Embrogami: Shape-Changing Textiles with Machine Embroidery

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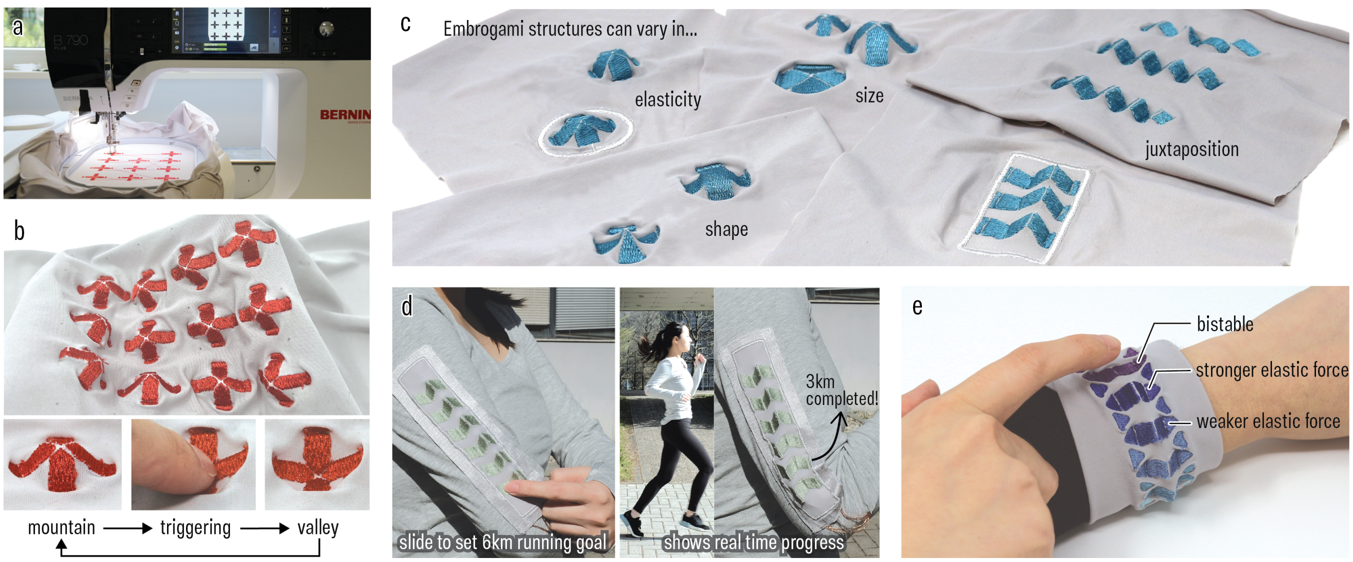

Figure 1: *Embrogami* leverages (a) machine embroidery on pre-stretched fabrics to create (b) integrated bistable structures that fold above or below the fabric surface without disrupting the fabric's soft and conformable nature. We present functional *Embrogami* primitives with (c) customizable visuo-tactile feedback and layouts to create versatile shape-changing textile structures. *Embrogami* opens up new textile-based interaction possibilities such as (d) interactive shape-changing controls on textiles that are inherently soft and deeply integrated to be more wearable and durable in sports scenarios, and (e) passive displays that respond to user input with tunable local and global shape-changing behaviors.

ABSTRACT

Machine embroidery is a versatile technique for creating custom and entirely fabric-based patterns on thin and conformable textile surfaces. However, existing machine-embroidered surfaces remain static, limiting the interactions they can support. We introduce *Embrogami*, an approach for fabricating textile structures with versatile shape-changing behaviors. Inspired by origami, we leverage machine embroidery to form finger-tip-scale mountain-and-valley structures on textiles with customized shapes, bistable or elastic behaviors, and modular composition. The structures can be actuated by the user or the system to modify the local textile surface topology, creating interactive elements like toggles and sliders or textile shape displays with an ultra-thin, flexible, and integrated form factor. We provide a dedicated software tool and report results of technical experiments to allow users to flexibly design, fabricate, and deploy customized *Embrogami* structures. With four application cases, we showcase *Embrogami*'s potential to create functional and flexible shape-changing textiles with diverse visuo-tactile feedback.

UIST '24, October 13–16, 2024, Pittsburgh, PA, USA

ACM ISBN 979-8-4007-0628-8/24/10.
https://doi.org/10.1145/3654777.3676431

CCS CONCEPTS

• **Human-centered computing** → **Interaction devices**; • **Hardware** → **Emerging interfaces**.

KEYWORDS

Fabrication; machine embroidery; shape-change; e-textiles.

ACM Reference Format:
Yu Jiang, Alice C. Haynes, Narjes Pourjafarian, Jan Borchers, and Jürgen Steimle. 2024. Embrogami: Shape-Changing Textiles with Machine Embroidery. In *The 37th Annual ACM Symposium on User Interface Software and Technology (UIST '24), October 13–16, 2024, Pittsburgh, PA, USA.* ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3654777.3676431

1 INTRODUCTION

Digital fabrication tools have opened up new opportunities for the rapid prototyping of customized objects [17, 40]. Among these tools, machine embroidery offers unique benefits for creating customized patterns on soft fabric through performing programmed stitches. Compared to textile fabrication approaches that employ knitting [2, 24] and weaving techniques [9, 26], machine embroidery requires less expertise and is accessible even to novices. Different from existing interactive textiles that oftentimes embed rigid electronic parts and foreign materials [34, 54] that disrupt the textile surfaces, embroidered stitches are seamlessly integrated into the base fabric, retaining its ultra-thin, lightweight, and conformable materiality.

Existing research uses machine embroidery to embed interactivity into textiles by stitching patterns that visually and tactually represent sliders and buttons [32, 36, 43, 57]. Such interactive surfaces afford rich interaction experiences and aesthetics and can be easily integrated into clothing or the built environment [1, 13]. However, current embroidered patterns remain primarily static without defined shape changes, limiting affordances for interaction as well as the expressiveness of textile patterns.

We introduce *Embrogami*, a novel design and fabrication approach for digitally embroidering self-forming and shape-changing origamic structures on textiles. *Embrogami* structures are (1) capable of producing out-of-plane shape changes parameterized for various shapes and sizes with tunable mechanical responses to user input, (2) thin, conformable, stretchable, and integrated into one piece of fabric, (3) capable of further integrating fabric-based sensing and lightweight actuation to realize digital control, and (4) easy to fabricate with an accessible digital fabrication process. This enables the rapid prototyping of functional, integrated, and highly customizable textile structures. Specifically, *Embrogami* structures realize shape-changing volumetric controls that are integrated into and can raise from the textile surface to afford versatile user-triggered or system-triggered deformation, enabling functional interactive elements such as buttons, toggles, and sliders.

The principle behind *Embrogami* is based on fundamental origamic folds, which are achieved by embroidering selective regions on a pre-stretched fabric. When the fabric is released, it contracts and causes the embroidered regions to buckle out-of-plane, forming *bistable* folds that can transition between folding above or below the surface. We use these folds to create visually and haptically prominent mountain primitives that rise above the surface by default to support user interactions. Each primitive can alternate between three states based on user input—its bistability enables it to transition between *mountain* and *valley* volumetric states, and the reversible self-forming process allows it to revert back to *planar* embroidered patterns when the base fabric is stretched again. Compared to past works that 3D-printed plastics onto pre-stretched fabrics [14], our fully textile-based structures are considerably thinner and softer; they are also more durable to large impact forces, substantial stretch, and washing.

Extending on these fundamental principles, we present functional origamic structures that offer diverse tactile and visual feedback and varied elasticity. We also demonstrate realizing more complex structures, such as toggles and sliders, by combining multiple basic primitives together. To further enhance the interactivity of *Embrogami*, we demonstrate embedding conductive fabric during embroidery and very thin shape memory alloys (SMA) wires to integrate sensing and actuation to enable digital processing of user input and system-actuated shape change. To streamline design and fabrication, we provide a design tool that lets users customize the cell primitives and layouts, preview the designed structure, and automatically generate the vector file for digital embroidery. With this, we hope to push towards interactive garments that are highly wearable and ergonomic in their form factor, and versatile and customizable in their functionality.

We validate *Embrogami* structures in a series of technical experiments and characterize how they are affected by the base fabric, the embroidery dimension, and the underlying surface. We demonstrate the practical feasibility by implementing several applications of computer-controlled or fully passive shape-changing textiles that can be deployed on the body or in the user's textile environment.

In summary, we make the following contributions:

(1) A novel design and fabrication approach for integrating shape-changing structures into textiles with machine embroidery based on bistable origamic folds that buckle above or below the surface.
(2) A set of functional volumetric structures with parameterized shapes, tunable elasticity, and flexible composition that can also integrate sensing and actuation, enabling versatile user interactions with rich tactile and visual feedback.
(3) A design tool and a series of technical evaluations to support customization, fabrication, and deployment of volumetric and interactive *Embrogami* textile interfaces.
(4) Four implemented example applications that demonstrate the practical feasibility of our technique.

2 RELATED WORK

This work draws inspiration from previous works on forming 3D structures from 2D materials, interactive textiles, and fabrication methods for textiles.

2.1 3D Structures from 2D Materials

With the rise of digital fabrication methods such as 3D printing, there is growing interest in the fabrication of custom 3D objects. However, fabricating 3D objects is oftentimes time-consuming. To tackle this, researchers have explored fabricating 3D structures from 2D materials. Such processes directly manipulate the 2D material, making the fabrication process faster and requiring less material. The processed planar materials are then triggered through a material-specific mechanism to transform into a 3D shape. Shape memory thermoplastics that shrink when heated have been used for self-forming 3D surfaces [15, 46, 50] and reversible paper actuators [49]. Hydrogel-based morphing structures [21] and electrostatically inflated mylar sheets [11] have also been demonstrated.

Self-forming 3D structures have also been demonstrated by 3D printing rigid plastic materials onto pre-stretched fabrics. Different from the methods above, which require an external material or device for triggering, self-forming 3D structures are actuated by the inherent tension within the textiles: when the textile is released, the tension around the printed filaments forces the rigid parts to bend and create 3D shapes. Past work investigated the effect that different parameters, such as filament thickness and fabric stretch factor, have on the produced 3D shapes [6, 16, 28]. Computational design tools that optimize and simulate user-defined geometries with self-forming textile structures have also been provided [17, 40]. While most of such fabric-based self-forming 3D structures remain static, some pioneering works have further enabled shape changes on these 3D structures by demonstrating a bistable button [25] and an elastic pushbutton [14]. However, these approaches deposit rigid materials that are considerably thicker than the basic fabric itself. This compromises the soft and flexible nature of textiles. We take inspiration from these past works but take a different approach to modify the fabric by integrating threads through machine embroidery to create entirely textile-based shape-changing structures on fabrics.

2.2 Interactive Textiles

With the advancement of ubiquitous and wearable computing, computers and interactive machines have since become smaller, lighter, softer, and more integrated into our existing physical environment. Textiles, which are soft in nature and exist everywhere around us in clothing, furniture, etc., have recently shown great potential to be interactive materials or devices.

Different approaches have been proposed to enable textiles to guide and process user input. With textiles' expressive aesthetics and textures, researchers have explored adapting traditional interactive elements (e.g., sliders, buttons, and icons) to textiles' surfaces [32, 36, 43]. Advances in sensing technologies on textiles have enabled processing user interactions. Existing works leveraged conductive materials [1, 19, 38, 53], coils [55], and eletronics [20] to sense and process a wide range of user input, including touchless [51] or contact-based [18, 22, 37, 39, 48] gestures, object recognition [13, 52], touch locations [27], and body motions [30].

Researchers have also demonstrated textiles' potential to produce different outputs during user interactions, e.g., textiles that change color [9, 10] and stiffness [7]. Textiles that perform shape changes are the most extensively studied as they produce expressive and oftentimes 3-dimensional information. To create shape changes, existing works have integrated shape memory alloys [26, 34], pneumatics [31, 41, 45], tendon structures [2], and fiber actuators [23] to create shape-changing interfaces [31, 48], tactile and haptic sensations [24, 33], and functional clothing that fold [5, 29].

Despite the demonstrated potential of interactive textiles, many existing ones require embedding foreign and/or active materials, such as rigid plastics and tubings, to create and change the 3D shapes on textiles. This adds inflexibility to the soft base fabric and limits the applicability of these interactive textiles in especially wearable scenarios. We thus explore integrating the interactivity directly into the material to create entirely textile-based interactive structures that process and respond to user inputs *passively*. To this end, *Embrogami* contributes shape-changing structures with tunable bistable or elastic deformation behaviors and customizable shapes that are integrated into the textile material using embroidery. These interactive structures can respond to user inputs passively, not requiring any electronics, or be system-triggered using SMAs.

2.3 Fabricating Textiles

The hierarchical structure (i.e., fiber, yarn, and fabric) of textiles enables its fabrication to happen at varying levels [23, 37], giving researchers flexibility in fabrication. Traditional textile fabrication methods like knitting [2, 24], weaving [9, 26], felting [5], and crocheting [10] are leveraged to engineer the internal structure of fabrics in order to create 3D or volumetric shapes on textiles [5, 44], engineer localized flexibility [20], or encase active elements [26, 47]. Yet even with digital fabrication tools that program, simplify, and guide the users during structural-level fabrication processes [3, 4, 12], it is still time-consuming and difficult for novices to learn techniques like weaving and knitting. This impedes the general maker community from creating and contributing to augmented functional textiles.

More accessible for users with no prior knowledge of textile fabrication methods are 3D printing and digital embroidery, which can programmatically create user-defined patterns. 3D printing has been used for overlaying conductive materials [30], creating user interface elements [42], and forming 3D shapes by printing on a pre-stretched fabric [14, 40]. Digital embroidery, which creates patterns with threads on textile surfaces, has been utilized for creating textile interfaces with versatile textures [32, 43, 57] and integrating conductive threads to build functional sensing surfaces [35, 56]. While typical embroidered surfaces remain largely planar and static, we use digital embroidery to create *volumetric* shape-changing structures. We take inspiration from works that 3D print rigid plastics onto the pre-stretched fabric [14], but instead stiffen selective parts of the fabric using digital embroidery. As a result, the structures of our approach are not only thinner (0.7mm). With shore hardness 50A (medium soft) they are also softer than structures made of TPU (shore 95A, hard) or PLA (shore 77D, extra hard). Finally, the embroidered structures are more durable than 3D printed structures, as adhesion of printed plastics to the fabric is a common issue [25]. Based on this, we contribute customizable shape-changing structures that can vary in shape, size, mechanical response, and combination to explore entirely textile-based versatile user interfaces.

3 *EMBROGAMI* PRIMITIVES

Embrogami is capable of creating customizable and functional volumetric textile structures with varied shapes, sizes, and shape-changing behaviors. These structures can remain fully passive or be augmented with integrated sensing and actuation to enable digital control, thus enabling versatile textile-based user interactions. In this section, we explain our fabrication technique that enables these versatile primitives.

3.1 Design Principle

Embrogami explores creating integrated volumetric structures that rise from the textile surface and change shapes. To achieve this, we take inspiration from previous works that 3D-print plastics (e.g., PLA [40]) onto pre-stretched fabrics. These approaches create selectively stiff areas on the fabric that resist the contraction when the base fabric is released, forcing the stiff areas to bend out-of-plane to produce volumetric shapes. We explore this principle with a different fabrication approach that forms *integrated and soft* volumetric structures on fabrics to vary the local surface topology. We leverage machine embroidery, which performs programmed stitches with threads on a fabric's surface, to selectively stiffen regions on a pre-stretched fabric to generate the out-of-plane folding behavior.

An *origamic fold* is created by embroidering two adjacent patches on a pre-stretched fabric, as demonstrated in Figure 2 a-c. After the base fabric is released, it contracts around the stiffened embroidery patches such that they are forced to buckle out-of-plane. The fold can buckle either upwards above the surface or downwards below the surface (Figure 2 b-c). This enables a fold to be *bistable* and can transition between two discrete states when a small external trigger force is provided.

An embroidered patch consists of four layers: the top embroidery thread, the base fabric, a soft tape-like stabilizer to hold the base fabric in place, and the bottom bobbin thread (Figure 2d). The stabilizer is torn away after embroidery to release the rest of the fabric but stays in place in the embroidered regions where it is stitched. When a fold is formed the first time by embroidering two adjacent patches and releasing, their default initial state is to buckle downwards. This is caused by the asymmetric number of layers above and below the base fabric with the stabilizer being slightly stiffer than the threads (Figure 2e-f). There is thus less resistance in a downward fold.

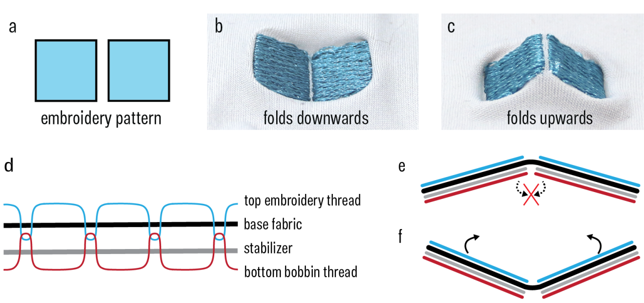

Figure 2: Basic Fold. (a) Embroidering two adjacent patches on a pre-stretched fabric creates a bistable fold that can either buckle (b) downwards or (c) upwards. (d) An embroidered patch has 4 layers. (e) The thicker bottom layers resist folding upwards, therefore initially forming a (f) downward fold.

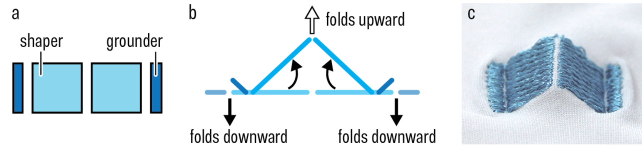

Figure 3: Mountain Primitive. (a) Aligning four adjacent patches generates three folds where (b) the outer folds have a downward initial state and force the middle 'shaper' patches to fold upwards. (c) This creates a default mountain.

Therefore, we modify this basic layout to create an origamic *mountain* primitive that rises up prominently from the fabric surface as their default initial state, affording external input in user interactions. We do so by aligning multiple folds together such that there is a larger strain along the outer edges as both outer downward folds force the middle patches to bend upwards. This creates a middle fold that rises above the surface (Figure 3). We call the middle patches *shapers* that define the shape of a mountain, and the side patches *grounders* that stay below the mountain fold.

In the following sections, we show how this mountain primitive can be employed to create *Embrogami* structures for user interaction, including interactive elements such as push buttons, toggles, or sliders and different configurations of the structures that enable more complex elements and local surface topologies.

For fabrication, we used a Bernina 790 PLUS digital embroidery machine with standard 40 weight polyester top thread, 60 weight polyester bobbin thread, and a strong stabilizer (Filmoplast Strong by SULKY) to keep the pre-stretched fabric in-place during embroidery. We set the stitch angle to be orthogonal to the fold line. A satin stitch pattern with the default 0.5 mm stitch spacing and 4.2 mm stitch length ensures that the pre-stretched fabric is strongly kept in place by the dense stitches. After preliminary experiments, we embroidered the patterns with two layers of stitch pattern, which create rigid enough embroideries for stable folds and are still thin and compliant. Our preliminary exploration also revealed that the size of the grounders does not affect the shape of the mountain fold. We therefore opted for small grounders of only 2 mm width. We tested different combinations of pre-stretch factors (i.e., the amount the base fabric is stretched before embroidery) and gap sizes between patches (i.e., the distance between two shapers and between a shaper and a grounder). The tests revealed that higher stretch factors form more prominent mountains and a 2 mm gap size creates stable fold lines while avoiding potential overlapping patches due to the fabric drifting during embroidery. *Embrogami* thus adopted a gap size of 2 mm and the base fabric was stretched to its maximum possible extent (200%) for fabrication.

To form stable origamic folds for *Embrogami* structures, the base fabric needs to have a two-way stretch (stretch horizontally) for unidimensional folds and a four-way stretch (stretch both horizontally and vertically) for folds on two dimensions. To stably create and maintain *Embrogami* structures over time, the base fabric should have good elastic recovery such that the fabric can reliably contract after being stretched to raise the embroidered patterns. The pre-stretched base fabric should also be able to be held in-place by the stabilizer during the embroidery. We empirically compare the performance of several base fabrics in the Evaluation Section 6.1.

3.2 Shape-changing Behavior

Different from existing embroidered surfaces that are static, *Embrogami* structures based on bistable origamic folds can dynamically alter the local surface topology and thereby create more responsive and interactive textile surfaces.

The shape-changing capability of *Embrogami* structures is enabled by their bistability and the reversible self-forming process. A mountain structure can be triggered to turn into a valley that folds below the fabric surface and then reset, allowing the structure to transform between two discrete volumetric states (Figure 4a-c). The user presses down the middle fold line; once it is indented more than the side fold lines, it buckles downwards to create a valley. The durability of the state change and the effect of the underlying surface on bistability are evaluated in Section 6.3 and Section 6.4.

To support versatile user interactions with *Embrogami* structures, we present three **resetting mechanisms** that reset the structures back to their mountain states locally or globally. First, *pressing* down the out-of-plane grounders resets a mountain from its triggered valley state to the default state (Figure 4d).

Second, we offer a resetting mechanism unique to our fabrication approach that enables resetting multiple primitives effortlessly with one motion. Triggered valleys can be easily reset to their default mountains by *pulling* the fabric until all patches lie flat and then releasing (Figure 4e). This recreates the self-forming process of the structures and reproduces all the structures in their default mountain state. The reversible self-forming process also allows the volumetric structures to be flattened to their planar embroidered patterns, enabling the structures to be hidden when not in use.

Third, we provide a *system-actuated* resetting strategy by embedding SMAs into the structure. This allows the system to digitally control the resetting of individual structures. To achieve this, we attach lightweight helical SMA wires (Flexinol actuators from Dynalloy, Inc., wire diameter 0.2 mm, spring diameter 1.4 mm) to the underside of the mountain, connecting the outer edges of the shapers, as shown in Figure 5. When activated, the SMA wire pulls the underside of the shapers together and resists the structure to fold downwards, forcing the structure to switch back into the default mountain state. When relaxed, the helical SMA wires are extensible, allowing a bistable mountain to be pressed into its valley state again. The SMA is only actuated during state transition and thus is much less energy intensive and of a minimum form factor compared to motors. We use silver jewelry crimps to connect electrical wires to the SMA and sew the crimps to the shaper elements. The assembly can be automated in the future. The SMA can be powered by an off-the-shelf microcontroller, and the time response is controlled using Pulse Width Modulation (PWM) of the actuation voltage. The actuation properties and behavior are evaluated in Section 6.7.

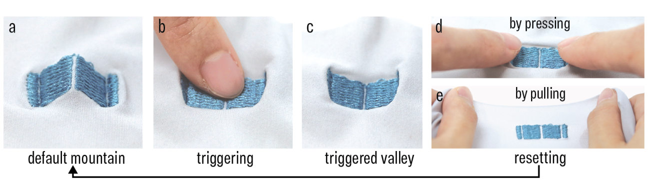

Figure 4: The basic shape changes. (a) A default mountain can be (b) triggered to become (c) a valley, which can be reset to its default state by (d) pressing down the grounders or (e) pulling the base fabric to recreate the self-forming process.

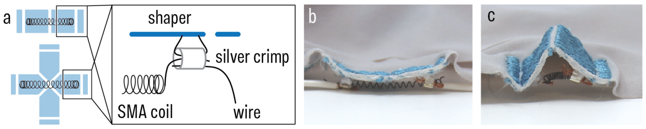

Figure 5: System-actuated Resetting. Triggered valleys can also be reset by (a) embedded SMAs, which actuate the (b) valley into its (c) mountain state.

3.3 Shaping *Embrogami* Structures

To make *Embrogami* structures aesthetically and tactually versatile, we vary the fundamental mountain structure to create diverse primitive shapes that offer various geometries and folding directions. Like the basic structure, all of them are bistable and can be reset with the three mechanisms introduced above.

Figure 6 top shows different variations of uniaxial-folding **linear** structures with two shapers and a single fold line defining the mountain. Square shapers produce a *basic* mountain, as introduced before. A *high* mountain with a greater amplitude can be realized by decreasing the length of the central fold line by 1/3 to create trapezoidal shapers. This leads to more surrounding fabric that pulls the spacers closer together, producing stronger out-of-plane buckling. Triangular shapers create a pyramid-like *pointy* mountain with curved edges. When touched, they provide spiky tactile feedback. A *dome*-shaped mountain can be realized by embroidering one continuous shaper and using only 1 layer of embroidery. This generates a thinner, more flexible shaper that bends uniformly to form the rounded dome structure. We also identify shapes that give directional cues, which can be useful during interactions: Asymmetrical shapers with different lengths (6 mm and 14 mm) create *tilted* mountains, which, when swiped, bring larger resistance at the shorter side with a steeper slope. This can guide users to swipe from the longer shaper side when swiping along a mountain. Parallelogram shapers (70° angle) create an arrow-shaped mountain which can provide *directional* guidance.

All these linear shapes can alternatively be realized in **radial** structures (Figure 6 bottom). Radial structures have more than two shapers that converge towards the center to allow multi-axial folding behaviors. Just like linear structures, they can also be varied to fine-tune the created geometry for personalized designs.

3.4 Tuning Elastic Behaviors

To enable users to design volumetric textile structures with more versatile shape-changing behaviors, we vary the structures' mechanical response to external deformation. Specifically, we allow modifying the bistable primitives after they are fabricated such that they become elastic. We provide two methods with different fabrication requirements and can provide elastic force in different ranges to give users flexibility in fabrication. These structures deform when pressed but immediately bounce back when the pressure is removed. Both methods allow fine-tuning the elastic restoring force that the structure exerts on the user's finger, which will be further characterized in Section 6.5.

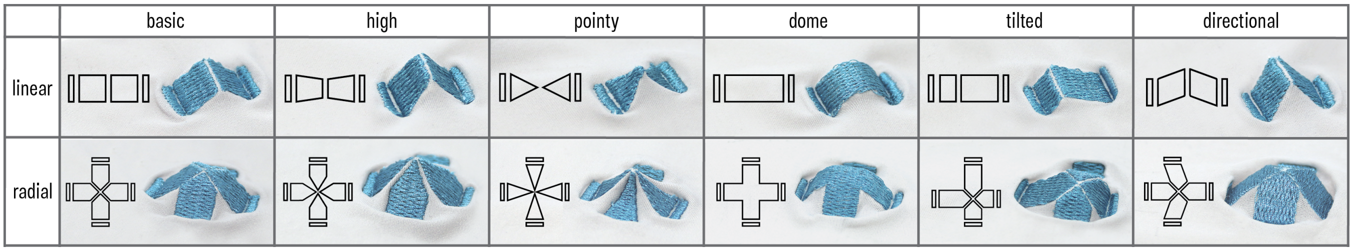

Figure 6: Linear and radial shapes of bistable *Embrogami* mountains.

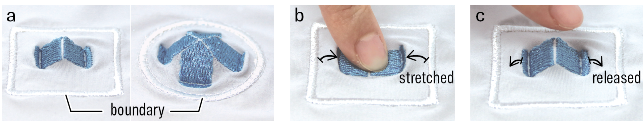

Figure 7: Elastic Mountains. (a) The *boundary* method can make a mountain elastic. The fabric is (b) stretched when the user presses and (c) immediately recreates the mountain when released.

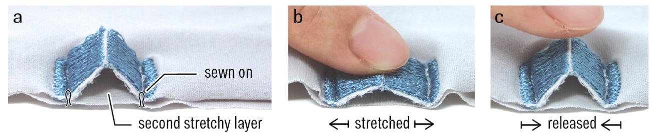

Figure 8: Elastic Mountains. (a) The *layering* method adds a second base fabric layer to create elastic mountains. The second layer (b) stretches when the mountain deforms, and (c) recreates the mountain when released.

The first method is the *boundary* method. We can make a bistable mountain elastic by embroidering a boundary around the formed mountain (Figure 7a). To fabricate the boundary, the mountain structure is first embroidered on stretched fabric and released. Then, with the mountain in its default raised state, the fabric is placed on a new layer of stabilizer and a 2 mm thick border is embroidered around the mountain at a calculated distance from the grounders.

When the user presses on a mountain with a boundary, the grounder patches bend upwards out-of-plane and stretch the fabric between the grounder and the boundary (Figure 7b). When the pressure from the user is removed, the grounders are pulled back down by the tension in the stretched fabric, pushing the mountain back to its default position (Figure 7c). For stable elastic performances, the boundary should always be held in place and backed by another layer or object. To achieve this, the boundary can be sewn onto an inextensible fabric layer underneath (retaining the thin flexible form factor), or fixed onto or tied tightly around a surface. The elastic force is determined by the distance between the boundary and the grounders, which decides how much the grounders' bending-up movement is constrained. If the boundary is large enough to not influence the out-of-plane movement of the grounders, the mountain would still be bistable. In Section 6.5, we characterize the elastic force of elastic *Embrogami* structures based on the boundary method with different boundary sizes.

The second method is the *layering* method, which makes formed mountains elastic by attaching a second layer of the base fabric underneath. The second layer is sewn onto the primary layer with straight stitches along the fold lines between the shapers and the grounders (Figure 8a). When the mountain is pressed, the connected second layer is stretched (Figure 8b), creating tension between the grounders that pull them together to recreate the mountain when pressure is removed (Figure 8c). To fabricate elastic mountains with this method, the mountain structure is first embroidered on stretched fabric and released. We then use the embroidery machine in manual sewing mode to sew the grounders of the formed mountain onto a second stretchy layer. The elastic force can be fine-tuned by altering the pre-stretch factor of the second base layer. We used a stabilizer to hold the second layer at the desired stretch factor during sewing and then removed it afterwards. We characterize the elastic force of the layering method with different second-layer stretch factors in Section 6.5.

3.5 Integrated Sensing with Conductive Fabric

Embrogami structures have passive interactivity integrated into their materiality: they respond to users' force input through shape changes without any electronics. For actively controlling *Embrogami* interfaces with digital systems, we demonstrate an approach that enables designers to integrate sensing into the structures. As demonstrated in Figure 9, we measure the capacitance between a shaper that is made conductive and a second conductive layer underneath that forms a simple two-plate capacitor. The second layer is sewn onto the base fabric and remains on the deployed surface. When the structure is in its mountain state, the distance between the two conductors is larger compared to when in its valley state, leading to a lower capacitance (Figure 9a-b). We make the shaper conductive by simply sandwiching a conductive fabric tape between the first and second embroidery layers during embroidery. The bottom conductor is made by digitally sewing another conductive fabric tape onto the base fabric. The fabric-based conductors can be seamlessly integrated into the structure with an easy fabrication process, preserving the *Embrogami* structures' soft and conformable nature. The sensing technique is compatible with the SMA-based actuation (Section 3.2) and together they allow *Embrogami* structures to be

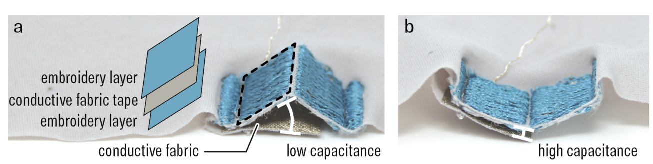

Figure 9: (a) We integrate a fabric-based capacitive sensor into *Embrogami* structures to sense (a-b) state changes.

integrated into other digital interfaces, making them applicable to more versatile and functional use cases.

We used 8 mm conductive Nylon fabric tape from Teensy and a high-resolution capacitive sensing chip (FDC2214, Texas Instruments) due to the small change of capacitance between the two states ($\approx 0.9pF$). With this setup, we were able to robustly sense touch and state changes in the structure. We provide a technical evaluation of the sensing in Section 6.6.

4 COMBINING MULTIPLE PRIMITIVES

Users can further extend the primitives' functionality by tiling the individual primitives to form more complex and diverse volumetric structure *layouts*. Here we explain how *Embrogami* primitives can be juxtaposed to function individually or be integrated in various ways for a combined response.

4.1 Juxtaposing Primitives

Users can flexibly form a larger layout of *Embrogami* structures by juxtaposing multiple primitives next to each other, as shown in Figure 10. These can consist of one primitive uniformly repeated, as exampled in Figure 10. This affords the creation of pixel or cell arrays to display information or can be used as an input array of buttons such as a number pad or keyboard. Alternatively, primitives of varied styles and sizes can be juxtaposed in flexible arrangements to suit specific user requirements or object form factors, such as placing buttons in an ergonomic layout on a curved surface.

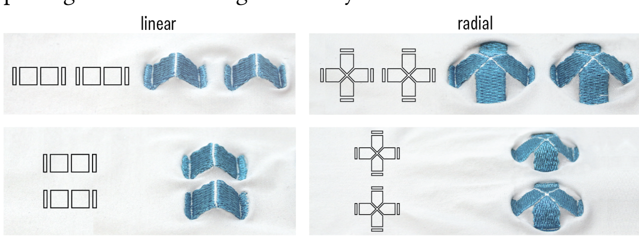

Figure 10: Linear and radial juxtapositions of primitives.

To enable juxtaposed primitives to each function *individually* without interfering with each other, we provide an approximation for the gap needed between two individual non-interfering cells. The tension between the structures is the greatest when the two cells are in different bistable states, at which the distance between the neighboring grounders of the primitives a and b is the maximum of their amplitudes, $max(amp_a, amp_b)$. To ensure that there is no stretch in the fabric in this case, the gap between the primitives should be $max(amp_a, amp_b)$. Thus given a base fabric pre-stretch factor s, the gap between the embroidery patterns for the primitives should be at least $max(amp_a, amp_b) \times s$. We empirically verified this approximation with the basic linear and radial mountains with shaper width and length of both 10 mm. The results showed that the calculated gaps created individually functional mountains while smaller gaps deformed the adjacent mountain.

4.2 Integrating Primitives

We identify two ways that the primitives can be integrated to form larger structures that enable versatile tactile feedback and more complex shape-changing behaviors.

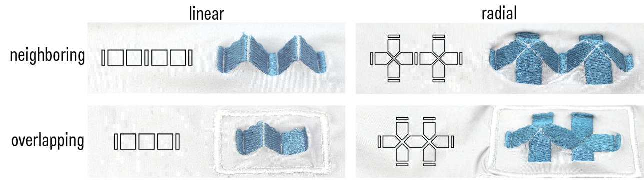

Figure 11: Neighbouring and overlapping strategies for integrating multiple primitives into larger structures.

4.2.1 Neighboring. Figure 11 (top) shows *neighboring* primitives that share common grounders. This creates a close array of mountains that users can swipe through and are aesthetically more continuous compared to juxtapositions of individual primitives. To provide versatile tactile swiping experiences for user interactions, we present three different ways to compose structures in neighboring primitives. Mountains can be uniformly tiled in a layout (Figure 12, top) for applications in which a uniform array of pixels or cells is desired, such as designating or labeling an area for a specific interaction. Alternatively, each pixel in the layout can provide varied tactile or visual affordances by composing differently shaped neighbors in a type-varying layout (Figure 12, middle). This enables encoding positional and tactile information, such as a menu that signals different functionalities at their corresponding locations. Finally, composing neighbors in an amplitude-varying layout (Figure 12, bottom) in which same-shape primitives are repeated with varied amplitude can be leveraged for conveying direction or change in magnitude in swiping interactions.

4.2.2 Overlapping. The mountains can also *overlap* each other by sharing a common shaper (Figure 11, bottom). This results in a toggling behavior in which the state of one primitive is determined by its adjacent primitive, e.g., triggering the current cell transforms its adjacent primitive into a mountain and vice versa. We demonstrate this behavior with two radial overlapping primitives in Figure 13a. To achieve a reliable toggling behavior, the structure has to be backed by some surface, such as being placed on the body or on a piece of furniture. This forces the valley state to be almost flat as it pushes against the surface, resulting in a larger tension in the fabric compared to its default mountain state. When we press one of the cells into its valley state, the paired valley pops up to relieve part of the tension in the fabric, creating a *toggle*.

Overlapping two primitives effectively creates the toggling behavior for interaction but does not have a default toggle state. In experiments, we found that overlapping more than two primitives led to unpredictable behaviors when triggered. System-actuated

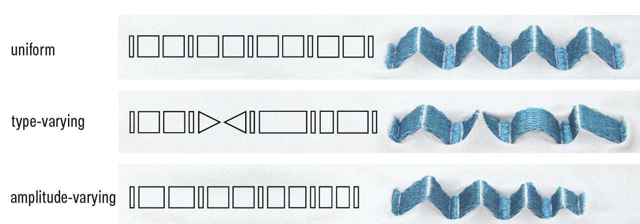

Figure 12: Composing uniform, type-varying, or amplitude-varying neighbors provides versatile swiping experiences.

shape change with SMA is also compatible with the toggling behavior. SMAs are connected between the side and the middle connected shapers, which reset a primitive to the mountain state and make its overlapped primitive buckle downwards.

Combining mountain primitives through juxtaposing and integrating the structures leads to larger structures with more complex shape-changing behaviors. The combined structures can have customized shape changes and visuo-tactile feedback, making them useful as *functional* elements for user interactions. We demonstrate one such example with a shape-changing *slider* composed of three overlapping linear directional primitives in Figure 13b. The user can swipe up and down orthogonally across the primitives. The directional primitives inform the sliding direction, and the users can trigger the toggle as they slide to record the sliding position.

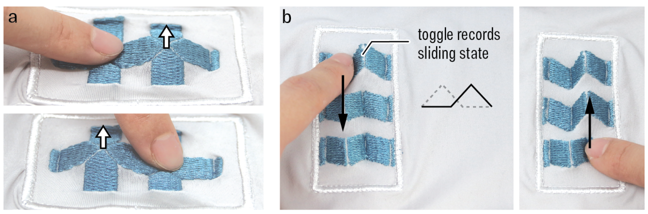

Figure 13: (a) Two overlapping cells make a toggle. (b) A slider composed of three overlapping linear directional primitives. The toggles are triggered to record the sliding status.

5 DESIGN TOOL

To support the customization of *Embrogami* structures, we provide a design tool that offers a visualization of the created volumetric geometries and helps generate design files for digital embroidery based on users' designs. The tool allows users to place, fine-tune, arrange, and combine primitives freely. Sensing can easily be integrated during the embroidery process as shown in Section 3.5 and SMA wires for actuation can be assembled after embroidery.

The design tool is implemented in JavaScript with the node.js and three.js 3D graphics frameworks. Figure 14 depicts the key features of the design tool which enable the following design process:

(1) Users can select linear and radial primitives to place on the canvas (Figure 14a). The grey 2D patterns show the embroidery pattern, and the overlaying black 3D structures visualize the formed mountain primitives. The green frame highlights the currently selected primitive. The amplitude and width of the volumetric mountain can be adjusted through two sliders, which automatically alters the shaper length and width of the embroidery patterns. The size customization is supported by the parameterization of formed mountain sizes based on embroidery pattern parameters in Section 6.2. Based on our empirically measured data, we used linear regression to approximate the amplitude (R^2 = 0.98) and width of the mountain (R^2 = 0.99) given the shaper length and width.

(2) The primitive structures are bistable by default but can be designed as elastic by changing the elasticity toggle (Figure 14b). This adds a boundary around the structure based on the boundary method which can be embroidered. Based on our elasticity characterization (Section 6.5) of the primitives, the tool allows users to fine-tune the elasticity of the structure by adjusting the elastic force of the primitive with a slider. This adjusts the size of the boundary in relation to the mountain accordingly.

(3) The visualized embroidery pattern also helps add sensing to any primitive based on the method shown in Section 3.5. The user can cut out two conductive fabric tapes the size of the shapers, tape one onto the shaper after the first embroidery layer is complete, and sew the other one along the edge between that shaper and its neighboring grounder.

(4) Multiple cells can be flexibly juxtaposed on the canvas. When the user moves a structure closer to a second one, a red boundary appears dynamically based on the calculations in Section 4.1 to alert the users that these structures would interfere with each other (Figure 14c-d). Users can integrate primitives by moving the primitives to either overlap the grounders (Figure 14c), which creates neighboring primitives, or overlap the shapers (Figure 14d), which creates overlapping primitives. The design tool automatically detects the overlapped parts and integrates the primitives accordingly.

(5) Users can fine tune the parameters of any single-cell mountain anytime and can export the designed svg file for digital embroidery. The exported file then can be loaded into the Bernina software for generating the embroidery.

6 TECHNICAL EVALUATION

We performed a series of technical experiments to characterize the behavior of bistable and elastic *Embrogami* structures, including the effect of different fabrics and *Embrogami* dimensions.

6.1 Effect of Fabric

To provide insight for choosing the base fabric, we compared five different lightweight fabrics with a four-way stretch and good elastic recovery sourced from Eurojersey[1]. Table 1 lists the composition and weight of the fabrics. To characterize their stretchability, we also report the force required to stretch the fabric to 150% of its original length. For all tests, a linear basic *Embrogami* structure of size 10mm was embroidered. Table 1 reports the amplitude of the formed mountain structure measured by a digital caliper. The results show that four of the five fabrics created mountains of considerable amplitude (≈ 7mm). More stretchable fabrics lead to slightly higher amplitudes. The least stretchable fabric did not create a mountain: due to its strong contracting force, it could not be held in-place by the tape stabilizer even with smaller stretch factors and thus could not be embroidered. Since we aim to create stable and prominent

composition (microfibre PA / EA(LYCRA®))	weight	150% stretch force	amplitude
74% / 26%	80g/m^2	1.09N	7.65mm
73% / 27%	117g/m^2	1.24N	7.49mm
73% / 27%	120g/m^2	1.42N	7.24mm
78% / 22%	143g/m^2	1.64N	6.9mm
73% / 27%	150g/m^2	4.16N	N/A

Table 1: Effect of Fabrics. Lighter fabrics that are easier to stretch can create *Embrogami* structures with higher mountain amplitude.

[1]https://www.sensitivefabrics.it/

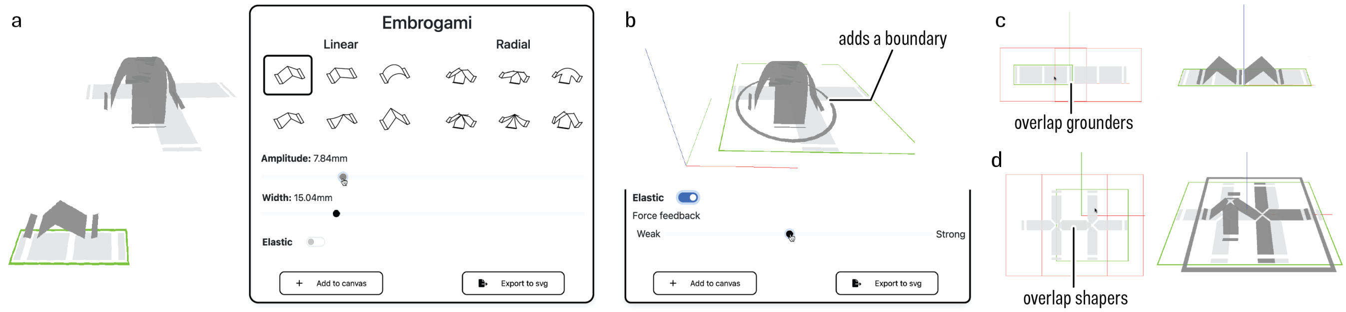

Figure 14: We provide a design tool that allows users to (a) flexibly place and fine-tune *Embrogami* primitives, (b) customize the elasticity of the primitives, (c-d) juxtapose and combine the primitives, and export the generated file for machine embroidery.

Embrogami volumetric structures, we chose the first fabric in the table for all subsequent experiments.

As *Embrogami* requires an elastic base fabric, non-stretchable fabric or fabric with low stretchability is not compatible. However, *Embrogami* structures created on light stretchable fabrics can be sewn or attached to such materials (e.g., our training patch application in Figure. 22).

6.2 Effect of Dimensions

To support users designing and customizing *Embrogami* structures of different scales, we characterize how the shaper length and width (Figure 15, top) affect the amplitude of the basic linear and radial mountain primitives. Shaper lengths and widths at 4 mm intervals within a range of 6 mm to 18 mm were tested. The resulting amplitudes are measured with a digital caliper and shown with heat maps in Figure 15. For linear mountains, the amplitude decreases slightly with an increasing shaper width but increases significantly with increasing lengths. For radial mountains, increasing the shaper width or length significantly increases the mountain amplitude. We can anecdotally report that this relationship similarly applies to other variant primitives.

We also measured the trigger force that is required to trigger a mountain into a valley. Radial structures with 10 mm shaper width and length and linear structures with 18 mm shaper width and length are the easiest to trigger with a 0.1 N force. The trigger

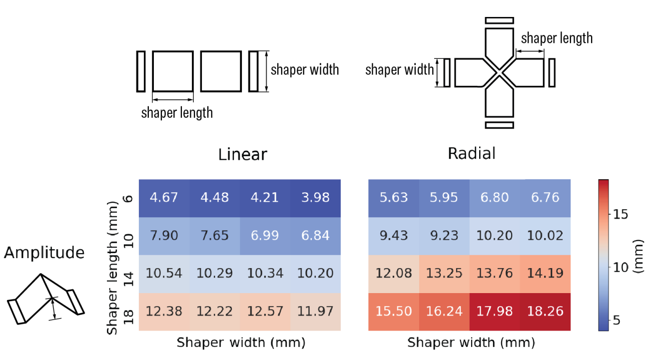

Figure 15: Effect of *Embrogami* dimensions. Shaper length and width of linear and radial structures affect the formed mountain amplitude.

force increases with increasing dimensions in radial structures (18 mm shaper length and width with a 0.15 N trigger force) but with decreasing dimensions in linear structures (10 mm shaper width and length with a 0.21 N trigger force). Overall the trigger force ranges from 0.1 N to 0.2 N for primitives of different dimensions which can be easily provided by normal finger presses from the user.

6.3 Repeatability

We used two opposing linear motors to repeatedly trigger the mid-air structures into their mountain and valley states. We tested linear and radial structures with 10 mm and 20 mm square shapers, each for 1500 cycles. The results showed that the structures remained bistable and kept the same trigger force after the cycles.

6.4 Effect of Underlying Surface

To provide insights into where to deploy *Embrogami* structures while maintaining their bistability, we characterized their mechanical behavior on surfaces of different curvature and softness. We tested linear and radial basic mountain structures, with a 10 mm shaper width and 10 mm, 14 mm, and 18 mm shaper lengths. We placed these on rigid spheres of 2 cm, 4 cm, 7 cm, and 11 cm diameters to simulate surfaces with varying curvatures. Moreover, to investigate the behavior on soft surfaces, we wrapped a 1.5 cm foam layer that is softer than most body parts (with ≈ 3.7 kPa Young's modulus) around the originally rigid sphere.

This gives us a comparison of how surfaces at the ends of the rigid–soft spectrum affect the bistability. The results are shown

			shaper length (mm)					
			linear			radial		
			10	14	18	10	14	18
surface type	flat soft		✓					
	flat rigid		✓					
	curved soft	sphere diameter (cm) 11	✓					
		7	✓	✓	✗	✓	✓	✗
		4	✓	✗	✗	✓	✗	✗
		2	✗					
	curved rigid		✗					

Table 2: Effect of the underlying surface. Checkmarks indicate bistability. Structures are bistable on planar surfaces and soft spheres of down to 4 cm in diameter.

in Table 2. Generally, bistability is maintained on flat surfaces, as linear and radial structures of all scales work on flat surfaces that are either soft or rigid. In contrast, the structures are not bistable on curved rigid surfaces because the mountain needs to be pressed down flat to transition into the valley while the rigid surface underneath the structure blocks the deflection. On curved soft surfaces with decreasing diameter, the bistability of linear and radial structures can be maintained with smaller shaper lengths - structures with 10 mm shaper length were bistable on soft spheres of down to 4 cm diameter. Therefore users should deploy bistable *Embrogami* structures on flat surfaces or curved soft surfaces with larger diameters (e.g., on the arms but not fingers) if possible and scale down the dimension of the structure accordingly.

6.5 Elasticity Characterization

To support further customization of the elastic force provided by elastic mountains, we characterize the elastic forces of the boundary and the layering methods introduced in Section 3.4. We varied the gap from the grounders to the boundaries in the boundary method and varied the stretch factor of the second layer in the layering method (Figure 16, top). The elastic force was measured with a force gauge (Baoshishan ZP-50 N with 0.01 N accuracy) and shown in Figure 16. For the boundary method, we tested gap sizes from 4 to 10 mm with 2 mm gaps for the basic 10 by 10 mm linear and radial mountains. The results reveal that smaller gaps make more elastic mountains with stronger force feedback. Gaps equal to or larger than 10 mm for linear and equal to or larger than 8 mm for radial primitives produce bistable instead of elastic mountains. For the layering method, we tested secondary layers stretched by a factor of 100%–160% for both 1D and 2D structures. The test shows that a larger stretch factor in the second layer leads to slightly reduced mountain widths and also produces bigger force feedback. The two methods allow tuning the elasticity in different ranges, with force feedback ranging from 0.05 N to 0.35 N using the boundary method and ranging from 0.15 N to 0.65 N using the layering method.

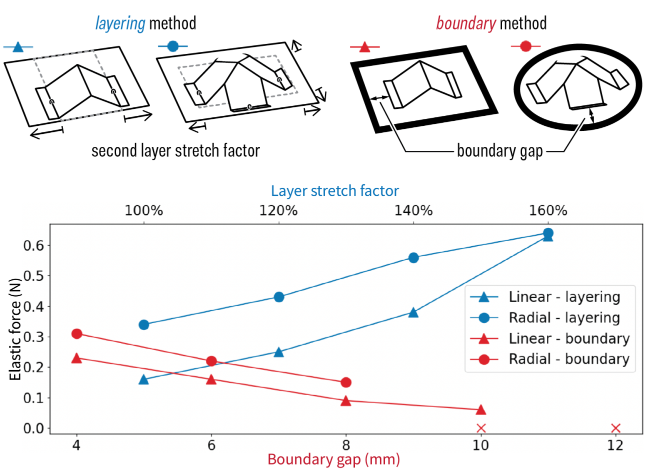

Figure 16: Elasticity characterization for the layering and the boundary methods. Parameters that fail to produce an elastic mountain are crossed out.

6.6 Sensing Evaluation

We now evaluate the robustness of detecting touch and state changes with our sensing mechanisms presented in Section 3.5. Different contexts are evaluated, including on a rigid and planar table, on a soft pillow, wrapped around the wrist of ≈ 7 cm diameter, and on the wrist with the user swinging the arm. The data was collected using a basic radial *Embrogami* structure with a 10mm size, as the sensor setup remains the same for different primitives with varying sizes. To evaluate touch sensing, we measured the capacitance between two electrodes in touch and no touch states (touching the structure with the index finger and removing the finger). In each context, we collected 10 cycles, alternating between the states every two seconds. The calculated signal-to-noise (SNR) ratios [8] showed that touch sensing is the most robust when placed stationary on the table (SNR = 204.9), less so when on the pillow (SNR = 67.6) and worn on the wrist (SNR = 26.0), and is still reasonably reliable when the person is moving (SNR = 11.7).

We repeat the same data collection process to evaluate state sensing. The structure was alternated between its mountain and valley state by pressing with the index finger to trigger into the valley state and with the index and the middle fingers to reset. We report the mean and the standard deviation of the measured capacitance values in the two states in Figure 17. The results suggest that the mountain and valley states can be accurately differentiated based on the capacitance values, with 0.6 pF - 0.9 pF difference between the two states. For classification, we used simple thresholding following an initial calibration step that records baseline data for both states. Future implementations could use a more sophisticated machine learning based classifier.

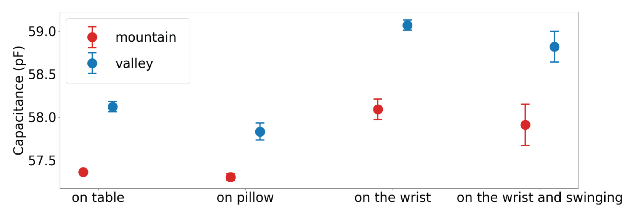

Figure 17: Evaluation of our sensing technique for detecting mountain and valley states (mean and standard deviation reported) in different contexts.

6.7 Actuation with SMA

The speed of actuating *Embrogami* structures can be adjusted by modifying the power supplied to the SMA. We now characterize the time response of activating the basic linear and radial mountains with different currents. Figure 18 shows the actuation time when activating the SMA at different currents up to a maximum of 0.7 A, the recommended current given by the manufacturer[2]. With a larger current, *Embrogami* structures can be triggered into their mountain states more quickly and linear structures can generally be triggered faster with the same current.

Due to the temperature of the SMA (90°C) during actuation, a heat-resistant fabric layer is required underneath actuated elements

[2]https://www.dynalloy.com/tech_data_springs.php

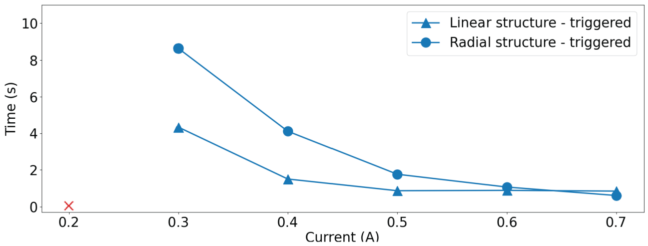

Figure 18: Actuation time of basic linear and radial primitives according to activation current. Structures can be triggered into mountains faster with larger currents.

for placement on the body or heat-sensitive surfaces. The peak surface temperature of the mountain and base layer (heat-resistant medium-weight waxed cotton) after 10 cycles of activating the SMA for 3.5 seconds at 0.5 A then cooling for 5 seconds were measured as 33.5°C and 34.9°C respectively in a room with an ambient temperature of 28°C.

7 APPLICATIONS

Here we demonstrate four example applications to showcase *Embrogami*'s capabilities in unlocking new textile-based interaction opportunities that benefit from textile shape change within a thin and conformable form factor.

7.1 Running Top with Embedded Control

Embrogami structures present new opportunities for clothing with textile-integrated shape-changing controls. We present a running top, that can be comfortably worn, with controls that enable quick and eyes-free actions. It includes a shape-changing slider for progress monitoring and a button for taking timed breaks.

Figure 19 is a shape-changing slider that shows the user's real-time running progress based on a goal set by the user. We lay out six directional toggles on the upper arm to compose the progress slider (a). Before running, the user can swipe down and trigger each toggle to change shape (b) to set a running goal. For example, a 6-km running goal is set in (c). As the user completes running one kilometer, the embedded SMA resets the toggle into its original shape (d). The user has completed the running goal when all toggles are reset. The slider provides information on the running progress, both visually and through eyes-free tactile feedback when sliding

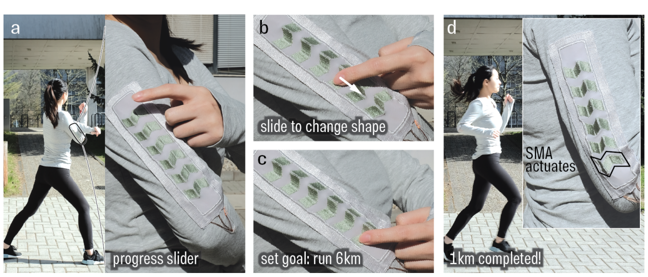

Figure 19: (a) The shape-changing progress slider allows users to (b-c) easily set a running goal. It (d) actuates to change shape for each km the user runs to give visuo-haptic feedback of the running progress.

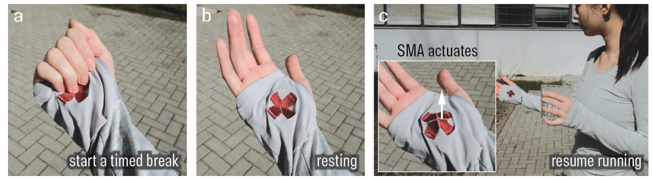

Figure 20: The user starts a timed break by (a) a simple clench and gets notified through the SMA-actuated shape change when the break has ended.

along. Its visual and tangible factor form factor also encourages interaction between friends while running.

A more conspicuous button at the user's palm allows taking timed breaks, as shown in Figure 20. While running, the user can start a timed break by simply clenching the fist, which triggers the structure into its valley state (a). When the time runs out, the embedded SMA actuates and transforms the structure back into its mountain state (b). The user gets noticed through the visual shape change and haptic feedback.

The slider and the button were fabricated as separate patches, with the second conductive fabric layer and the SMA attached after embroidery as shown in Section 3.5. The patches are then sewn onto the upper arm and the palm positions on the top with an additional heat-insulating felt layer in between the top and the patches. For controlling, we used the FDC2214 capacitive sensing board together with a Teensy 4.1 which also controls the SMA actuation.

7.2 Anywhere-nowhere Game Controller

Embrogami structures can be virtually *anywhere*: their thin and conformable form factor allows them to be wrapped around arbitrary surfaces, and they can be easily removed and reattached to different physical contexts. *Embrogami* structures can also be *nowhere*: they can transform between volumetric and flat to seamlessly blend in with other textile surfaces around us or be scrunched and folded up to occupy very little space when they are not in use.

We demonstrate such flexibility in form factor with an anywhere-nowhere game controller (Figure 21). We created a game-controlling patch for the game Overcooked[3]. The interface consists of four linear directional elastic primitives for moving around, a linear dome elastic primitive for dashing, a radial pointy elastic primitive for

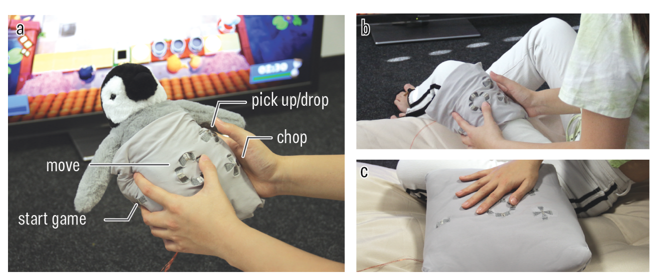

Figure 21: We used *Embrogami* structures to design a (a) textile-based game controller that can (b) be wrapped around anywhere to allow playing in changing physical contexts or (c) be flattened to disable the controls and blend in with other furniture.

[3]https://store.steampowered.com/app/448510/Overcooked/

chopping, and a basic elastic primitive for picking up and dropping objects (a). The patch flexibly allows the user to play the game in different physical contexts with changing body postures. When sitting on the sofa, the patch can be wrapped around the user's lap; when lying down or standing, the user can grab an object (i.e., the toy) and wrap the patch around it (a-b). Regardless of the locations, the volumetric structures on the patch provide rich tactile feedback to enhance the gaming experience. We also made this patch into a pillow cover so that when not playing the game, the patch can be pulled flat and wrapped around the pillow to disable the controls and blend in seamlessly with the built environment (c).

7.3 Training Patch with Contact Feedback

The bistable *Embrogami* structures can be juxtaposed in a larger layout to form a shape *display* in which each primitive acts like a one-bit cell that can transition between the mountain and the valley states. The shape display can be system-actuated to produce a specific shape or be triggered by the user, for instance through body movements or contact with an object. Our application demonstrates how user-triggered shape change can be helpful for visualizing contact with an object for posture correction and motion guidance in sports learning. For instance, boxing beginners very often kick and punch with the wrong positions on their feet and hands. Such implicit motion error is hard to visually detect from the user's rapid movements but can severely injure the ankle and the wrist.

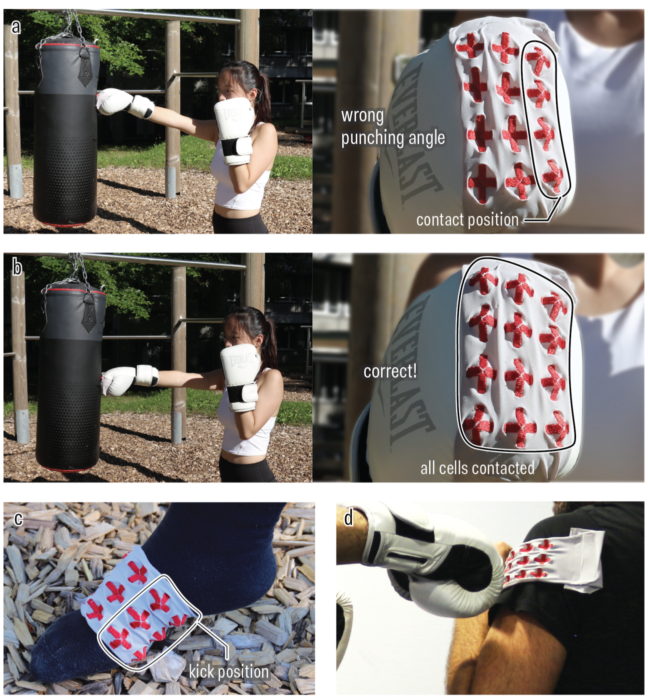

Figure 22: We design a user-triggered shape display for visualizing contact in boxing training. (a) Contacted structures pop out to tell the contact position such that the users can (b) adjust their postures and get immediate feedback. The patch can also flexibly wrap around different body parts for (c) kicking and (d) dodging exercises.

We designed a patch that can be flexibly worn at different locations on the body and is useful for training such as kicking, punching, and dodging in boxing exercises (Figure 22). The patch consists of a dense layout (3 by 4) of small radial mountain primitives (shaper length 8 mm, shaper width 5 mm). It features velcro straps on the back for wrapping around different body parts. The structures are set in their valley states before punching and are triggered into their default mountain states if contacted. When (a-b) punching, (c) punching, or (d) dodging, the patch can be worn on the feet, glove, or shoulder of the user. After the contact, the contacted primitives are triggered and popped out (a-b). Thus, by observing the patch, users can get feedback on whether a contact happened and the positions of the contact to adjust their movements accordingly.

The benefits of using a passive shape display for visualizing contact is that without additional wiring and electronics, the thin and conformable form factor of the fabricated garments makes them durable to high-speed motions and high impact forces and also adaptable to different surfaces and body parts.

7.4 Aesthetic Wristband with Haptic Feedback

We demonstrate how *Embrogami* structures can realize customized aesthetic appearances that blend in with existing clothing, while also integrating simple functionalities through passive shape change. We fabricated a wristband that includes a rainbow pattern of nine linear *Embrogami* structures (Figure 23). It serves as a mnemonic aid to remember a code. Using the layering method, we customized each structure's elasticity such that when pressed, the structure either transforms into the valley or bounces back with different elastic forces (b). This allows visually identical structures to have varying haptic feedback. We use this to encode information that only can be perceived haptically by pressing the structures thus conspicuous to bystanders (c). For example, the wristband encodes a code 253 that (d) unlocks a suitcase by making the 2nd, 3th, and 5th structure elastic, with the 2nd having the strongest elastic force and the 3th the weakest. The wristband is completely passive. All the patterns are fabricated in one-pass through machine embroidery and the second layer with different stretch factors to control the force feedback can be digitally sewn onto the pattern after.

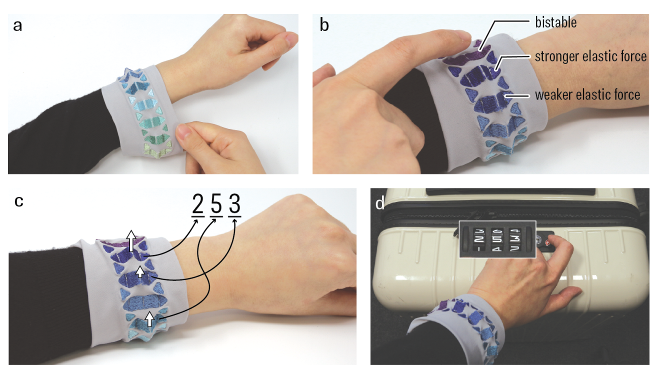

Figure 23: We present (a) an aesthetic wristband with (b) locally varying bistability and elastic force. The different mechanical behaviors can (c) encode a code that can be "read" haptically by touching to (d) unlock a suitcase.

8 LIMITATIONS AND FUTURE WORK

Our proposed technique is subject to several limitations that should be further explored in future work.

Varying stitching parameters. In our implementation, we used standard stitching parameters for all embroidery patches to create stable buckling behaviors and to simplify the fabrication process. Varying and fine-tuning the stitching parameters, such as stitching pattern, angle, layers, spacing, etc., can potentially further broaden the space of shapes, tactile feedback, and mechanical properties.

Enabling bi-directional actuation with SMA. The system-actuated shape change through integrated SMA at the back of the structure is currently limited to uni-directional shape change, which transforms a valley into a mountain. Mechanically, attaching a symmetric SMA wire on top of the embroidery pattern can turn a mountain into a valley when the SMA contracts. This, however, disturbs both the aesthetic and the tactile feedback of the volumetric structures. We thus leave it to future work to explore integrating SMAs or other actuation mechanisms that will achieve digitally-controlled bi-directional shape changes in *Embrogami* structures.

Augmenting shape-changing outputs. The shape-changing output of *Embrogami* structures is currently limited to the mountain and valley states but can be made more versatile and customizable. In experiments we have successfully embroidered patterns that go well beyond the finger-tip scale (15 cm). There is thus potential to make the patterns much bigger and of varying shapes such that a larger-scale, personalized shape change can happen when the structures are triggered to bend out-of-plane. To enable this, the bistability of *Embrogami* primitives needs to be further evaluated with varying pattern parameters and shapes.

Further integrating sensing and actuation. The current sensing technique, albeit fabric-based, still requires an additional layer attached to the *Embrogami* primitive. Similarly, the lightweight SMA wire requires manual assembly onto the structure and does not offer instant actuation. The difficulty of leveraging more integrated and automated fabrication techniques for sensing and actuation lies in the small scale of the *Embrogami* structures and the requirement to be soft and noise-free for on-body applications. We expect future research on thread- or fiber-based sensing and actuation techniques can further help the sensing and actuation techniques to be more integrated and even be fabricated in one go.

Extending functionalities. This paper presents functional textile structures that interact with users with shape changes that are user-triggered, making interactive textiles lightweight, flexible, passive, and integrated. *Embrogami*'s simple primitives encourage future researchers to explore more complex layouts to further extend the functionality of such passive yet interactive textiles. One such possibility could be pushing towards programmable textiles that mechanically encode more complex behavior or even performing simple computations based on the bistable 'bit cells' that we demonstrated.

9 CONCLUSION

Embrogami presents an approach for creating finger-tip-scale mountain and valley structures on textiles with machine embroidery. By embroidering on pre-stretched fabric, we create bistable origamic structures that can be user-triggered or system-actuated to transform between a mountain that rises above the surface and a valley that extends below it, allowing users to modify the local surface topology after fabrication. We introduced individual *Embrogami* primitives with varying shapes, elasticity, sizes, and integrated sensing and demonstrated how multiple primitives can be juxtaposed or integrated to form more complex structures. The functional *Embrogami* primitives are integrated into ultra-thin and flexible textiles and allow us to create interactive elements with diverse visuo-tactile feedback such as toggles and sliders, and textile shape displays. We enable customization of *Embrogami* structures with a design tool, informed by technical experiments, that allows users to design, arrange, and visualize these structures. Finally, we demonstrate *Embrogami*'s potential to create customizable and flexible shape-changing textiles that support versatile user interactions in passive or computer-controlled setups, not only for interactive clothing but also for applications in the lived environment.

ACKNOWLEDGMENTS

This work is partly supported by the Deutsche Forschungsgemeinschaft under Grant No. 521586817 within the Priority Program SPP 2199 Scalable Interaction Paradigms for Pervasive Computing Environments.

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