Embroidered Inflatables: Exploring Sample Making in Research through Design

Journal of Textile Design Research and Practice

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rftd20

Embroidered Inflatables: Exploring Sample Making in Research through Design

Bruna Goveia da Rocha, Oscar Tomico, Daniel Tetteroo, Kristina Andersen & Panos Markopoulos

To cite this article: Bruna Goveia da Rocha, Oscar Tomico, Daniel Tetteroo, Kristina Andersen & Panos Markopoulos (2021) Embroidered Inflatables: Exploring Sample Making in Research through Design, Journal of Textile Design Research and Practice, 9:1, 62-86, DOI: 10.1080/20511787.2021.1885586

To link to this article: https://doi.org/10.1080/20511787.2021.1885586

Published online: 18 Mar 2021.

Embroidered Inflatables: Exploring Sample Making in Research through Design

Bruna Goveia da Rocha, Oscar Tomico, Daniel Tetteroo, Kristina Andersen and Panos Markopoulos

Bruna Goveia da Rocha is a PhD candidate at the Future Everyday group of the department of Industrial Design (TU/e). Her research is focused on the design process of soft things. She is particularly interested in exploring the combination of digital craftsmanship and emerging technologies, such as inflatables.
b.goveia.da.rocha@tue.nl

Oscar Tomico is Head of the Design Engineering Bachelor program at ELISAVA Design and Engineering school, and assistant Professor at the Future Everyday group of the department of Industrial Design (TU/e). His research focuses on how to design, develop, produce and deploy Soft Wearables.

Daniel Tetteroo is Assistant Professor of Physical Rehabilitation at the Future Everyday group, and the co-founder of Picoo BV, a startup that develops interactive toys for active play. Tetteroo is

ABSTRACT This paper reflects on the experience of sample making to develop interactive materials. Sample making is a way to explore possibilities related to different materials techniques. In recent years design research has put an increasing emphasis on making as a mode of exploration, which in turn has made such exploration an increasingly popular and effective design research approach. However, sample making is a messy and complex process that is hard to document and communicate. To mitigate this, design researchers typically report their journeys from the perspective of their success, retroactively editing out or reducing the accounts of experiments that did not directly contribute to their goal. Although it is a useful way to of contextualizing a design process, it can contribute to a loss of richness and complexity of the work done along the way. Samples can be seen as instantiations of socio-techno systems of production, which means that they can be

Journal of Textile Design Research and Practice
Volume 9, Issue 1, pp 62–86
DOI: 10.1080/20511787.2021.1885586

looked at from different perspectives and can potentially become the starting points of new design explorations. In recognition of this quality, we aim to investigate ways that samples can be appropriated in future journeys. To do so, we analyzed and reflected on the sample making process of the Embroidered Inflatables as a design case. The project resulted in 27 samples that explored distinct challenges related to designing actuators for soft wearables through the combination of silicone casting and embroidery techniques. To explore the potential of sample appropriation, we invited a fashion designer to a creative session that analyzed these samples from her personal perspective to identify new design directions. We detail the design process, reflect on our sample making experience and present strategies to support us in the process of reevaluating and appropriating samples.

KEYWORDS: Research through design, sample making, design process, materials, embroidery, soft actuators

interested in the design end-user adaptable systems and technology for physical rehabilitation.

Kristina Andersen is Assistant Professor at the Future Everyday cluster of the Department of Industrial Design. Her work is concerned with how we can allow each other to imagine our possible technological futures through digital craftsmanship and collaborations with semi intelligent machines in the context of material practices of soft fiber-based things.

Panos Markopoulos is Full Professor of Design for Behavior Change. Markopoulos is currently working on ambient intelligence, behavior change support technology, sleep quality monitoring, end-user development, interaction design and children, and wearable rehabilitation technology.

1. Introduction

The design research community is currently engaged in a process of creating a broader context for Research Through Design (RtD), beyond the well-established frameworks for HCI and user-centered design (Redström and Heather 2019). This broader context for RtD is supported through a series of concepts coming from different streams of thought in science and technology studies (STS) and philosophy, which share the interest in re-examining the relationship between humans and the material world from the perspective of the role of tools (Frauenberger 2020). Concepts like troubling design processes (Haraway 2016), correspondences (Ingold 2017) and radical interrelations (de la Bellacasa 2017) are opening new possibilities for design. In practice-led design research, we see similar ideas being articulated through digital craft (Oxman 2007), material assemblages (Wiberg et al. 2013), infrastructuring (Ehn 2008), intentional drifting (Krogh and Koskinen 2020) and traveling (Goveia da Rocha and Andersen 2020). They differ from user centered design tradition in the way they embrace the full complexities involved in the act of making and designing, allowing a number of concerns and considerations to co-exist and take part in a common design space.

For decades, materiality of interaction has gained focus and interest in design research. Design researchers have begun to shift from metaphor-centered interaction design towards direct forms of interaction through materials and their properties (Wiberg 2018). At the same time, the growing adoption of digital fabrication methods has opened up opportunities for more design researchers to explore design practices that are materially driven. By designing from the capabilities of digital fabrication machines, it is possible to transition towards a more integrated approach to designing with and through technology, which expands our views on the relationships between designers, machines and materials as well as between the physical and the digital (Nachtigall 2019).

Approaches based on material exploration allow the development of designs grounded in the real possibilities emerging from interacting with fabrication systems. As a part of this exploration, we are able to metaphorically stand next to the machines and materials we work with to ask them "what if?" and "what else?" (Andersen et al. 2019). In doing so, we emphasize the roles that machines and materials play in introducing opportunities, create intimacy with the making process, facilitate detours and, ultimately, develop different kinds of knowledge. The process is rich and multifaceted, and as a result it is difficult to document and communicate. This is in part due to the high number of samples or artifacts created in materially driven processes and the tendency to focus on final outcomes rather than in the details of how we got there (Krogh, Markussen, and Bang 2015). As a result, this type of design research is often reported from the perspective of how certain experiments led to the reaching of a specific goal (Goveia da Rocha and Andersen 2020). Experiments that do not directly contribute to this "success" are usually unaccounted for or collectively summarized as part of an exploratory phase that mainly serves to provide the reader with a rationalization of the process and evidence of the quality of its outcome. This can create a gap between the reporting of design research and the actual experienced design practice (Scrivener 2000), but maybe more importantly it can be seen as a limiting and wasteful practice, as samples or prototypes are treated as means to an end rather than valued in their own right for the potentially intricate relations that they embody.

By recognizing that the experiments we make may answer more questions than the ones we asked through their making, we join a broader discussion about drifting in design (Krogh, Markussen, and Bang 2015; Krogh and Koskinen 2020) and craftsmanship (Andersen et al. 2019) to consider the role of making samples in Research through Design. More specifically, we reflect on whether we can consider these samples research objects separated from their original context. As a guiding line through the discussion in this text, we will look at the samples created in the Embroidered Inflatables project, which allowed drifting and complexity throughout the sample making process. In this project, we engaged in a materially driven exploration, making use of state-of-the-art digital machine embroidery combined with silicone casting to create inflatables. Beyond the making experience, in this paper we explore the use of interactive material samples and their appropriation in design processes as a means to draw an outline of the complexities that samples embody. In doing so, we address the community of design researchers and makers engaged with material driven research and digital craftsmanship, and contribute a practical design case of the Embroidered Inflatables, an exploration of the possibility of considering samples research objects in a manner that is in part separated from their original context and a set of strategies to facilitate the revisiting of samples. As such, we aim to open up opportunities of appropriating the samples of Research through Design projects in other design journeys. In the following, we make use of the travelers metaphor (Goveia da Rocha and Andersen 2020) to look back at the Embroidered Inflatable samples as previous places that could be revisited and be appropriated as the starting points of other journeys.

1.1. The Previous Places

In this paper, we embrace the search for these other places (Goveia da Rocha and Andersen 2020) and aim to articulate how samples that may have been seen as failures within a design journey (van Dongen et al. 2019) can be seen as outcomes on their own terms. In other words, we aim to demonstrate that "failed" samples can be actionable (Rutkowska, Visser, and Lamas 2019) as new starting points for other journeys. To demonstrate this approach, we build on two previous projects: Flow (Goveia da Rocha and Tomico 2019) and, mainly, the Embroidered Inflatables project (Goveia da Rocha et al. 2019), both aimed at investigating actuation in soft wearables.

Flow was a wearable artifact, made entirely of cast silicone, that aimed at supporting the learning of physical activities through directional cues given by elastic inflatables that push against the body. This one-sided behavior of the inflatables was achieved through a difference in the thickness of its walls, allowing them to push against the body to communicate the user about the direction of movement. The limitations of the fabrication technique were the bulkiness needed to create this asymmetrical inflation and scale. Large garments made of silicone alone are not convenient to fabricate or comfortable to wear, limiting the application possibilities of the technique.

As a follow-up of Flow, the Embroidered Inflatables project was started to explore if the one-sided behavior of the inflatables could be achieved through a combination of silicone and a textile production technique to integrate elastic inflatable actuators in soft wearables. Inspired by techniques that use mesh to reinforce silicone or other materials, we opted to combine casting with chemical embroidery. Chemical embroidery (Mecnika et al. 2014) is a technique, typically used to create machine-made lace, that uses a water-soluble stabilizer to create self-supporting embroidery. Through this technique, we were able to take advantage of the accuracy and freedom of routing of digital machine embroidery to program the properties of this lace-like embroidered substrate as well as determine the shape and behavior of the inflatables.

By revisiting the analysis of these two works, we aim to unpack some of the opportunities that sample making offer beyond abstractions of the lessons learned. In the following sections, we articulate how samples may outlive the context of specific design journeys.

1.2. Old Samples, New Starting Points

Our initial motivation was to recreate the specific behavior of the inflatables in Flow through a hybrid technique that combined a textile production technique and silicone casting. Nonetheless, we were open to explore emergent questions and ideas. As a result, we created 24 samples that explored different challenges: 1) sewing attributes to create properties of inflatables; 2) fit & support; 3) improving integration and resolution of complex shapes; 4) enlarging area of actuation; and 5) textile integration. From these samples, we identified three actuation behaviors based on which we created three extra samples that we called Interaction Modes.

In the first account of this project (Goveia da Rocha et al. 2019), we presented the complete set of sample series generated in our project, including the Interaction Modes, together with lessons learned throughout the process of creating them. In the following, we propose a way that these samples may be seen to contribute beyond the traditional notion of lessons learned or guidelines.

By analyzing and reflecting on the design process, we observed how a goal-oriented approach could be combined with a more explorative process. Each sample can be seen to stand on its own and answer more questions than it was designed to answer. As such, samples can be seen as instantiations of a socio-technical system of production, and this view allowed us to look at them from different perspectives of the system, such as the interactive qualities of the material outcomes, the design of the digital assets or the experienced collaboration with the machines.

In the following, we present the design process of the Embroidered Inflatables project. Then, we detail findings from a session with a fashion tech design researcher, in which the sample series was used to identify opportunities and qualities that could be forwarded to the design of interactive garments. This session supported the reflection on strategies that can support us in making samples actionable beyond their original contexts of creation, such as how to store/display and document them, presented in section 4. Based on this framing of samples, the following sections provide: 1) the description of the process of making samples by means of digital machine embroidery; 2) a reflection on how to support appropriation of samples as starting points for new journeys.

Our intention is to support our community in finding ways to acknowledge, produce and share knowledge about our material sample work. We hope this is a way towards a more explicit exchange of material knowledge across projects and design researchers.

2. Case Study: Embroidered Inflatables

As a design case, we look into the sample making process of the Embroidered Inflatables. This project was developed in the context of investigating actuation in wearables (Markopoulos et al. 2020). Through this project, we were able to experience a highly paced process of making samples. The samples were executed on the same level of finish and explored different parts of the design space of creating inflatables based on digital machine embroidery. The variety in the collection of samples and their equal level of finish contributed for us to continue to revisit these samples for the purposes of advancing the project towards designing soft wearables based on inflatables, as well as in different contexts and discussions. Looking at them from the proposition of designing as travelers (Goveia da Rocha and Andersen 2020), we gained a new understanding of the potential role of samples in Research through Design. More than steps towards a goal or failures, samples have the potential of taking us to other places by answering different questions than the ones that originated them.

Before discussing our approach to samples (in Section 3), we first present the specific challenges we aimed to address through our design process by introducing the context of existing work in actuation in wearables and techniques for creating inflatables.

2.1. Actuation in Wearables and Textile Production Techniques

From self-expression to health monitoring, (soft) wearable technologies can open up many opportunities of bringing technology close to the body in engaging and unobtrusive ways. The challenges of integrating technology into garments include bulk/weight/stiffness, thermal and moisture management, flexibility/durability, sizing and fit, and device interface (Dunne, Ashdown, and Smyth 2005). 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) to overcome such challenges. 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 (Linz et al. 2008) to create soft circuits (Post et al. 2000; Hamdan, Voelker, and Borchers 2018) and it requires a relatively low threshold of experience. Moreover, it enables direct interconnections with conventional flexible electronics (Linz et al. 2008) and fabricating a variety of sensors (Linz, Gourmelon, and Langereis 2007; Aigner et al. 2020).

While textile-based sensors have reached a higher level of maturity, having been integrated to commercial products such as smart garments for sports ("Hexoskin" 2019; "Sensoria Fitness" 2019), soft alternatives to actuators remain relatively unexplored. Usually, wearables are actuated through external mechanisms, such as motors, which restrain their wearability (Du et al. 2018). Among other forms of actuation, inflatables have been gaining the interest of designers of wearable applications due to their versatility and the possibility to conform to the body. 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 from the area of actuation (Goveia da Rocha and Tomico 2019). This could be used to respect guidelines of wearability such as weight distribution or proxemics (Zeagler and Clint 2017).

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 (Ou et al. 2018), 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 (Delazio et al. 2018) to support augmented reality experiences. The WRAP project (Raitor et al. 2017) also explored the heat-sealing technique 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. These actuators were implemented into a wristband to guide movement through directional metaphors by actuating four points around the wrist.

Reporting similar material dynamic behaviors as the Aeromorph, PneUI (Yao et al. 2013) 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 difference in elasticities to control the behavior of inflatables was also explored to create self-sensing soft actuators based on machine embroidery (Ceron et al. 2018). 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. The project Flow (Goveia da Rocha and Tomico 2019) 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 design of the air pockets and paths.

While heat sealing allows creating textile-based inflatables, their integration into garments is limited by the inelasticity of airtight 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 wearability. Therefore, solutions for integrating silicone-based actuators with textiles are needed in order to broaden the range of applications of this form of actuation. Chemical

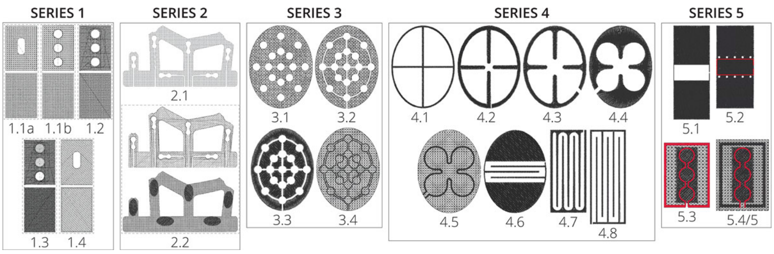

Figure 1
Overview of the design process of the Embroidered Inflatables. The samples were divided in five series based on the different challenges they addressed.

embroidery (Mecnika et al. 2014), the technique of embroidering on water-soluble film used by Ceron at al. to embedded Kevlar and optical fibers in silicone (Ceron et al. 2018), was also used to create sensorized soft wearables as research products (Goveia da Rocha et al. 2020). In the Embroidered Inflatables project, we built on these techniques to develop reproducible textile integrated and highly customizable inflatables for on-body applications. As such, we aimed to contribute with new ways of using digital machine embroidery to develop soft wearables and textile interfaces (Post et al. 2000; Gilliland et al. 2010; Mecnika et al. 2014).

For details about the fabrication techniques used in the project and implications of designing inflatables based on embroidery, refer to an earlier publication (Goveia da Rocha et al. 2019). In the context of this paper, we are specifically looking at the complexity of the process of making samples above the specific outcome of the project.

2.2. The Design Process of the Embroidered Inflatables

The starting point of the explorative design process of the Embroidered Inflatables (Figure 1) was the Flow project (Goveia da Rocha and Tomico 2019). Flow (Figure 2a) was a wearable designed to support the learning process of physical activities. Fabricated as a single piece, cast in silicone, Flow integrated six inflatable actuators into a wrist-worn artifact meant to create pressure points for embodied guidance (Figure 2b). Our interests in the project were both the overall concept of using pressure to communicate with the body and, most importantly, the use of materials as extension of the pumps needed to actuate the inflatables. As such, our original intention with our exploration of embroidery-based inflatables was to transpose the fabrication method used to create Flow to textile (compatible) techniques that would allow implementing the concept of crafting soft wearables with integrated actuators to larger parts of the body.

Flow was made by casting silicone (ecoflex-030) in a 3D printed mold made of PLA filament, using a 3D printed PVA insert to create the cavities that operated as inflatable chambers. In the embroidery-based samples, we used the freedom of routing of the embroidery

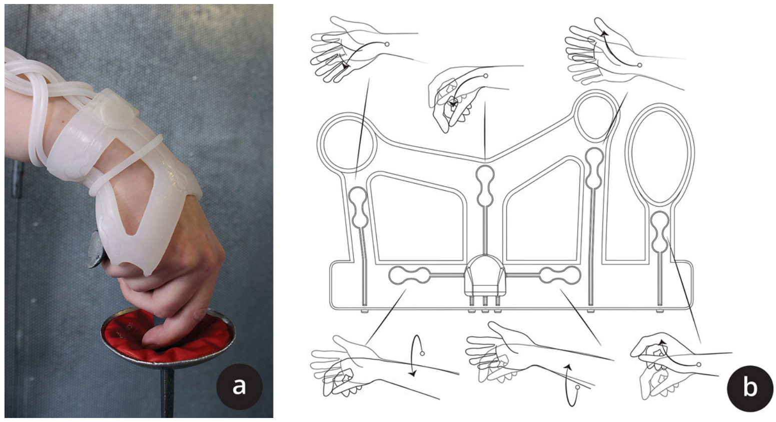

Figure 2
(a) Flow was a wearable designed to support the learning process of physical activities through directional cues. (b) The wearables integrated six inflatable actuators corresponding to the fundamental joint movements of the wrist and forearm.

technique to flip the complexity of the design to the embroidery, which gave us more freedom to create the shapes of inflatables and facilitated the stacking of layers to achieve the single sided behavior. Instead of the 3D printed PVA inserts, the same PVA stabilizer film used to embroider the free-standing embroidery (Gunold Ultra Solvy 80) was used to create the chambers. The embroidery machine served multiple purposes, including creating a strong integration of silicone with textiles through its open structure, creating free-standing substrates, cutting out the film in the desired shapes, cutting out textiles through cutwork needles to integrate the substrates into ready-made fabrics and to assemble layers. The molds were simple, needing to only demarcate the outside shape of the casting area while the shape of the inflatable area could be easily customized through the embroidery.

Interestingly, it was in series 2 (Figure 3), when we recreated the design of Flow, that we started to shift our design approach towards intentionally drifting. On the one hand, we continued to pursue the goal of exploring how to create the asymmetrical inflation through a textile-based technique. On the other, we deliberately drifted to explore the possibilities of designing inflatables through the embroidery technique.

In series 2, our aim was to recreate Flow through a similar approach to the one presented by the Smart Sock project (Goveia da Rocha et al. 2020), in which the chemical embroidery technique is used to create the free-standing embroidery already shaped as the wearable (parts). Different from the Smart Sock, this design had a complex outline to integrate the paths of inflation and inflatable pockets into the shape of the wearable. To create the free-standing embroidery in the shape of Flow, the machine had to travel all around and back several times, resulting in excessive stitch repetition. Although it is possible to edit each stitch manually, the overlap of

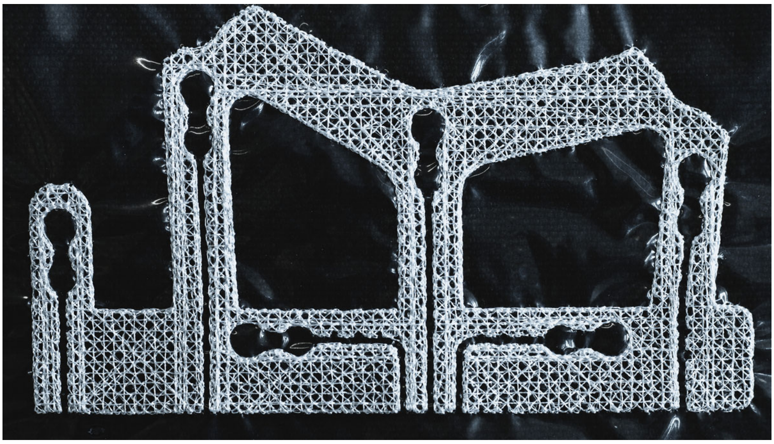

Figure 3
In the samples of series 2, we recreated the design of Flow. The wearable shape with integrated inflatable air paths and pockets was complex, resulting in a repetition of stitches. This motivated us to explore layering and the sewing attributes of the embroidery.

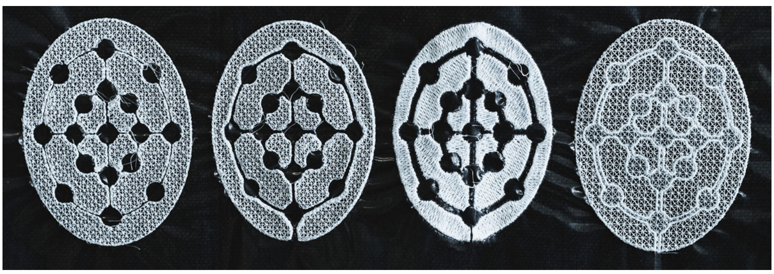

Figure 4
Series 3 explored complex shapes and varying sewing attributes.

multiple stitches in the same spot made it impractical to edit the automatically generated net fill stitch pattern we used. Instead, to reduce the repetition of stitches, we recreated the net fill stitch pattern through four layers of low-density fill stitch, each in a different direction. To further investigate how to overcome the challenge of creating complex shapes, we moved onto exploring different structures and stitch types through other samples that we later identified as Series 3 (Figure 4).

As we proceeded in engaging with materials and techniques, we shifted our focus from a goal-oriented journey to also embrace questions and opportunities that emerged from the experience of making. The process of moving from one sample to the next happened organically. For the most part, we can see the process of moving through these questions as a process of itineration (Ingold 2010), in which every step is a development of the previous one and a preparation for the next. Because the questions we let lead our way were not incremental, our process could also be characterized as an expansive way of drifting (Krogh, Markussen, and Bang 2015), that aimed to explore

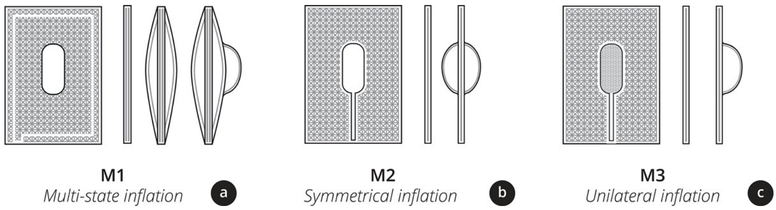

Figure 5
Front views of Interaction Modes 1, 2 and 3, accompanied by their side views in neutral and actuated states. M1 is a multi-state inflatable, M2 inflates symmetrically and M3 inflates unilaterally.

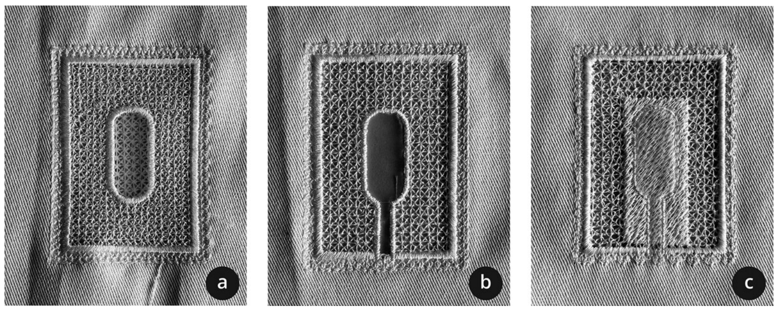

Figure 6
Embroidered substrates of Interaction modes 1, 2 and 3 integrated into woven textile. (a) Mode 1 is made from two separate embroidered parts. (b) Mode 2 consists of a single embroidery part. (c) Mode 3 is a single substrate sewn as layers that integrate a sheet of water-soluble film over the substrate and support pad.

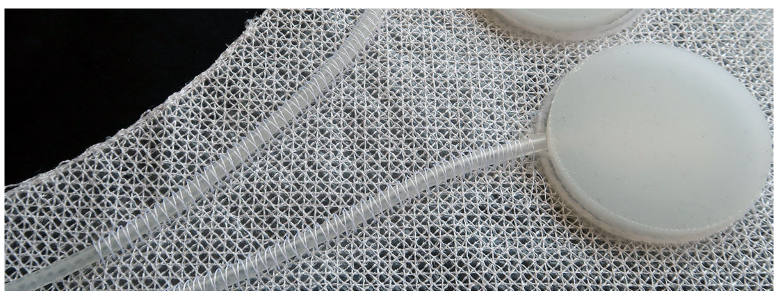

Figure 7
Embroidered sample with integrated tubing. To achieve this, the production happens in three stages. First the substrate and inflatable area are embroidered, then the silicone is cast. Lastly, the tubing can be connected and integrated to the embroidered substrate through a couching stitch.

the possibilities of creating inflatables through digital machine embroidery and, particularly, chemical embroidery technique.

In this process, we created twenty-four designs that addressed different emergent challenges and questions. Each sample was thoroughly documented. The documentation incorporated technical attributes of the embroidery designs, materials, methods of fabrication and reflections on the design journey (goal, behavior of the inflatable and insights). By revisiting the documentation and reflecting on our process, we identified how we addressed five main topics: 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. These topics were used to divide our process into five series of samples. Based on our experience and documentation, we reflected on the design implications of fabricating inflatables through machine embroidery.

Our reflection also allowed us to identify three actuation behaviors (Figure 5). We created three new samples, one per behavior, which we refer to as Interaction Modes 1, 2 and 3 (Figure 6). The modes are defined by the deformation of the actuators resulting from their construction and the substrate structure.

In the original account of our project (Goveia da Rocha et al. 2019), presenting the Interaction Modes as a final outcome seemed like the logical endpoint for the process. However, other emerging opportunities showed us otherwise. As an example, we improved the casting process reported in our previous publication through different mold methods for casting locally to avoid bleeding through the fabric. One method was 3D printing the mold onto the embroidery (Goveia da Rocha, van der Kolk, and Andersen, 2021) and the other by using magnetic laser cut acrylic molds. These versions of the molds allowed us to keep the samples in the embroidery hoop so that they could return to the embroidery machine for possible post-production such as embedding tubing, as seen in Figure 7.

While the Interaction Modes were considered an endpoint for the process, there were other possible outcomes to our process as well as interesting loose ends worth revisiting and pursuing in other design journeys. These relationships across projects likely happen in design practice, particularly for designers working closely with a specific craft. We would like to propose that samples can be approached as living things, prone to be revisited and re-signified by new questions which allow us to more explicitly forward concepts, insights, materials and techniques across projects and design researchers. Our process indicated that the formats of presentation and documentation are key to support a shift of approach and to enable a deeper understanding of the samples and artifacts we make.

3. Sample Making and the Search for Other Places

Unpacking design processes is challenging. For many years, our community has been engaging with questions over the nature of our work and how to expand our understanding over what is the knowledge we can generate by carrying out design actions (Wensveen and Matthews 2015). Therefore, the discussion on the role of prototypes and prototyping remains central in design research.

Peter Krogh et al (Krogh, Markussen, and Bang 2015), acknowledge that designers drift in design processes to continuously learn and adjust themselves to opportunities or challenges that emerge. There are multiple ways we drift in design research to gain depth, acknowledge complexity, systematize knowledge, broaden knowledge and to exploit opportunities that emerge along the way.

The notion of infrastructuring (Ehn 2008), also points out at design objects as more than accomplished dead ends. The things we design are also relational and open to being appropriated and appreciated in other contexts outside the one in which they were created. Designing 'for design after design' involves considering the relationships between people, methods, facilities, tools, materials, machines. This relational view also supported the culture of prototyping developed within the Smart Textile Services project (STS), part of CRISP (Tomico and Wensveen 2014). The STS testbed is a platform in which prototypes are the drivers of design processes through a bottom-up approach, and the act of prototyping is seen as a craft that enables shared ownership and community building through dissemination of the work (exhibitions, facility sharing and designers in residence).

William Gaver (Gaver 2012) echoes the idea that designs objects should remain open for appropriation and appreciation by arguing that “an endless string of design examples is precisely at the core of how design research should operate, and that the role of theory should be to annotate those examples rather than replace them.”

Seamful design presents yet another perspective that values the complexity of design processes that argues for making the connections and gaps between physical, digital and social spaces explicit (Rudström, Höök, and Svensson 2005). About design practice and collaborative work, Anne Galloway questions the political and ethical implications of "seams and scars" in design processes (Galloway 2007). More specifically, she argues that the "seams and scars" are markers of past actions or interventions – like things that are cut apart and put back together in a new way. Making them explicit supports us in questioning the conditions in which they occurred, meaning how processes unfolded and what was the role of the players involved. This can encourage a search for "places where interventions can be made, or where potential can be found and acted upon" (Galloway 2007).

While each of these design philosophies or research traditions articulates our relationships around practical work differently, all of these approaches look beyond user-centered design to acknowledge and embrace the social, technical and material complexities involved in design practice and, consequently, in Research through Design. In our work, we explore this understanding of the relational characteristic of design practice by questioning which strategies can assist us in opening our experiments up to new relations and opportunities.

We focus on samples because, in HCI and in design research, this is a broad term that has been used to refer to the outcomes of materially driven approaches, meaning that the value and interactive

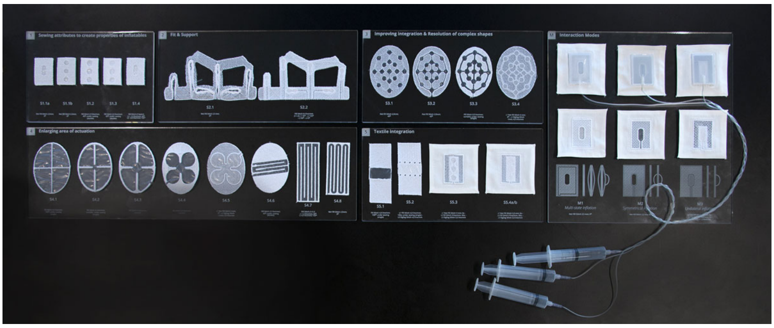

Figure 8
Display setup for the INTERSECTIONS Collaborations in Textile Design Research Exhibition. All samples of Embroidered Inflatables project were recreated and mounted on six acrylic displays. Visitors were encouraged to interact with the Interaction Modes samples by actuating them through syringes.

possibilities offered by these prototypes is intrinsically related to their fabrication methods and materials. Similarly to how research products are characterized (Odom et al. 2016), samples can be seen as prototypes that are evaluated by what they really are and what they can do. When engaging with such samples, we may discover that more than the (interactive) qualities we planned on materializing are present. These qualities and behaviors of samples are composed by the negotiations between our intentions with those of the entire socio-technical system of production: material, the machine and the circumstances. When judged based solely on our intentions, a sample may be a failure or a success within our journey towards a specific goal. Yet, that does not eliminate the other opportunities its qualities may offer to another process.

We build on these ideas together with the notion that this way of working is akin to traveling (Goveia da Rocha and Andersen 2020). The designer allows new ideas to emerge through a mindset that invests time in creating things in collaboration with people, ideas, tools and materials. The making process is curiosity driven, but the designer is systematic about documenting experiments so that they stay open for appropriation in other journeys.

3.1. Revisiting Samples

We presented the Embroidered Inflatables project at the "INTERSECTIONS: Collaborations in Textile Design Research Exhibition" (Morgan et al. 2019). The exhibition gave us the opportunity of seeing all the samples as a collection, with the same type of finish and level of importance.

In preparation for the exhibition, we recreated all samples and mounted them in acrylic displays (Figure 8). The sample series 1 to 5 were not cast in silicone to highlight the embroidery. The Interaction Modes, on the other hand, were cast in silicone and connected to syringes so that visitors could actuate them. While in design research we are most used to creating new things or improving them, experiencing the process of "reproducing" samples brought us different insights about the situatedness of sample making. We place "reproduce" here between quotation marks because, as Ingold points out, no two steps are the same (Ingold 2010). The final outcomes were highly reproducible because the embroidery files were the same, but everything else was slightly changed. Unlike in the original set, we embroidered all new samples in the same color for uniformity. The machine was working sometimes better, sometimes worse than before. There were different people in the lab asking us questions about digital machine embroidery, what were we doing or how long it would take before they could use the machine. Receiving questions about embroidery while making them was particularly interesting as it supported us in looking at our samples from new perspectives to use them as answers. This way, recreating the samples allowed us to deepen our appreciation of the technical attributes of the embroidery and, more importantly, our understanding of sample making.

Such samples do not only present a high level of fidelity of look and feel in relation to interaction capabilities. Samples are open ended products with specific properties and behaviors. They are instantiations of the socio-technical systems of production. While their properties are concrete, their meaning is open for change through negotiations with and within a given context (Bergström et al. 2010). To us, this understanding of samples as becoming materials does also relate to how we should allow our work to be revisited. As designers who learn through making, the insights we gain from experiments are also situated in the level of experience we have with the production systems we interact with and the motivation that drives our process at a given time. As such, we propose separating the objects of design, the samples, from our design journey to allow ourselves to come back to them for new negotiations.

To explore further this possibility, we invited a fashion design researcher, specialized in wearable technology for a creative analysis session. In the session, we used the embroidered inflatable samples to discuss possibilities of designing interactive garments that included our actuators. A vest with three integrated embroidered inflatables (Interaction Mode 3 designs), one on each shoulder and one on the lower back, was also used in the session as a starting point. Both sets of samples were present but mostly the original set was used because the samples could be easily taken out of the binder where they were stored to be manipulated. This meant that the original ordering of items in a series became irrelevant during the session. Instead, they were all seen as a wide collection and samples were analyzed based on emerging questions.

The session included two parts. The first part was an embroidery workshop to explain the techniques used to create the samples. The second part was a discussion of possible applications and the possibilities of designing garments from the samples (bottom up

Figure 9
Samples used to discuss actuation and expressiveness. The three samples demonstrate three different active behaviors (a) Multi-state inflation, (b) symmetrical inflation, (c) Unilateral inflation.

approach). To allow unexpected topics to arise, we let her take the lead of the discussion to ask things she felt that she needed to know in order to ideate with and from the samples.

Her questions related to four main topics: actuation and expressiveness, color, layering of materials over the inflatables and transitions between materials (from embroidered substrates to other textiles). We detail the new opportunities that emerged through discussions in each of these topics below.

3.1.1. Actuation and Expressiveness

Most discussion points about actuation and expressiveness related to understanding the possibilities of designing the inflatables through digital machine embroidery. Questions on this topic included what the size and shape limitations of the inflatables were and how the airways could be integrated. These questions could be easily answered through our samples (Figure 9) because this topic was directly related to challenges addressed during the process of making them. An interesting point that emerged from this session was what other possible functions could the actuators serve in wearables other than pushing against the body: "Is it an option to create active behaviors on the garments through this technique?" To create push against the body, the fit of a garment should be tight. Looking at creating active behaviors on the garment instead opened up a different view on possible silhouettes that could integrate the actuators. Consequently, a new perspective on the drapability of the samples emerged as a direction to explore. Some features like the shape, the density of embroidery, the direction of the embroidery and the thickness of the silicone could contribute to a higher malleability of the resulting inflatables.

3.1.2. Color

We were not concerned with color during the creation of the original samples. We only made active decisions on color for the exhibition, opting for white for the sake of uniformity and to highlight the

Figure 10
Sample 2.2 recreated Flow. The color changed significantly after casting, particularly on the denser areas.

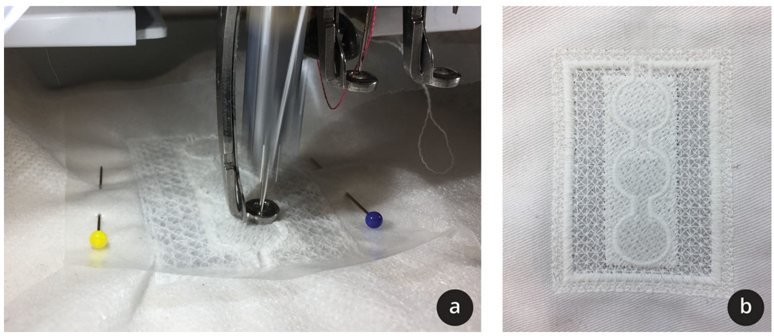

Figure 11
We used layering in many of our samples. (a) To create Interaction Mode 3, we layered sheets of water-soluble stabilizer in between different stages of the embroidery. (b) This sample was made by layering embroidery under the inflatable area to direct the inflation and appliquéing the water-soluble film to determine the inflatable shape.

embroidery attributes. From the perspective of the fashion designer, however, knowing “What is the impact of the silicone and the embroidery in color? Are there restrictions?” was essential to guide a bottom-up process of designing a garment from the samples. A few of the samples in the original set were embroidered in different colors. Therefore, we could analyze the effect of the silicone over the thread color by comparing the bright yellow and white samples with darker pink ones. While the bright colors seemed unchanged under the silicone, darker shades changed significantly, as seen in a sample from series 2 (Figure 10). The density of the embroidery and the thickness of the silicone also had an impact on color: the denser the embroidery or the thicker the silicone layer, the more it darkened the color. This could be used as a feature by exploring how to blend colors

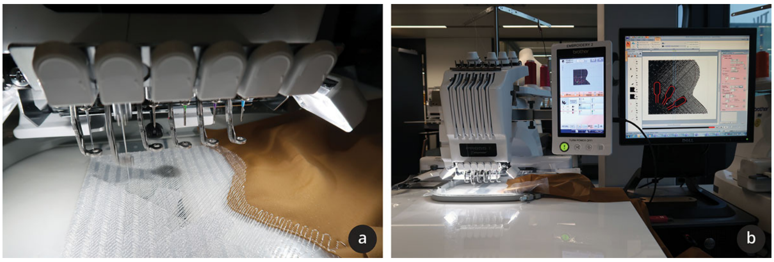

Figure 12
Inspired by lace and lingerie, a new opportunity of combining the embroidered substrate and other materials emerged from samples of series 5 and Interaction Modes.

through embroidery gradations as well as through varying silicone thickness.

3.1.3. Layering of Materials over the Inflatables

In our work, we overlayed embroidered designs and materials to create specific properties and actuation behaviors, such as the behaviors seen in Interaction Modes 1 and 3 (Figure 11). Although layering techniques were fundamental to design our samples, in our process we had not considered how layering could be used to change the surface of the inflatables. For the fashion designer, knowing whether it was possible to cover the silicone could open up opportunities for making decisions on concepts for application and look & feel of the inflatables: “Is it possible to cover the silicone? Say, add a liner for comfort or an outside material in case I do not wish the silicone to be visible?.” Although we knew that layering could be used in multiple ways, including embedding or appliquéing extra materials, this helped us realize that the technique could be used to add lining, texture or other effects to the samples.

3.1.4. Transitions between Materials

The question about the transition between materials pertains to fit. We explored fit in sample series 2 (Figure 10), in which the full form factor of Flow was recreated. From those samples, we knew that one interesting direction to explore was to manipulate locally the fabric character of the embroidery and so create properties like stretch in parts of the wearable for improving fit. During the session, an alternative approach emerged. Looking at the vest as an example, she suggested that “for a more forgiving fit, the side panels of the vest could be stretchable." The samples created in series 5 demonstrated that we could achieve a robust integration between embroidered substrates and other textiles, both woven and knitted. However, these transitions only included straight lines. To explore a more organic and subtle transition, we created an extra sample together (Figure 12). In this sample, we already began to move towards a new direction to explore the delicate qualities of lace and transitions between lace and other textiles as seen in garments such as lingerie.

Through this session, we could demonstrate how samples can potentially be appropriated to open up new opportunities. As potential new directions, we identified opportunities of appropriating our samples, including: searching for qualities of drape; creating blends of color through the combination of silicone and thread; applying our layering for other ends such as lining to garments; and further exploring the delicate quality of our substrates.

3.2. Strategies

In design research processes we tend to treat our understanding of experiments as permanent and conclusive. In this view, an experiment is a failure when it does not offer us a direct way of progress towards our goal and it can therefore be discarded. In such an approach, new findings come from making other things towards new goals. Embracing ambiguity as a resource (Gaver, Beaver, and Benford 2003), the traveler approach sees that "the finding of new things also means looking at old things with new perspectives" (Goveia da Rocha and Andersen 2020). This means that instead of discarding samples that deviate from a given goal, they can be left as open opportunities for drifting (Krogh and Koskinen 2020) towards future journeys. To enable this, we need to explore strategies that support us in preserving encountered opportunities. Through our experience with the Embroidered Inflatables, we found that considering how we document and present our samples is key to ensuring they can be seen as open opportunities.

3.2.1. Documenting Samples

The process of sample making through digital fabrication tools presents a challenge of decentralization of data over all the socio-technical systems of production. The knowledge created from making a sample is divided between the experience of making, the digital file, the hardware we use, the post-production and our interactions with the samples. To appropriate a sample in a new journey, we need all of this data to be accessible. Therefore, we see the integration of data as a key factor of allowing samples to outlive the processes that create them.

As previously stated, emergent questions lead our process of making the Embroidered Inflatables. Considering that we did not know which samples would turn out to be the most interesting or when we would return to them, the likelihood that we would have forgotten the details of how a sample was made was high. To support this, we kept a spreadsheet with very detailed documentation of the samples. The format we used recorded data from a) the design journey, b) the software and hardware technical specifications, and c) our experience with the sample. During the process of making, we mostly used this documentation to reflect on our design journey, registering what happened with each sample and what could be done next. Later, the documentation also helped in identifying correlations between sewing attributes and material properties or active behaviors of the samples.

Integrating the data about each sample helped us develop a sensitivity about the relationships between materials, digital assets, and the machine that is necessary to appreciate what each sample is or can do. It allowed us to see the motivations and interpretations that carried us through our design journey, while preserving the details of how they are made and what they can do (properties and behaviors) in a way that allows for appropriation and new interpretations.

Documenting the design process can be time-consuming (Dalsgaard and Halskov 2012). Further investigation on the ways of documenting samples should be conducted to allow for as much data to be collected and centralized without overburdening designers.

3.2.2. Presenting Samples

The way we present or store our samples carries an impact in their actionability. Our sample series were presented in two formats: a binder used to store all the samples with their corresponding documentation and annotations; and six acrylic displays that showcased the five-sample series and the Interaction Modes series. On its own, the binder emphasizes the apparent linearity of the process, supporting the telling of a story of how we succeeded in achieving our goal. The exhibition displays, on the other hand, puts all samples at the same level of importance, supporting an overview of the design process.

Throughout our new analysis of our work, we began to explore these formats as ways of supporting revisiting samples. We found that it is important to create ways to reach the samples (the material and the documentation) both individually and within collections. Collections help us in identifying similarities and differences between samples but also gaps of opportunity regarding topics that we have not yet contemplated. Engaging with samples individually supports us to reinvestigate them, leading us towards engaging with other aspects of the socio-techno system of production they embody.

In our process, we dealt with samples as a collection, sub-collections (each sample series) and as individuals. We imagine that collections should expand beyond a single project to embrace an entire body of work, open to being revisited. For that to work, we should be able to easily access material samples and their documentation.

4. Conclusions

Inspired by the streams of thought in design research that aim to create a broader context for design research processes, we have presented a perspective on samples in Research through Design. This perspective builds on ideas presented by the travelers' approach, which proposes that not only the experiments that fit coherent stories should be valued. Seeing each sample as instantiations of socio-technical systems of production, valued for what it is and does, supports us in keeping samples open to potentially kick off new processes.

We developed this through a description of the sample making process of the Embroidered Inflatables and with our reflections on the strategies that enable the revisiting of samples to answer new questions. Suggested strategies included integrating the data about a sample into a single form of documentation and dealing with samples individually as well as in collections.

In our session with a fashion designer, examining samples for what they were and could do supported us in identifying opportunities for other design journeys. While the limitations and implications of taking this approach to samples still need to be explored further, we believe this approach offers the possibility of fostering different relationships with samples within and across projects. Further work in this direction should seek to further specify the characteristics of such samples and investigate documentation formats.

Lastly, we recognize the need for deepening our understanding of the moments when this approach may work. Our samples did lend themselves to the possibility of being revisited, and arguably, this happened because they are material samples, which makes it easier to disconnect them from their original contexts. In addition to this, with the exception of series 2, our samples did not have form factors that connected them to a particular use. This may have facilitated us in playing with them to find interesting qualities to be explored elsewhere. Can other types of prototypes, constructed for specific application contexts, also be easily treated this way? In the future development of this approach, it would be valuable to explore whether research products (Odom et al. 2016), prototypes of high level of fidelity and finish, can be treated in the same way as our samples.

Funding

This work is part of the i2-CoRT project, being carried out within the context of Interreg V-A Euregio Meuse-Rhine from the European Regional Development Fund.

ORCID

Daniel Tetteroo http://orcid.org/0000-0002-2295-5022

References

Aigner, R., Pointner, A., Preindl, T., Parzer, P., and Haller, M. 2020. "Embroidered Resistive Pressure Sensors: A Novel Approach for Textile Interfaces." In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (CHI'20). Honolulu: ACM.

Andersen, K., Wakkary, R., Devendorf, L. and McLean, A. 2019. "Digital Crafts-Machine-Ship: Creative Collaborations with Machines," *Interactions*, *27*: 30–35.

Bergström, J., Clark, B., Frigo, A., Mazé, R., Redström, J. and Vallgårda, A. 2010. "Becoming Materials: Material Forms and Forms of Practice," *Digital Creativity*, 21(3): 155–172.

Ceron, S., Cohen, I., Shepherd, R., Pikul, J., Harnett, C., Ceron, S., Cohen, I., Shepherd, R.F., Pikul, J.H. and Harnett, C. 2018. "Fiber Embroidery of Self-Sensing Soft Actuators," *Biomimetics*, 3 (3): 24.

Dalsgaard, P., and Halskov, K. 2012. "Reflective Design Documentation." In *Proceedings of the Designing Interactive Systems Conference - DIS '12*, 428–437. Association for Computing Machinery.

de la Bellacasa, M.P. 2017. *Matters of Care*. Minnesota: University of Minnesota Press.

Delazio, A., Nakagaki, K., Klatzky, R.L., Hudson, S.E., Lehman, J.F., and Sample, A.P. 2018. "Force Jacket." In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*, 1–12. New York: ACM Press.

Dongen, P. V., Wakkary, R., Tomico, O. and Wensveen, S. 2019. "Towards a Postphenomenological Approach to Wearable Technology through Design Journeys." In *Proceedings of the 2nd International Conference Textile Intersections 2019*. London: Loughborough University.

Du, J., Markopoulos, P., Wang, Q., Toeters, M., and Gong, T. 2018. "ShapeTex." In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '18*, 166–176. New York: ACM Press.

Dunne, L.E., Ashdown, S.P. and Smyth, B. 2005. "Expanding Garment Functionality through Embedded Electronic Technology," *Article Designation: Refereed JTATM*, 4 (3): 1–11.

Ehn, P. 2008. "Participation in Design Things." In *Proceedings of the Tenth Anniversary Conference on Participatory Design 2008*, 92–101. Indiana University.

Frauenberger, C. 2020. "Entanglement HCI The Next Wave?," *ACM Transactions on Computer-Human Interaction*, 27 (1): 1–27.

Galloway, A. 2007. "Seams and Scars, or How to Locate Accountability in Collaborative Work." In C. Brickwood, B. Ferran, D. Garcia, and T. Putnam (eds.) *Uncommon Ground*. Amsterdam: BIS Publisher.

Gaver, W. 2012. "What Should We Expect from Research through Design?" In *Conference on Human Factors in Computing Systems - Proceedings*. New York: Association for Computing Machinery.

Gaver, W., Beaver, J., and Benford, S. 2003. "Ambiguity as a Resource for Design." In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '03)*, 233–240. New York: Association for Computing Machinery (ACM).

Gilliland, S., Komor, N., Starner, T., and Zeagler, C. 2010. "The Textile Interface Swatchbook: Creating Graphical User Interface-like Widgets with Conductive Embroidery." In *International Symposium on Wearable Computers* (ISWC) 2010, 1–8. IEEE.

Goveia da Rocha, B., and Andersen, K. 2020. "Becoming Travelers : Enabling the Material Drift." In *DIS '20 Companion*, 215–219. Eindhoven: ACM.

Goveia da Rocha, B., and Tomico, O. 2019. "Flow: Towards Communicating Directional Cues through Inflatables." In *Proceedings of the 2019 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI '19*. New York: ACM.

Goveia da Rocha, B., Tomico, O., Markopoulos, P., and Tetteroo, D. 2020. "Crafting Research Products through Digital Machine Embroidery." In *DIS '20: Proceedings of the 2020 ACM on Designing Interactive Systems Conference*, 341–350. Eindhoven: Association for Computing Machinery.

Goveia da Rocha, B., Tomico, O., Tetteroo, D. and Markopoulos, P. 2019. "Inflatable Actuators Based on Machine Embroidery." In *Proceedings of the 2nd International Conference Textile Intersections 2019*. London: Loughborough University.

Goveia da Rocha, B., van der Kolk, J.M.L. and Andersen, K. 2021. "Exquisite Fabrication: Exploring Turn-Taking between Designers and Digital Fabrication Machines." In *CHI '21: CHI Conference on Human Factors in Computing Systems Proceedings*. Yokohama, Japan: Association for Computing Machinery.

Hamdan, N. A-h., Voelker, S., and Borchers, J. 2018. "Sketch&Stitch: Interactive Embroidery for E-Textiles." In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*, 1–13. New York: ACM Press.

Haraway, D. 2016. *Staying with the Trouble: Making Kin in the Chthulucene*. North Carolina: Duke University Press.

"Hexoskin Health Sensors & AI". 2019. Accessed June 6. https://www.hexoskin.com/.

Ingold, T. 2010. "The Textility of Making," *Cambridge Journal of Economics*, 34: 91–102.

Ingold, T. 2017. *Correspondences*. University of Aberdeen. https://knowingfromtheinside.org/files/correspondences.pdf.

Krogh, P.G., and Koskinen, I. 2020. *Drifting by Intention: Four Epistemic Traditions from within Constructive Design Research*. Cham, CH: Springer International Publishing.

Krogh, P., Markussen, T. and Bang, A.L. 2015. "Ways of Drifting – 5 Methods of Experimentation in Research through Design," ICoRD'15 International Conference on Research into Design, 34: 641–651.

Linz, T., Gourmelon, L. and Langereis, G. 2007. "Contactless EMG Sensors Embroidered onto Textile." In S. Leonhardt, T. Falck, and P. Mähönen (eds.), *4th International Workshop on Wearable and*

Implantable Body Sensor Networks (BSN 2007), 29–34. Berlin: Springer.
Linz, T., Vieroth, R., Dils, C., Koch, M., Braun, T., Becker, K.F., Kallmayer, C. and Hong, S.M. 2008. "Embroidered Interconnections and Encapsulation for Electronics in Textiles for Wearable Electronics Applications," *Advances in Science and Technology*, 60: 85–94.
Markopoulos, P., Wang, Q., Tomico, O., Goveia da Rocha, B., ten Bhömer, M., Giacolini, L., Palaima, M. and Virtala, N. 2020. "Actuating Wearables for Motor Skill Learning: A Constructive Design Research Perspective," *Design for Health*, 4(2): 231–251.
Mecnika, V., Hoerr, M., Krievins, I., Jockenhoevel, S. and Gries, T. 2014. "Technical Embroidery for Smart Textiles: Review," *Materials Science. Textile and Clothing Technology*.*9*, 9: 56–63. doi:10.7250/mstct.2014.009.
Morgan, L., Winters, A., O'Nascimento, R., and Wood, S., eds. 2019. *INTERSECTIONS: Collaborations in Textile Design Research Exhibition*. London. www.textile-intersections.com.
Nachtigall, T.R. 2019. "Materializing Data". PhD diss., Technische Universiteit Eindhoven.
Odom, W., Wakkary, R., Lim, Y-K., Desjardins, A., Hengeveld, B., and Banks, R. 2016. "From Research Prototype to Research Product." In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*, 2549–2561. New York: ACM Press.
Ou, J., Skouras, M., Vlavianos, N., Heibeck, F., Cheng, C.-Y., Peters, J., and Ishii, H. 2018. "AeroMorph – Heat-Sealing Inflatable Shape-Change Materials for Interaction Design," ACM. Accessed September 6.
Oxman, N. 2007. "Digital Craft: Fabrication-Based Design in the Age of Digital Production." In *Workshop Proceedings for Ubicomp 2007: International Conference on Ubiquitous Computing*, 534–538. Innsbruck, Austria.
Post, R., Orth, M., Russo, P. and Gershenfeld, N. 2000. "E-Broidery: Design and Fabrication of Textile-Based Computing," *IBM Systems Journal*, 39 (3.4): 840–860.
Raitor, M., Walker, J.M., Okamura, A.M., and Culbertson, H. 2017. "WRAP: Wearable, Restricted-Aperture Pneumatics for Haptic Guidance." In *Proceedings - IEEE International Conference on Robotics and Automation*.
Redström, J. and Heather, W. 2019. "Changing Things: Innovation through Design Philosophy." In *Academy for Design Innovation Management Conference*. London.
Rudström, Å., Höök, K. and Svensson, M. 2005. "Social positioning: Designing the Seams between Social, Physical and Digital Space". In *First International Conference on Online Communities and Social Computing*, at HCII 2005, 24–27 July 2005, Las Vegas, USA.

Rutkowska, J., Visser, F.S. and Lamas, D. 2019. "Towards Actionable Forms of Communicating and Sharing Design Knowledge." In *EKSIG 2019: Knowing Together – Experiential Knowledge and Collaboration*, 252–277. Tallin, Estonia: Estonian Academy of Arts

Scrivener, S. 2000. "Reflection in and on Action and Practice in Creative-Production Doctoral Projects in Art and Design," *Working Papers in Art and Design*, 1 (1). Retrieved on 2020-10-08 from https://www.herts.ac.uk/__data/assets/pdf_file/0014/12281/WPIAAD_vol1_scrivener.pdf

"Sensoria Fitness". 2019. Accessed April 1. http://www.sensoriafitness.com/.

Tomico, O. and Wensveen, S. 2014. "Crafting a Culture of Prototyping." *Crisp Magazine #3 "Fake It/Make It,"* May. https://issuu.com/crispnl/docs/crisp__3_-_fake_it_make_it_-_issuu/40.

Wensveen, S., and Matthews, B. 2015. "Prototypes and Prototyping in Design Research." In J. Yee and P.A. Rodgers (eds.) *The Routledge Companion to Design Research*, 14th ed., 262–276. Abingdon: Routledge.

Wiberg, M. 2018. *The Materiality of Interaction: Notes on the Materials of Interaction Design*. Cambridge, MA: The MIT Press.

Wiberg, M., Ishii, H., Dourish, P., Vallgårda, A., Kerridge, T., Sundström, P., Rosner, D. and Rolston, M. 2013. "Materiality Matters–Experience Materials," *Interactions*, 20(2): 54.

Yao, L., Niiyama, R., Ou, J., Follmer, S., Della Silva, C., and Ishii, H. 2013. "PneUI." In Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology - UIST '13.

Zeagler, C., and Clint, C. 2017. "Where to Wear It." In *Proceedings of the 2017 ACM International Symposium on Wearable Computers - ISWC '17*, 150–157. New York: ACM Press.