Inflatable Actuators Based on Machine Embroidery

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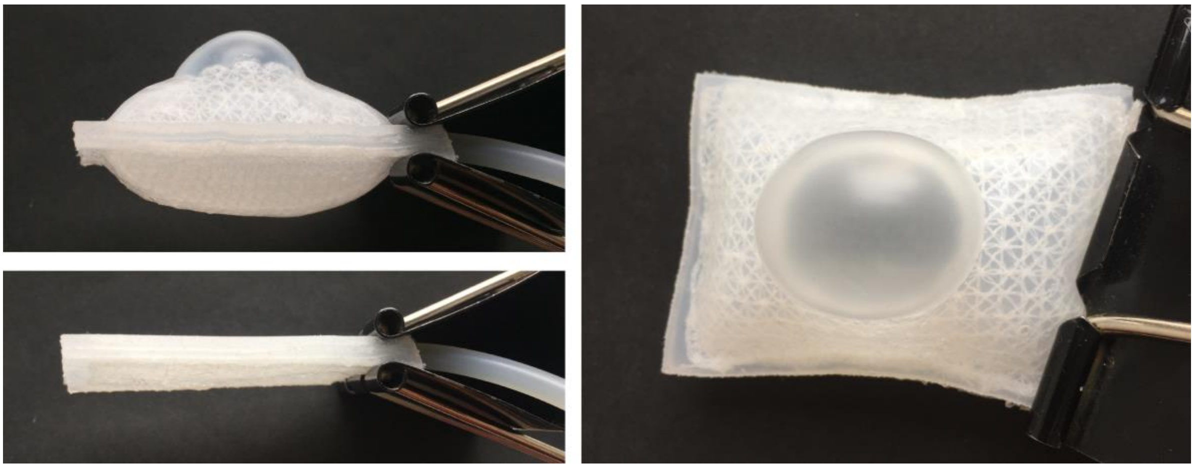

Fig. 1 Series 1 multi-state inflatable sample in relaxed state (bottom left) and actuated (top left and on right side). Sample made through two parts of embroidered substrate, a water-soluble sheet and silicone.

The growing interest in wearable technologies has prompted the development of new techniques for integrating electronics into garments, and more specifically to overcome the challenges interfacing hard and soft components. In comparison to sensors and leads, the textile-based or integrated solutions for actuation remain underexplored. Approaching materials as extensions of actuators, we investigate machine embroidery as means to integrate silicone-based inflatables into garments. Following a research through design methodology, we created inflatables whose design and behavior are determined by machine embroidered substrates. Our iterative process resulted in 24 samples, divided in five series, exploring distinct challenges: 1) sewing attributes to create properties of inflatables; 2) fit & support; 3) improving integration & resolution of complex shapes; 4) enlarging area of actuation; and 5) textile integration. We discuss the impact of different parameters to the fabrication and the interaction possibilities of soft actuators. We show how machine embroidery allows shifting the complexity of the designs away from the casting process, simplifying fabrication, while enabling the creation of a wide range of shapes and behaviors through layering of textile structures. Our work extends the possibilities of integrating different technologies into garments through a single manufacturing process. We contribute with the detailed description of our design process and reflections on designing inflatables by means of machine embroidery.

Additional Key Words and Phrases: Research through design, soft actuation, digital fabrication, machine embroidery, technical embroidery

1 INTRODUCTION

Textile production techniques, such as knitting, weaving and embroidery have been widely employed for the creation of electronic friendly or electronic integrated wearable technologies (wearables). Embroidery, in particular, has shown the potential of supporting the design of interactive garments as it offers more freedom of routing than knitting or weaving [9] to create soft circuits [7, 14]. Moreover, it enables direct interconnections with conventional flexible electronics [9] and fabricating a variety of sensors.

While textile-based sensors have reached a higher level of maturity, having been integrated to commercial products such as smart garments for sports [8, 16], soft alternatives to actuators remains relatively unexplored. Usually, wearables are actuated through external mechanisms, such as motors, which restrain their wearability [3]. Among other forms of actuation, inflatable soft actuators (inflatables) are gaining

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interest for their use in a range of applications such as navigation through tactile feedback [15] and augmented reality to create languages of feel effects [2]. Although the integration of air pumps into wearables still needs to be further explored for a completely unobtrusive user experience, inflatables can be produced through many techniques and materials, offering opportunities for customizing their form factor, material properties and dynamic behaviors. Additionally, the air pumps can be removed of the area of actuation [6]. This could be used to respect guidelines of wearability such as weight distribution or proxemics [18].

The challenges of integrating technology into garments include bulk/weight/stiffness, thermal and moisture management, flexibility/durability, sizing and fit, and device interface [4]. Additionally, the amount of manual work involved in realizing prototypes often makes it difficult to accurately reproduce them and compare variations/incremental changes. This is particularly an issue in contexts where high standards for reliability and safety are expected, such as in healthcare applications. Digital fabrication can support iterative design processes through highly reproducible prototypes by allowing designers to make isolated and precise changes per iteration. Specifically, digital machine embroidery can support such approaches while requiring a relatively low threshold of experience.

The present body of work builds upon earlier research on silicone-based inflatables for supporting tactile motion instructions [6], combining it with machine embroidery to develop reproducible textile integrated on-body applications. As such, we aim to contribute with new ways of using technical embroidery to develop soft wearables and textile interfaces [5, 12, 14]. The scope of this paper is limited to exploring how to fabricate silicone and embroidery-based inflatables (Fig. 1) to understand the implications of using machine embroidery for their fabrication and some of their actuation possibilities. We do so by reflecting on our research through design (RtD) process of five sample series of inflatables, culminating in three identified behaviors, which we refer to as interaction modes. To support our reflection about the reproducibility of the inflatables, the interaction mode designs were given to industrial design students, without prior experience with machine embroidery or casting, to be reproduced and implemented in their research projects within the context of physical rehabilitation.

2 INFLATABLE ACTUATION IN WEARABLES

While still relatively unexplored, inflatables have been gaining interest by designers of wearable applications due to their versatility and the possibility to conform to the body. Inflatables can be fabricated through a variety of processes and materials, both elastic and inelastic. The customization of the inflatable artifacts allows for creating simple to complex structures that behave in very specific ways.

AeroMorph [13], for example, presented a heat-sealing approach that allows fabricating inflatables made of different sheet materials coated in TPU (thermoplastic polyurethane) capable of curling, folding and changing texture. Polyurethane heat-sealed inflatables have also been adopted by The Force Jacket [2] to adapt a life-vest to support augmented reality experiences. Through 26 inflatables on the upper body, this wearable simulates a variety of sensations like feeling rain, being punched and being hugged. The WRAP [15] also explored the heat-sealing technique for creating inflatables made of plastic sheeting to propose an alternative to vibrotactile stimulation to avoid sensory adaptation in haptic applications. The low-profile switchback channels are used to enlarge the actuation area. As a demonstrator, these actuators were implemented into a wristband to guide movement through four points around the wrist. Rotation was indicated through a directional metaphor, in a similar approach to saltation via vibrotactile stimulation [11], having each actuator inflate and deflate in sequence.

Reporting similar material dynamic behaviors as the Aeromorph, PneUI [17] presented approaches to create soft composites both inelastic and elastic. For their inelastic actuators, plastic welding was used. For the elastic composites, materials of varying elasticities were embedded into silicone to control their behavior. The casting processes presented by PneUI include inserts to create dynamic textures and two-part 3D printed molds to cast silicone parts that are bonded together after cured to create air channel shapes. The difference in elasticities to control the behavior of inflatables was also explored to create self-sensing soft actuators based on machine embroidery [1]. Spiral patterns made of Kevlar fiber and optical fiber were embroidered on water-soluble film then embedded in silicone to control the shape of inflation and sense the deformation. Flow [6] used a 3D printed mold and 3D printed PVA inserts to cast silicone-based inflatables that provide users with tactile motion instructions to support motor learning. The wearable was entirely made in silicone which unified the process of form giving of the wearable with the

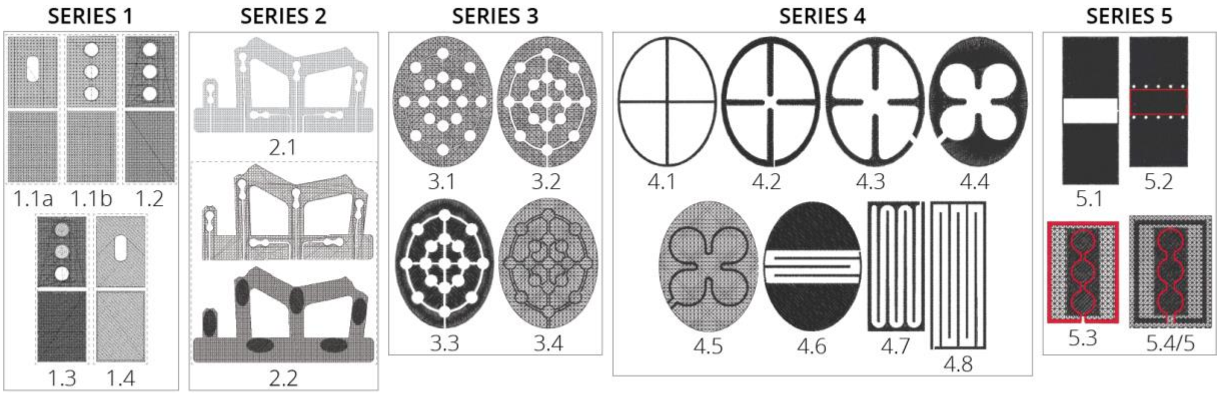

Fig. 2 Overview of the five-sample series. Each series of samples each addressed different challenges: 1) sewing attributes to create properties of inflatables; 2) fit & support; 3) improving integration & resolution of complex shapes; 4) enlarging area of actuation; and 5) textile integration.

design of the air pockets and paths. As an alternative to casting, the Self Assembly Lab [10] has explored additive technologies to develop liquid printed pneumatics which enable creating complex dynamically shape-changing structures.

While heat sealing allows creating textile-based inflatables, their integration into garments is limited by the inelasticity of air tight fabrics. Silicone-based inflatables, on the other hand, offer elasticity and work well for wearables designed for smaller areas of the body, such as wrist/hand. For larger areas of the body such as the torso, however, crafting an entire wearable out of silicone presents challenges to fabrication and usability. Therefore, solutions for integrating silicone-based actuators with textiles are needed in order to broaden the range of applications of this form of actuation. By using chemical embroidery [12] to create a free-standing lace-like substrate and by exploring the programmable nature of machine embroidery, we present a technique for integrating silicone-based inflatable actuators into garments. Our approach considered three strategies facilitated by machine embroidery: *layering & manipulating the fabric character, component alignment,* and *shaping & construction*. In the next section, we describe how we explored designing inflatables through machine embroidery and reflect on our process.

3 DESIGN PROCESS OF THE EMBROIDERY-BASED INFLATABLES

We followed a research through design (RtD) to explore how to create inflatables through machine embroidery and, particularly, chemical embroidery. Chemical embroidery is a technique used to create machine-made lace. Designs are embroidered on a water-soluble film that, when dissolved, results in free-standing substrate [12]. Our explorations resulted in twenty-four designs, divided in five series of samples (Fig. 2) each addressing different challenges: 1) sewing attributes to create properties of inflatables; 2) fit & support; 3) improving integration & resolution of complex shapes; 4) enlarging area of actuation; and 5) textile integration.

The actuators were made through the combination of free-standing embroidered substrates and silicone (Ecoflex 00-30). They were designed using Adobe Illustrator and PE-Design 10 software. The fabrication process was done through semi-professional digital embroidery machines to sew the designs on water-soluble film, and acrylic laser-cut molds for casting. Apart from some short experiments with alternative materials such as monofilament and elastic thread, the samples were made entirely using conventional polyester embroidery threads. During the development of the sample series, the inflatables were manually actuated through syringes.

Different procedures were used to construct and cast the samples throughout the process resulting in different inflation dynamics. In some cases, like in Series 1 (Fig. 2), an additional layer of the water-soluble film was used in between substrates. Similar to the textures created through laser cut fabric described by PneUI [17], the difference in the properties of the embroidered textile and the silicone create the possibility of multi-state deformation. In other cases, like most samples in Series 4 (Fig. 2), the film used for the embroidery serves to create the air pockets which means the actuator inflates to both sides. As a third construction possibility, samples have a support pad over which another piece of water-soluble film is sewn

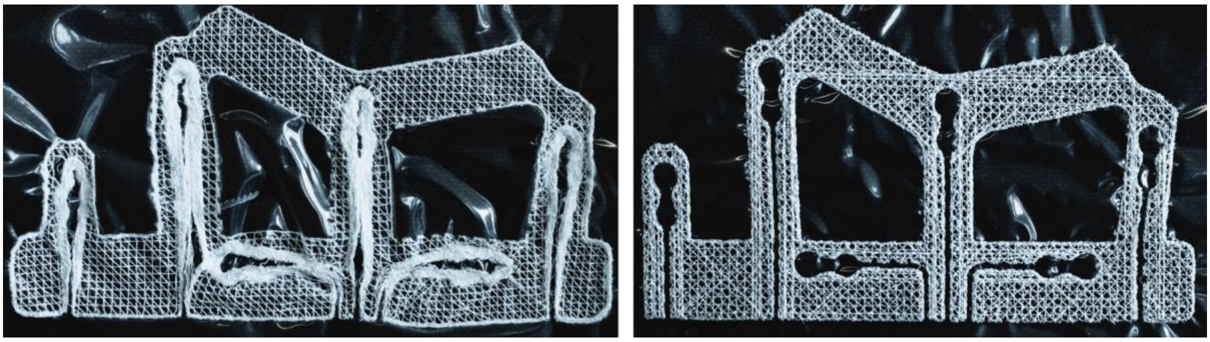

Fig. 3 Series 2 samples explored different sewing attributes to the same complex shape. As seen on the left, Net Fill Stitch causes excessive repetition of stitches to complete the design, deforming the outcome. On the left, the same shape was sewn as layers of Fill Stitch in two different directions that interlock.

in the shape of the actuation area causing the inflation to be one sided. Based on the main learnings from the sample series and these three observed actuation possibilities, a final set was made including three samples which we refer to as interaction modes (Fig. 3).

Below, we present our approach to designing inflatables through machine embroidery and reflect on the insights gained throughout sample series 1 to 5.

3.1 Embroidery-based inflatable sample series

Our approach to designing the sample series considered three strategies: layering & manipulating the fabric character, component alignment, and shaping & construction.

Layering & manipulating the fabric character, was the most relevant to this work. It pertains to defining the material properties of the substrate through sewing attributes and by sewing layers of different attributes on top of each other to manipulate the fabric character, globally or locally. We have explored this technique throughout all sample series. In Series 2 and 5 (Fig. 2), for example, we used layering to create support pads used to direct the inflation. We also used layering as a solution for avoiding stitch repetitions when sewing complex shapes (Fig. 4).

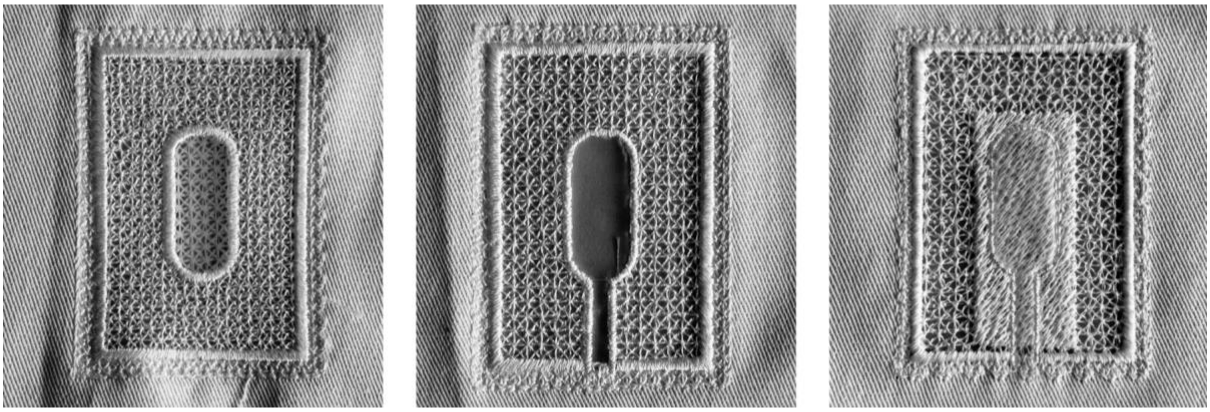

Fig. 4 Embroidered substrates of Interaction modes 1, 2 and 3 integrated into woven textile. Mode 1 is made from two separate embroidered parts. Mode 2 consists of a single embroidery part. Mode 3 is a single substrate sewn as layers that integrate a sheet of water-soluble film over the substrate and support pad.

The second technique, *Component alignment,* concerns the possibility of machine embroidery facilitating iterative design by enabling precise changes to be made to prototypes while the position of components (embroidered or embedded) is preserved. We used this technique in Series 2 in which we recreated in embroidery the design of Flow [6], a wrist worn soft wearable originally made of silicone only that included six inflatables to push against the body. Between our two design iterations, the location of the six inflatables was preserved while we experimented with the sewing attributes of the substrate.

Finally, *Shaping & construction,* relates to reducing the amount of manual labor in patterning, cutting and assembly of prototypes by designing complete wearables through embroidery. Entire wearable form factors or garment pieces can be shaped through the embroidered substrate as in Series 2. We focused mostly on the construction of samples and integration to fabric. In Series 5, for instance, we created a technique for integrating the inflatables into fabrics through cutwork needle. This opens up possibilities to increase the accuracy of reproducing the actuators as well as the way they are integrated into garments.

3.2 Reflections on designing embroidery-based inflatables throughout iterative series

Based on our experience, we reflected on the design implications of fabricating inflatables through machine embroidery. Together with the approach presented in section 3.1, the following points can serve as design guidelines to explore this fabrication technique:

- **Material properties**: the type of thread used to embroider affected the casting process more than it influenced the actuation. In Series 1, for example, we recreated the samples made of polyester in monofilament to compare the outcomes. While the deformation of actuators was equivalent, the casting process of the monofilament substrates was more challenging. The substrate did not absorb the silicone and tended to curl in the mold during casting, resulting in bubbles in the silicone. Rather than achieving different properties through the thread, we explored variable material properties of the substrate through layering. Layering allows creating variable material properties on the substrate, including creating support pads that direct the inflation to one side. This could be explored to support fit around the body through areas of variable flexibility/stretch.
- **Deformation**: we explored different factors that influence the actuation. In multi-state actuators (e.g. Series 1), for instance, the sewing direction had greater impact in deforming the actuator (pocket stretchiness) than small variations of density/spacing of the sew region types of embroidery. Size impacted the homogeneity of actuation. While multiple chambers allow for enlarging the actuation area of the inflatables, their actuation is gradual. For a homogeneous inflation of this kind of structure, multiple input points are likely to work better than one.
- **Integration**: open structured substrates allow for the silicone to flow to both sides of the embroidery during casting, creating a better bond between materials. Round edges further support the robustness of the actuators as they reduce the chances of breakage between embroidery and silicone through air pressure. This is particularly pertinent for actuators that use thin walls for enlarging the actuation area through compartmentalization. To integrate the inflatables into fabrics, employing cut-outwork needles creates a smooth integration. Overlapping the substrate and the textile edge allows for a robust connection that works both for woven and knitted fabrics.
- **Accuracy**: we observed accuracy in two instances. The first was the accurate translation of the design into embroidery. Excessive repetition of stitches can deform the embroidery or tear the water-soluble film. When sewing complex shapes, multiple layers of low-density Fill Stich in various directions work better than Net Fill Stitch for achieving a flexible result. If flexibility is not a priority, a single layer of dense Fill stitch can be used. Alternatively, the outline of complex shapes can be sewn over a new sheet of water-soluble film on the substrate. The result is one-sided inflation. The second instance of accuracy related to using the embroidery frame throughout the various stages of fabrication. This improved the reproducibility of samples and allowed for combining techniques like cutout needle work or washing off the stabilizer for layering.

4 FABRICATION PROCESS OF THE INTERACTION MODES

Reflecting on Series 1 to 5, we discern three actuation behaviors which we refer to as interaction modes 1, 2 and 3 (Fig. 5). The modes are defined by the deformation of the actuators, consequence of their construction and the substrate structure.

The actuators are integrated by machine embroidery in woven fabrics through cutwork needles. The cutwork needles are four blades, each in a different angle, that are installed in the embroidery machine in place of regular needles. The blades punch through the fabric to cut it out. Using this technique allowed us to keep the fabric hooped through most of the fabrication process, supporting the reproducibility of samples. For casting locally, acrylic hoops were laser cut to be attached to the fabric. Another piece of acrylic was used to close the mold at the bottom.

Below, we present the three modes, their fabrication and the experiences of students implementing them in their projects.

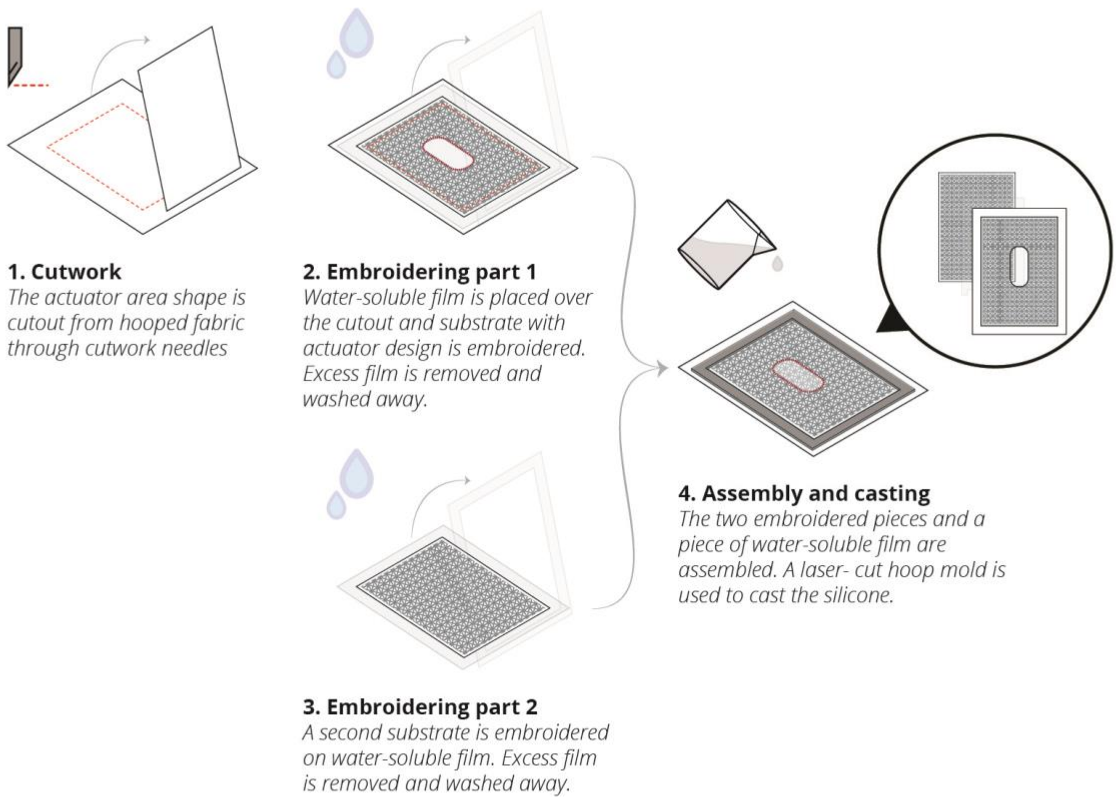

Fig. 5 Mode 1 fabrication process. Two embroidered substrates are sewn separately, then assembled on the hoop-mold with a piece of water-soluble film in between parts.

4.1 Mode 1

Mode 1 is made by embroidering two separate parts and a sheet of water-soluble film. The top part is integrated to fabric and the second is a free-standing substrate used as back of the actuators. As seen on Figure 6, this actuator is a multi-state inflatable. It begins to inflate as a pillow until the cut-out shape on the embroidery starts to protrude.

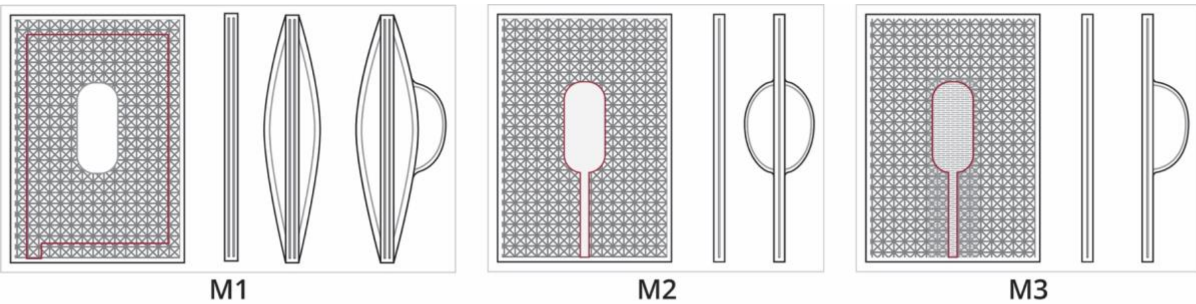

Fig. 6 Front views of Interaction Modes 1, 2 and 3, accompanied by their side views in neutral and actuated states. The red markings correspond to the water-soluble film that creates the actuators. M1 is a multi-state inflatable, M2 inflates symmetrically and M3 inflates unilaterally.

4.2 Mode 2

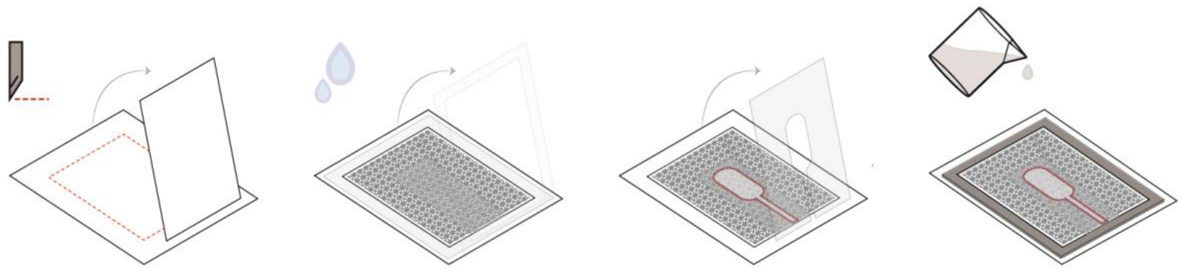

Fig. 7 Mode 3 fabrication process. The embroidery process is divided in two parts. First the substrate and support pad are sewn in layers. The water-soluble film is washed away before another piece of water-soluble film is integrated to through sewing the outline of the actuator shape.

Mode 2 is a double-sided inflation of the negative space in the embroidered substrate. The fabrication (Fig. 7) requires only one layer of embroidery. The most delicate part of the process is that, unlike the other two modes, the film used to create the inflatable pocket is the same as the one used for embroidering the substrate. That means that for a better interface with the silicone, parts of the film need to be carefully washed away from the substrate without dissolving the center part of the sample. Another downside of this mode is that, based on the experiences of Series 2 and 3, we could not create a complex-shaped actuator that remains as flexible.

4.3 Mode 3

Mode 3 was created by layering a dense support pad over the substrate then adding a layer of water-soluble film to create the active area. This construction enables directing the inflation to one side only, which can be used to implement directional cues in garments. The fabrication process requires washing off the sample, still on the embroidery hoop, after step 2 (Fig. 8), then bringing the hoop back to the machine to finalize sewing the actuation area. This way, the silicone can flow to both sides of the substrate, without dissolving the middle.

4.4 Case studies: interaction modes reproduced by design students

To begin to assess the reproducibility of the inflatables, we offered the designs of the interaction modes to one master and four bachelor and industrial design students. They had no prior experience with machine embroidery or casting. Their assignment was to reproduce the three modes and to explore possible applications in the context of physical rehabilitation as case studies for their research semester. They had freedom to use the inflatables in their projects as they saw fit, including how to actuate them.

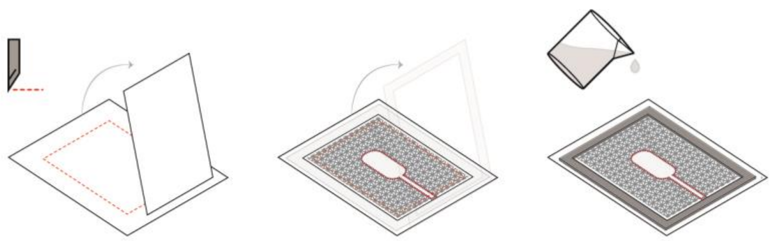

Fig. 8 Mode 2 fabrication process. The substrate is embroidered as a single part containing a negative space with the shape of the inflatable.

For reproducing the samples, students received the embroidery files and the laser cut molds. The process was explained through an introduction workshop in which we reproduced mode 1 as an example, so all techniques could be demonstrated. A follow up session addressed questions about the fabrication process and their research directions.

The four bachelor students worked as a group to examine the potential of correcting back posture through inflatables by comparing the three modes in three wearing locations. They actuated them manually. The second project, conducted by the master student, tested the use of mode 3 to provide directional cues on four trigger muscles involved in activating the arm to support physical physiotherapy. The inflatables were actuated through air pressure pumps and valves, controlled by a microcontroller. Combined, the students reproduced a total of 26 working samples for their studies, which involved twenty participants each.

At the end of their projects, we conducted a final group session to collect their experiences reproducing the interaction modes for their studies. In the session, the students stated that they struggled with the amount of novel information of the introduction session which, according to one of them, "made it hard to visualize the whole process". Thus, when they began to reproduce the samples, two parts of the process were misunderstood. The first was how to continue the embroidery process for fabricating mode 3 after washing off the water-soluble film (step 3, Fig. 8). The other was understanding that the second embroidered part used in mode 1 was meant for all modes. They only realized this was a mistake while casting their first batch of samples.

About learning how to reproduce the substrates, one of the students said that "starting the process of embroidery was somewhat time consuming at first [and] it took us a day just to learn how to use the machine" but that it got easy with experience. The process of casting, on the other hand, was troublesome as they found it difficult to reproduce the same pressure on the mold as well as pouring equal amounts of silicone to each sample. Also detrimental to the accuracy of reproducing actuators was the attachment of the air tubes to the samples. They glued them together, resulting in some samples being bulkier than others depending on the amount of glue.

The feedback given by the students suggests that replicating the process is overall easy, provided that novel information is presented through a hands-on experience. The number of samples they reproduced corroborates with our assumption that machine embroidery requires a low threshold of experience from designers. The difficulties they reported with casting and making the connection between actuators and air tubes are relevant for future work.

5 CONCLUSIONS

Following a RtD approach, we explored the possibilities of designing soft inflatable actuators by combining machine embroidered substrates and silicone. Our samples explored how to integrate embroidery-based inflatables into textiles and how to design complete form factors.

We contribute with an approach to machine embroidery, several lessons learned through our process and a detailed description of the fabrication process of our interaction modes. The techniques we presented extend the possibilities of designing interactive garments and soft interfaces through machine embroidery. Our reflections offer guidelines for design and open up research questions about potential applications and automatizing the production process of inflatable actuators based on digital machine embroidery. In our work, we dealt with complex shapes through layering pre-programmed sewn region fills in different directions, thus avoiding excessive repetition of stitches.

Design students without previous experience with embroidery or casting reproduced our designs and incorporated them in their research projects. Through their feedback, we found that the potential of scalability and accuracy of the current method of fabrication of the actuators is reduced by the casting procedure. Therefore, further exploration of the casting process is needed. Keeping the samples on the embroidery hoop during the different stages of production supported accurate layering and allowed combining techniques and materials during the process. One way we envision improving the accurate reproducibility of the final outcome is to keep the fabrics in the embroidery hoop until the end of the fabrication.

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