fabrication: Our design tool exposes high-level parameters to the designer, such as the desired elasticity and actuation geometry, automatically generating a customised template for production. However, the tool can be extended further, in particular by having a more sophisticated visualisation of actuation that can, for example, allow the designer to view the behaviour of their pattern with different fabrics and under different counter-forces. It could also offer tailored templates, for example, a template for lasercutting accurate holes in the fabric for fabricating porous smocked structures. In this work, we fabricated our swatches and application cases manually, and discussions with designers highlighted this as a strength of combining traditional techniques with modern materials. However, we recognise that designers may also find value in methods that enable more rapid prototyping of ideas. Thus, an interesting direction for future work is to investigate how this process can be partly or fully automated.

Exploring Flextile interactions: Within the discussions with designers and practitioners, an aspect that stood out was the 'life-like' quality of *Flex*tiles movement and the unique properties SMA-actuated textiles have of being silent, soft, and familiar. Our qualitative findings complement prior work (e.g. [11, 26]), highlighting textile interfaces' unique aesthetics and behaviours compared to other technologies. So far, our designers engaged with *Flex*tile samples in an interview or workshop context, but our next step is to explore their perspectives on *Flex*tiles via in-the-wild encounters. We are interested in exploring the interactions afforded by these qualities and how people respond to them when situated in their homes and on their bodies.

10 CONCLUSION

Using a traditional honeycomb smocking technique, we present *Flex*tiles, a parameterised design schema for embedding SMA-actuated planar shape change into fabrics. The technique is compatible with off-the-shelf fabrics and requires minimal fabrication tools, allowing designers to easily prototype with *Flex*tiles in their projects. The development of *Flex*tiles was informed by consultations with design experts. These conversations inspired customisation strategies such as modifying scale, elasticity, actuation geometry and location, and aesthetic properties such as colour, texture and porosity. We provide a design tool to aid the implementation of *Flex*tile designs, and characterise their performance, demonstrating that they can be deployed in diverse fabrics, actuate against counter-forces of up to 5N and behave consistently over time and from different initial displacements. Finally, we explore application areas for *Flex*tiles by conducting a workshop with practitioners and realising four application cases that showcase dynamic changes in shape, fit, and style. *Flex*tiles extend the current design space of SMA-actuation in textiles, providing designers with further techniques for augmenting textile projects with shape change.

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Theme	Example ideas	Participant generated ideas
Changing style/function	Work clothing transforming to evening wear; party outfit that is less exposed for walking late at night; a hat that can provide more protection when the sun is shining.	P1: Venting shoes; adaptive climbing shoes; non-opening shoelaces; self-folding shirt; really flexible glasses. P2: Non-standard sizes - clothes to fit body; change for environment such as temperature / water levels; long-term wear and changing body sizes; belts and pants that adapt to stay fitted throughout the day. P3: Changing shape to protect from rain (scarf or umbrella); providing cooling; trousers that change between short and long to protect from bugs or plants when walking; scarf becomes hood; headgear. P4: Tent to sleeping bag; bag to suitcase; long to short trousers; rain coat to jacket; Towel; top that changes to crop top. Author: Shoes become boots; clothing that doesn't need ironing; automatic tightening; tank top becomes crop top; alternative to shoe laces; scarf that can be long or short.
Medical/health purposes	Providing adaptive stiffness support for an injury.	P1: Hot water bottle that deforms to indicate temperature. P2: Rigid casts that can breathe or be removed; heart rate monitors that actually fit (e.g. when jogging); therapeutic garments for pressure therapy or movement support; compression socks; haptic reminders for eating, medication, exercise etc. P3: Heat regulation for fevers; compression socks or compression system for capillary vessels; holding fluids - for example in adult nappies. P4: Phone cover for sport; protection for biking/driving; methods for sweat while exercising; helmet for biking; Knicker-pocker. F: Bracing for people with tremors; support for lifting heavy objects when frail or ill; notifications when heart rate or physiological measures are too high/low; adaptive clothing for physiotherapy.
Responsive furnishings	Window blinds that respond to light level in specific areas; encouraging people not to sit for too long or with bad posture (e.g. on sofa); dynamically change lighting level and patterns.	P1: Non-intrusive signalling that is quiet and smooth (e.g. dishwasher done); kinetic sculpture indicating 'time to work' or 'time to relax'; curtains that block or let in the sun. P2: Sunlight restriction for plants - covering when too hot/bright; kitchen mats/coasters that expand under hot dishes; bed sheets that get more surface area when cold - trap heat in the structure; warning systems for heat in kitchen/devices; table cloths that expand for extra people. P3: Chairs that can change height or wideness; furniture that can change airflow or layers to adapt air circulation. P4: Growing chairs / tables; light that grows with the sun or opposite; roof growing and letting more/less sunlight in; dish for smaller/bigger food; chair with or without backrest. F: Table that can fold away or get bigger; moldable table for sat in bed or sofa - adaptive shape; children's sleeping lamp that slowly changes making shadow patterns; subtle notifications.

Table 3: Participant (P1-P4) and facilitator (F) ideas generated in the workshop for themes 1 to 3. The example ideas were given by the facilitator when introducing each topic.

Theme	Example ideas	Participant generated ideas
Costume/fashion	Costumes that dynamically respond to performer; statement structural elements in clothing that can be shown/hidden/modified during wear; actuated costumes that change shape are very heavy and bulky with motors - can they be made more wearable.	P1: SMA hairs that stand on end or lie flat; suit or dress that changes outline to display emotion - like a paradise bird; facial mimics for animatronic masks. P2: Extra limbs in costuming (e.g.expanding wings); fabric layers on dresses/shirts that flow and change shape; coordinated clothing movement in dance/theatre; sensing garments which shape to the body. P3: Dancing with the garment; garment getting larger or smaller in 3D with different temperature air flows from different directions; breathing effect pulsation; protection for performers; teeth or spines that move (e.g. dragon costume); showing areas of skin and covering again. P4: Form responding to movement; 'freeze' a motion of the performer (e.g. costume freezes in a position); metamorphosis such as changing animal that you want to be; clothing that changes function (e.g. hood becomes trousers becomes shirt). F: Clothing that changes shape with performer's temperature; costume that closes to restrict movement of performer; audience controlling costume behaviour.
Interactive clothing	Clothing that lets you know a loved one is thinking of you; clothing that is playful or gives us reminders; clothing responding to temperature (e.g. sleeves roll up).	P1: Clothing which pokes you to enforce behaviour - negative feedback. P2: Toy which scrunches when you tickle it; clothing that reassures - squeezing my anxiety; hugging shirts for long-distance relationships; stress balls that increase resistance the more they are squeezed. P4: Clothing telling your emotion / thoughts; clothing changing in response to how healthy you are being; clothing becoming holey if you need space / breath; clothing that takes body information of your partner / family (e.g. body heat). F: Clothing that gets really annoying to make you move; clothing that expresses its own emotions (e.g. gets 'happy' when outside); correcting or informing you of bad posture.
Biomimicry	Replicating how plants follow the sun (e.g. for small elements of solar panels); Replicate petals or leaves opening and closing (e.g. for decoration on clothing).	P1: SMA sculpture - soft, organic, silent; soft robotic worm made of textile and SMA; sequins flipping up or down on clothing to mimic feathers. P2: Wings opening and closing; expanding surface area to manage heat; turning towards sun - gathering light; express anger/fear as an animal does with hair/feathers standing up. P3: Intimate interactions; touch interactions; transporting emotions or information - connection; body has its own response independent from the mind - communicating emotional states, sexiness; respond to heat in sports; protection from rash / heat / bugs; circulation of heat / sweat / air; calming babies with swaddling. P4: Cover something up; holding a baby to the body or swaddling baby. F: Reflective elements or surface facing towards the sun to help stay cool; feathers / hairs responding to the cold.

Table 4: Participant (P1-P4) and facilitator (F) ideas generated in the workshop for themes 4 to 6. The example ideas were given by the facilitator when introducing each topic.