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GRADUATION MASTER THESIS

EXPLORING ANIMATED TEXTILES USING PNEUMATIC ACTUATORS: TOWARDS A TOOLKIT

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Project

Exploring Animated Textiles Using Pneumatic Actuators:
Towards a Toolkit

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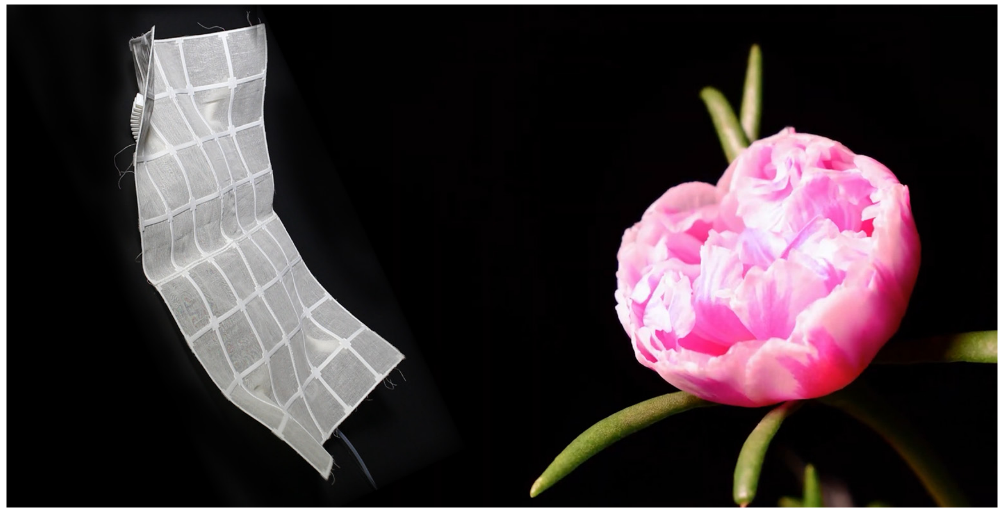

EXECUTIVE SUMMARY

This project explores how 3D printed pneumatic soft actuators can be used to enhance the expressiveness of textiles with alive-like movement. The research begins by studying current literature on shape changing materials and interfaces in order to select the best candidate material to explore during the project. The project then uses a material driven approach to characterize the 3D printed pneumatic textiles for enhancing their performance and ease of fabrication. Based on the characterization, a material concept is created to showcase the material qualities found during the research and to help study the material experience of shape changing interfaces in future research.

As a result of the research, we introduce **Textalive: The Animated Textile Toolkit**, a fully 3D printed approach to explore shape changing interfaces and alive-like expressions including its hardware augmented by the computational tool. The toolkit uses accessible 3D printed pneumatic actuators commonly used in soft robotics due to their controllability and ease of fabrication compared to other shape changing materials. The 3D printed pneumatic actuators can be arranged along a 3D printed textile composite to create a variety of shape morphologies. The hardware allows the user to control the kinetic parameters of the movement of the textile to create different expressions. Additionally, the computational design tool allows the designer to predict the shape and movement of the textile by digitally varying the location of the actuator. The toolkit was validated with various designers ranging from different levels of expertise with smart materials showing its potential as a design tool for easily exploring shape changing interfaces and alive-like expressions.

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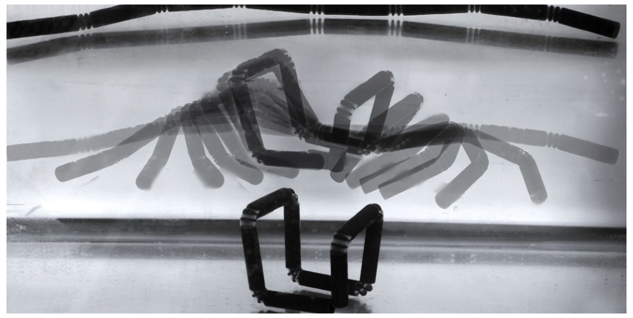
This chapter shows an overview of humanity's fascination with motion and shape change and explores the individual parameters that affect how shape change is perceived and experienced. Based on literature findings, a connection between shape changing materials and material experience research is made followed by the material guidelines needed to properly study shape change from a material experience perspective.



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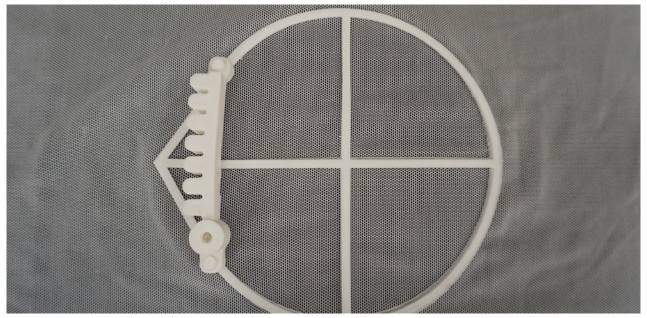

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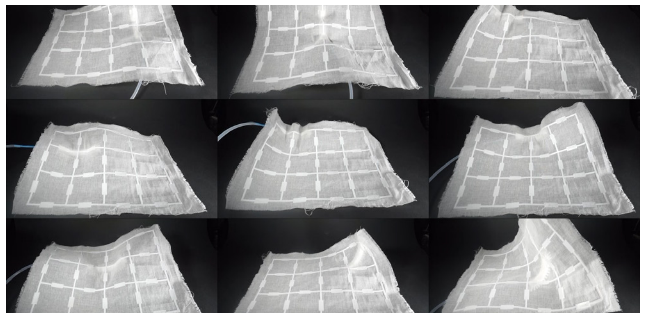

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This chapter brings together the findings from the literature review, material tinkering, and technical characterisation to create a material vision and product concept that best suits the material studied. Additionally, this section presents an overview of the material qualities and material benchmark showcasing other applications of shape changing materials.

8. CREATING THE TOOLKIT

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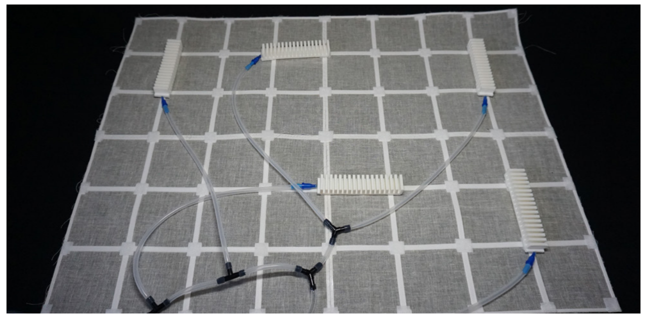

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In order to validate the toolkit as an aid for designers to explore shape changing interfaces, a user study was conducted to understand how users explore shape change with the toolkit, the types of applications that they create, and the material experience of interacting with shape changing interfaces.

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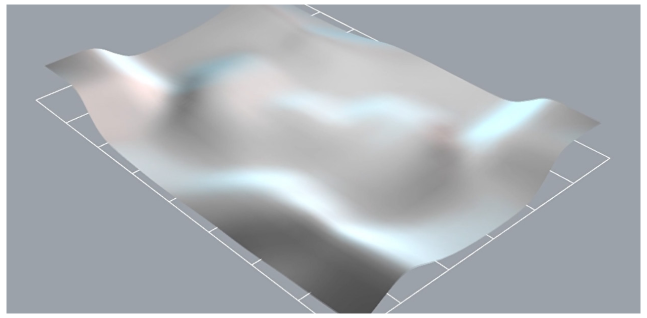
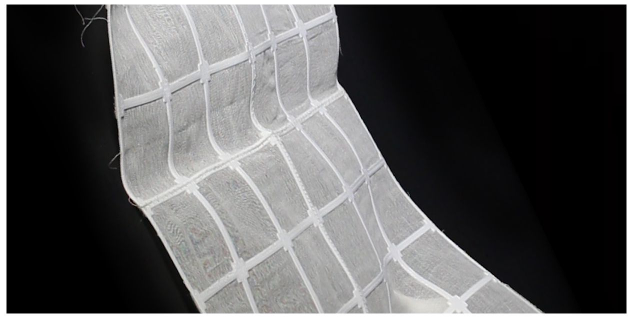
To enhance the toolkit, a computational simulation of the forms created with Textalive was created. This chapter explains the programming behind the simulation to aid future designers in recreating the results and compares the simulated forms with the physical prototype as a means of validating the simulation tool.





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As a finale to the project, this chapter concludes with final remarks on the desirability, feasibility, and viability of the project followed by future recommendations in studying shape changing interfaces. Finally, a short personal reflection is included alongside a thank you message to all the people involved with the project.

CHAPTER **ONE**

INTRODUCTION

This chapter introduces the project by explaining the motivation for studying shape changing interfaces. This is followed by an explanation on the approach and methodologies used throughout the design process and finishes with an overview of the research questions studied alongside a breakdown of the thesis report.

1.1 PROJECT DESCRIPTION

Motivation

Our current digital world is filled with interfaces and screens that push us to interact with our environment in unfamiliar ways. In contrast to this, our natural world is full of complex shape changes and alive movements that humans are naturally attracted to. New interfaces using shape changing materials show promise in creating more interactive, engaging systems with our environment. Current shape changing research focuses heavily on the technical and functional aspects of these materials yet understanding how people perceive and experience these new interfaces is critical to their success. Understanding the qualities that make a shape changing material feel alive could be the key to unlocking their true potential as a design material. Therefore, this project explores how we can aid the exploration of livingness in shape changing materials in the design field.

Approach

Understanding livingness in shape changing interfaces is a rather broad question to ask and must be broken down into smaller pieces to be approached udring a design project. For this reason, the project was broken down into a material driven design project where a selected shape changing material would be explored with the goal of creating props or a final prototype that could be used to test the material experience of livingness with user evaluation studies. Figure 1 shows a breakdown of the process taken during this design project.

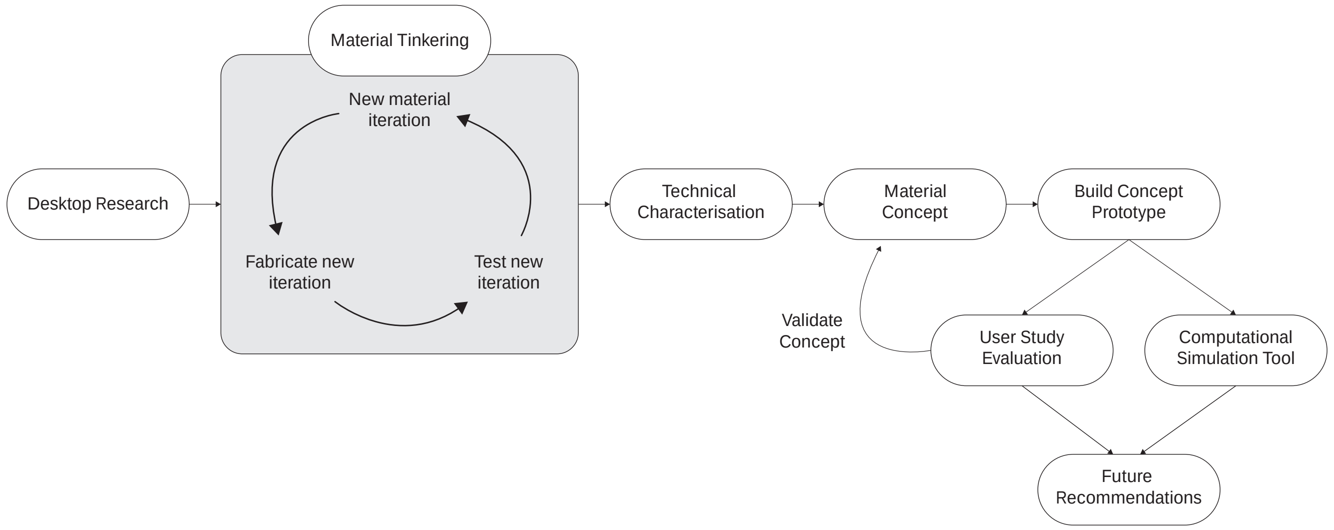


Figure 1
Personal approach to the project

1.2 METHODOLOGY

This project uses the Material Driven Design method as its main methodology with some slight modifications (Karana, Barati, Rognoli, & Zeeuw van der Laan, 2015). The Material Driven Design method is a methodology used to explore the design possibilities of a material beyond only the technical characteristics (Fig. 2). The method additionally explores the experiential qualities of a material and how it compares to other current materials. This method is best utilized with novel materials to bring out their unique qualities in interesting future applications. By combining the technical qualitieis, experiential qualities, and material benchmarking of a novel material, a material vision and concept are created to showcase the possibilities of the material. Due to technical difficulties with the material studied, the experiential qualities were not studied prior to the material concept being developed, but are studied in the user evaluation using the final material prototype.

Additionally, this project explores how computational design methodologies can be used to aid in the design of shape changing materials. Computational design refers to the use of computational methods to digitally aid in design decisions or to aid in simulating material behavior in a virtual environment. In the research of programmable materials, designers use perceived material behavior observed in the real world and translate it into the digital environment to further explore material possibilities without the need of prototyping. These new digital tools can then help designers in making novel complex design. The initial aim of this project was to use computational design to program the material behavior during the design of the material concept. Due to the modular design direction taken during the design process, computational design is instead use in this project to validate the concept design through simulations and show the material's programmable potential for future contexts.

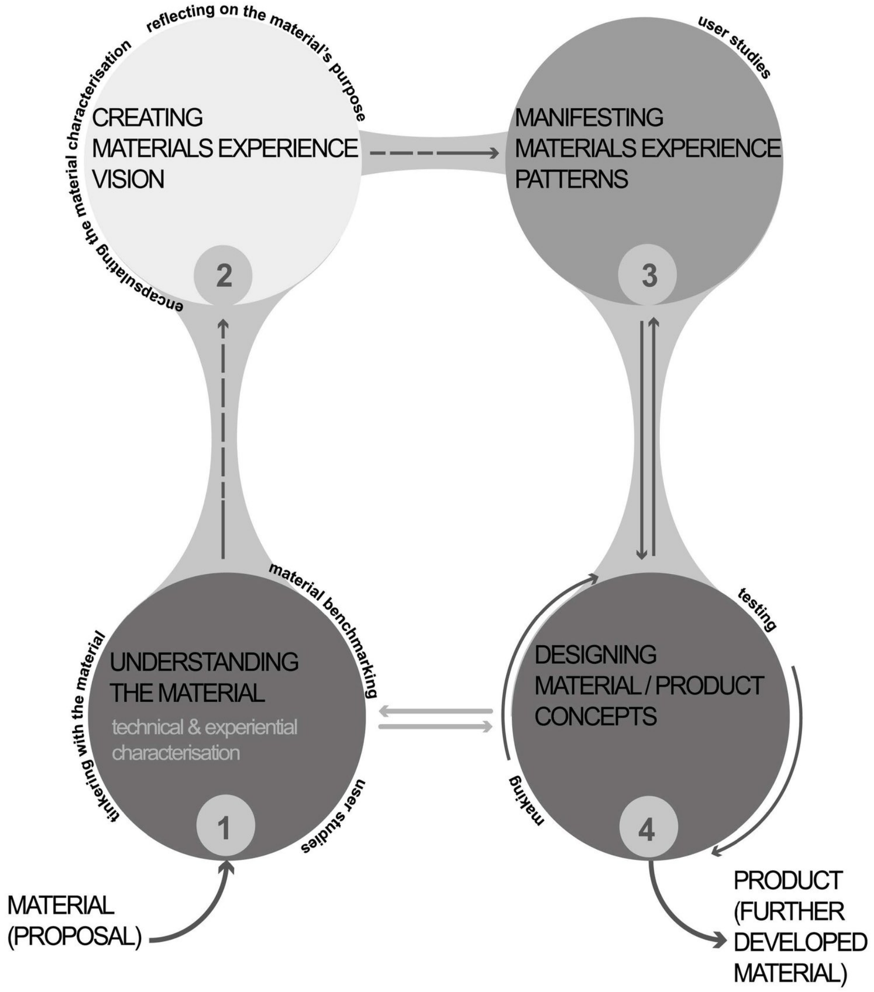


Figure 2
Material Driven Design Methodology (Karana et al., 2015)

1.3 RESEARCH QUESTIONS

The research questions of the project serve as the driving force of this project. At the top, you find the high-level questions. These are questions that inspired the journey of the project yet can only be partially answered due to their broad scope. At the bottom, you find the low-level questions, which are the questions that needed to be answered in this project to get one step closer to understanding livingness in shape changing interfaces.

The low-level questions were created during the process of material driven design as a response to the iterative process of material exploration and tinkering. Through the project, it was found necessary to break down the problem into these smaller, approachable pieces to ease the process. Understanding livingness is a big question that will require many future studies be performed, and this project aims to be a start to this research.

High level questions

How does the spatial-temporal form of shape-changing interfaces affect the material experience of livingness?

How can design facilitate the exploration of livingness in shape changing interfaces?

What are the material experience qualities of 3D printed pneumatic textiles?

How can we best combine 3D printed pneumatic actuators and 3D printing on textiles to explore shape changing interfaces?

How can we best fabricate air tight 3D printed pneumatic actuators to create a shape changing material?

Low level questions

1.4 THESIS STRUCTURE

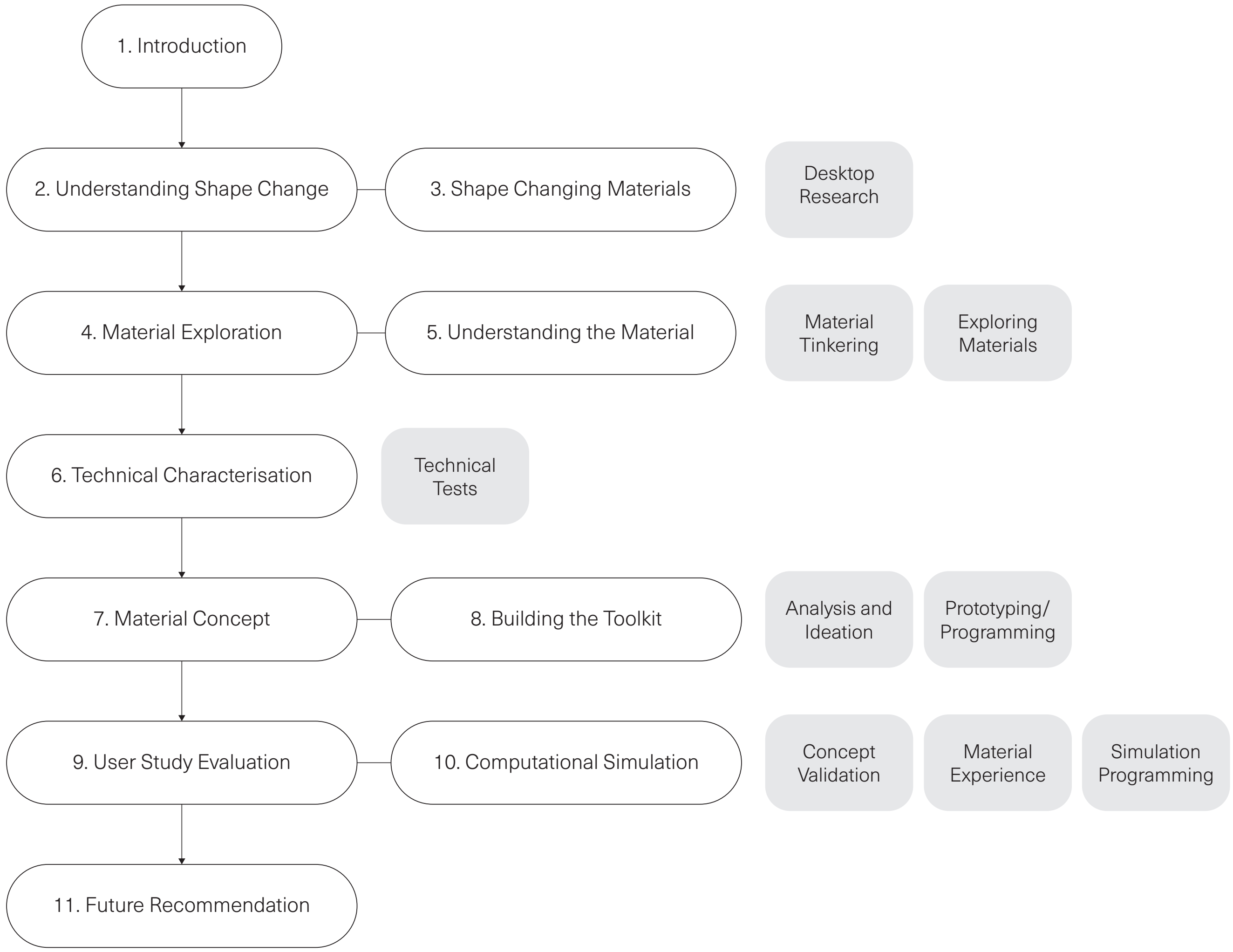


Figure 3
Overview of thesis structures

CHAPTER **TWO**

UNDERSTANDING SHAPE CHANGE

This chapter shows an overview of humanity’s fascination with motion and shape change and explores the individual parameters that affect how shape change is perceived and experienced. Based on literature findings, a connection between shape changing materials and material experience research is made followed by the material guidelines needed to properly study shape change from a material experience perspective.

2.1 EXPRESSIVENESS OF MOVEMENT

People have a deeply rooted connection to movement bringing about a quality of livingness that creates a stronger and deeper emotional response during interaction (Parkes, Poupyrev, & Ishii, 2008). Our artificial world is rather static when compared to the vibrant, ever changing natural environment. Throughout history, artists and designers have been fascinated with bringing this quality of movement to our artificial creations as can be seen in the work of Alexander Calder's captivating mobiles (Fig. 4) or Studio Ini's immersive kinetic architecture pieces (Fig. 5). Alexander Calder's mobiles invite interaction from the audience, moving in response to the user and producing motion that is always changing and unique depending on the interaction. Studio Ini's Urban Impact installation questions the need of us humans to constantly adapt to our static environment. Urban Impact displays a physical environment that instead changes shape and adapts to the motion and action of the human presence (Fig. 5).

Both these examples of movement and shape change in our material world display two important expressive qualities of shape change: uniqueness in interactions and adaptiveness. Shape changing interfaces have the potential to create more compelling continuous interactions in the short term and more engaging behaviors that adapt to user's needs and trends in the long terms when compared to static interfaces (Kwak & Frens, 2015). The behavior of shape changing interfaces are often designed as an afterthought, focusing instead on the technical or functional qualities of the material. This approach misses the potential opportunities that expressive movement qualities can have on user interaction.

Figure 4
Rouge Triomphant mobile by Alexander Calder

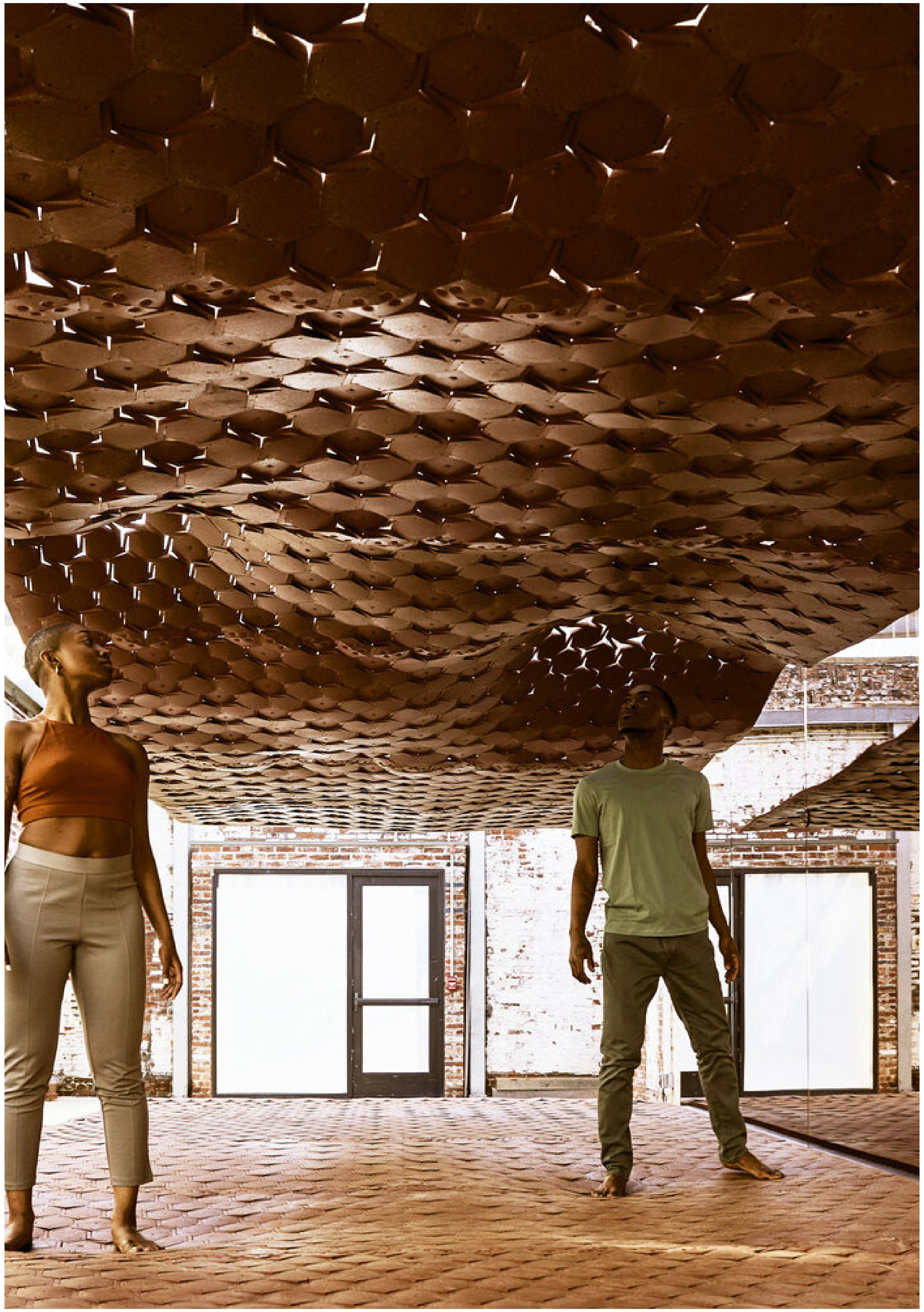


Figure 5
urban Impact by Studion Ini

Figure 6
Bloom of a flower in response to light stimuli by NextObserver

Shape Change in Nature

Nature is the original engineer of shape changing materials. From the unpredictability and delicacy of a flower slowly opening up its petals during the sunny season (Fig. 6) to the rapid, snapping movement of a venus flytrap closing itselft to trap its next prey, shape change is one of the vital forces allowing natural materials to adapt to its environment. Many of these shape changes are triggered by natural phenomenom or environmental stimuli such as heat, water, light, and many others. This ability for a material to react to its surroundings have inspired scientist to research for novel, shape changing materials that are able to react to their environemnt in the way natural materials can. Whether this be biodesigners directly using living materials that can respond to their environment or material researchers exploring artificial materials that share these unique qualities, having shape change be part of our material world can allow for more responsive and unique interactions not possible with today's products. As our material world begins to take more and more inspiration from nature to the point of mimicking its shape changing abilities, it raises the question:

Can livingness be used in product design as a material quality to enhance our interaction with the material world?

Figure 7
Shylight by Studio Drift

Livingness as a Material Quality

In the publication Still Alive, Prof. Dr. Elvin Karana poses the question "what if livingness was a quality of everyday artefacts?" (Karana, 2020). Designers have always been inspired by living materials and the natural environment to create "alive-like" expressions that have superior artistic and functional performance over conventional design. Projects such as Studio Drift's Shylight take direct inspiration from the circadian rhythm of plants in response to changes in light called nyctinasty (Fig. 7). Shylight mimics this movement through a flower-like textile that opens and closes similar to the movement of real flowers. This concept of livingness has been applied in other thesis projects in the faculty such as mimicking the locomotion of caterpillars using SMAs and 3D printed textiles (Atmopawiro, 2019) and creating a soft robotic fish with bio-inspired movement to improve swimming performance underwater (van den Berg, 2019). The quality of livingness in these shape changing materials is a highly complex parameter that is often sought after through biomimicry. Toolkits such as Morphino have been proposed to aid designers in bringing living qualities into shape changing interfaces by mimicking movements and forms found in nature (Qamar et al., 2020). From a design perspective, livingness in shape changing interfaces is governed by multiple spatial-temporal parameters that in turn define the expressive qualities the material evokes. The grand challenge in this research project is to identify how the parameter of shape changing interfaces affect the experience of livingness the material.

2.2 PARAMETERS OF SHAPE CHANGING INTERFACES

Shape changing interfaces in the HCI field are defined by three parameters:

spatial
kinetic
expressive

This section will focus on presenting the work of Rasmussen et al. on shape changing parameters and comparing and expanding on it using other research in the shape changing and material experience field.

The spatial parameters include the various shape morphologies that are achievable by the shape changing material. Kinetic parameters influence the movement in time of the interface and include variables such as velocity, path, direction, and space. Expressive parameters relate to the way people express their experience with shape changing interfaces such as descriptive adjectives or associations (Rasmussen, Pedersen, Petersen, & Hornbaek, 2012).

Spatial Parameters

One of the unique qualities of shape changing interfaces is their ability to transform into different shapes during use, e.g. changing from a 2D sheet to a 3D volume. Rasmussen et al. propose an overview of the different types of shape change morphology possible in the field of user interface design (Fig. 8). Depending on the material studied, the possible shape changes will be limited by constraints of the material. For example, MIT projects PneUI and Aeromorph defined the possible shape morphologies for pneumatic interfaces as limited to orientation, form, volume, and texture. The PneUI project classified the basic types of shape changes that it was able to achieve with its composite proposed design (Fig. 9) (Yao et al., 2013). Aeromorph then expanded the vocabulary of shape change possible by pneumatic actuation by additionally adding self-assembly shape changes such as folding and popping with their novel inflatable fabric origami-like concept (Ou et al., 2016).

The effect shape morphology has on the experience of interaction and livingness remains a subject to be explored. A repertory grid study has been conducted on the experience of shape changing interfaces using changes in form, orientation, volume, and texture (Hornbaek, Bruns Alonso, Kwak, & Markopoulos, 2014). It was found that users created their own personal constructs depending on the shape morphology using anthropomorphic descriptions and complex behaviors that go beyond current models of shape changing interfaces. These anthropomorphic qualities that users identify to different shape interactions gives a promising insight into how people associate living characteristics to these novel interfaces.

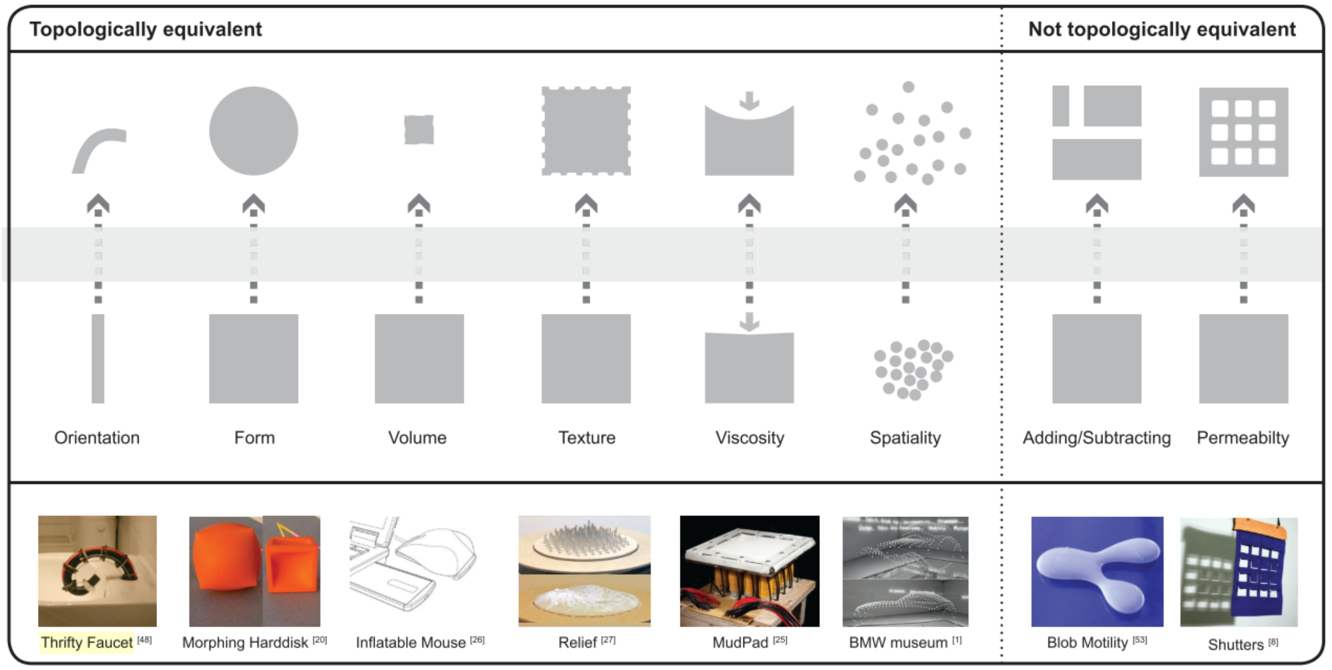


Figure 8
Types of Shape Change (Rasmussen et al., 2012)

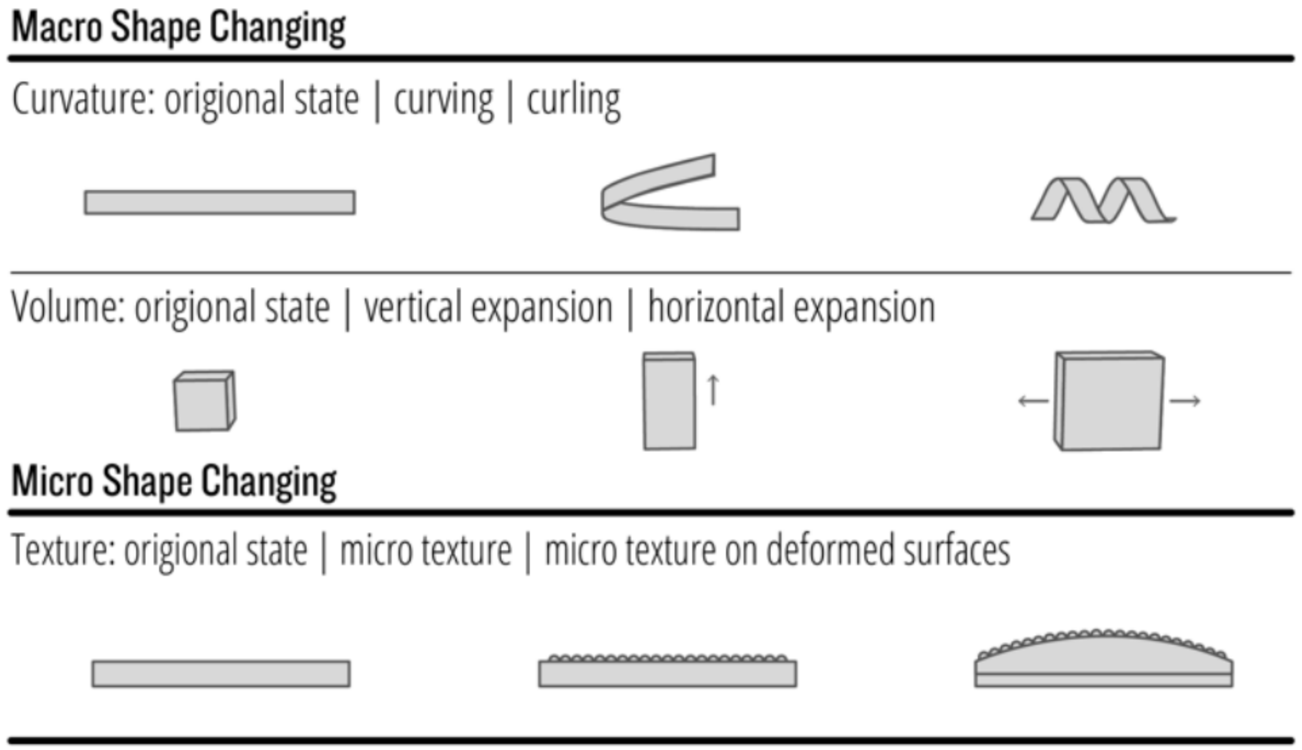


Figure 9
Shape Changing Morphologies of the PneUI soft composite (Yao et al., 2013)

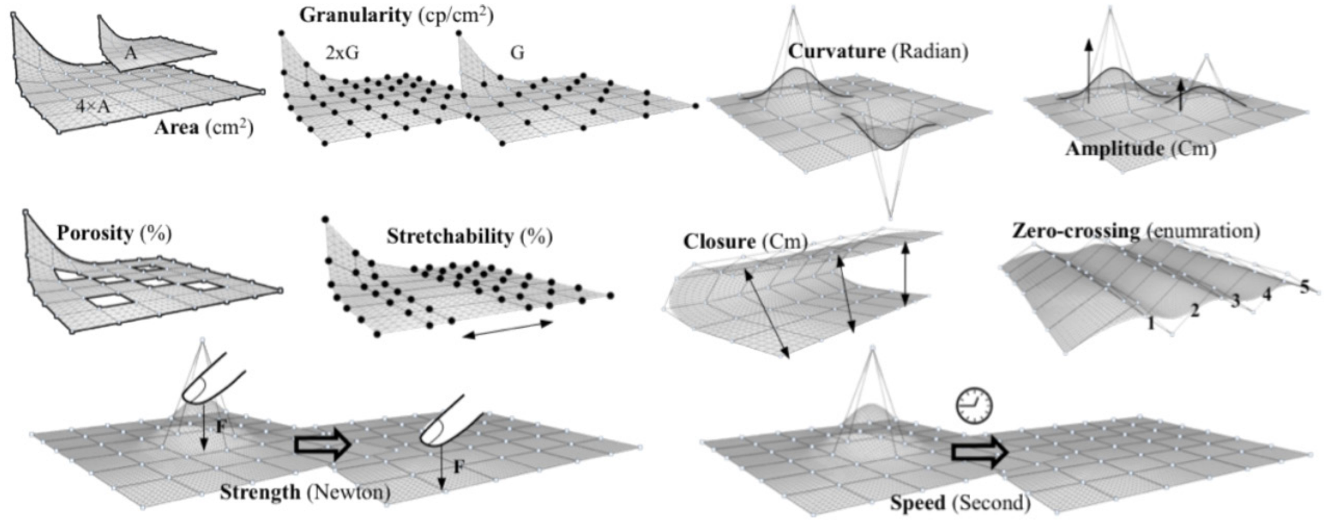
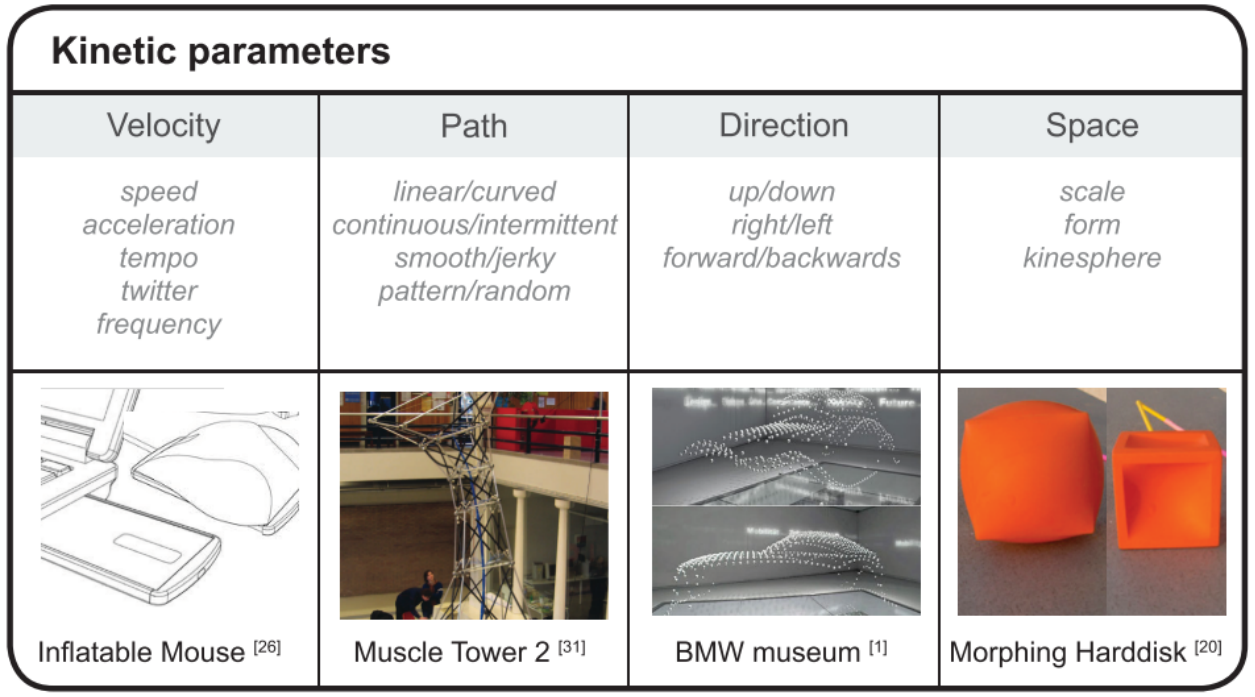


Figure 10
10 Features of shape resolution (Roudaut, Karnik, Löchtefeld, & Subramanian, 2013)



Kinetic parameters

Velocity	Path	Direction	Space
speed *acceleration* *tempo* *twitter* *frequency*	*linear/curved* *continuous/intermittent* *smooth/jerky* *pattern/random*	*up/down* *right/left* *forward/backwards*	*scale* *form* *kinesphere*
Inflatable Mouse [26]	Muscle Tower 2 [31]	BMW museum [1]	Morphing Harddisk [20]

Figure 11
Kinetic Parameters of Shape Change (Rasmussen et al., 2012)

Kinetic Parameters

The addition of kinetic elements to create movement brings the shape morphologies previously discussed to life. Rasmussen et al. categorizes the kinetic parameters of shape changing interfaces into velocity, path, direction and space (Fig. 11). In tangible user interfaces, force is an additional kinetic parameter that can be perceived by user touch (Poupyrev, Nashida, & Okabe, 2007). In interaction design, an interaction vocabulary has also been proposed showing that parameters within the velocity and path category play an important role in the emotional response (Fig. 12) (Diefenbach, Lenz, & Hassenzahl, 2013). Some similarities found between the shape change and interaction vocabulary include:

speed (slow/fast)

continuous/intermittent (stepwise/fluent)

pattern/random (constant/inconstant)

tempo/frequency (instant/delayed)

By varying one or two of these parameters (low level interaction), we can elicit a different emotional response (high level interaction). In addition to the variables listed above, it is also speculated that adding a degree of imperfection or "noise" in the movement of the shape changing interface can create a more "organic natural feeling" (Parkes et al., 2008). The key in understanding how these variables affect the livingness of the material lies in making a connection between the sensorial level to the interpretive and affective level of the material, which involves the expressive parameters of these interfaces.

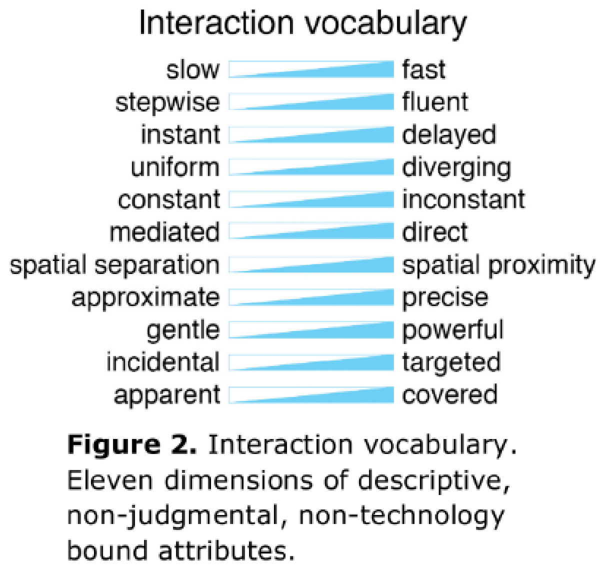


Figure 12
Interaction Vocabulary (Diefenbach et al., 2013)

Expressive Parameters

The spatial and temporal parameters of shape changing interfaces are in direct control of the designer. When these interfaces are shown to users, the spatial-temporal form is perceived by the user into expressive parameters affecting a higher level of interaction. These expressive parameters are defined by associations and adjectives (Fig. 14) (Rasmussen et al., 2012). In the Material Driven Design method, these two parameters are related to the interpretive and affective level of material experience (Fig. 13) (Serena & Elvin, 2018).

Associations in the interpretive level relates to the associations generated in user's mind when they experience the shape change of the material. These associations are mainly divided into two groups: organic or mechanical. Organic associations are made when the interface is reminiscent of a human or animal quality or resembles an aspect of our natural world. The use of organic associations to describe shape changing interfaces is confirmed by Hornbaek et al. results of anthropomorphic descriptions used by their participants. Mechanical associations are on the opposite end of the spectrum where the movement feels artificial due to qualities such as jerky or repetitive movement. Most designers aim to give the shape changing interfaces organic or alive-like qualities to enhance the experience of the interface. The Thrifty Faucet is a perfect example of a product with intentional alive-like movements where the designers used continual, small movements to enhance the livingness of the product (Togler, Hemmert, & Wettach, 2009).

Adjectives used to express the interpretive and affective level of experience describe the personality traits and qualities associated with the spatial-temporal form. These traits and qualities that designers and users associate to movement in shape changing research are similar to the interpretive and affective vocabulary presented in the Ma2E4 Toolkit (Serena & Elvin, 2018). Rasmussen et al. suggests that these traits and qualities are often derived from the intention of the designer and can be highly subjective. It is uncommon to see experiential studies to confirm whether the same emotional descriptions are also perceived by users. In this case, the Ma2E4 toolkit is well suited to compare the intentional expressions of movements created by the designer with the response of users.

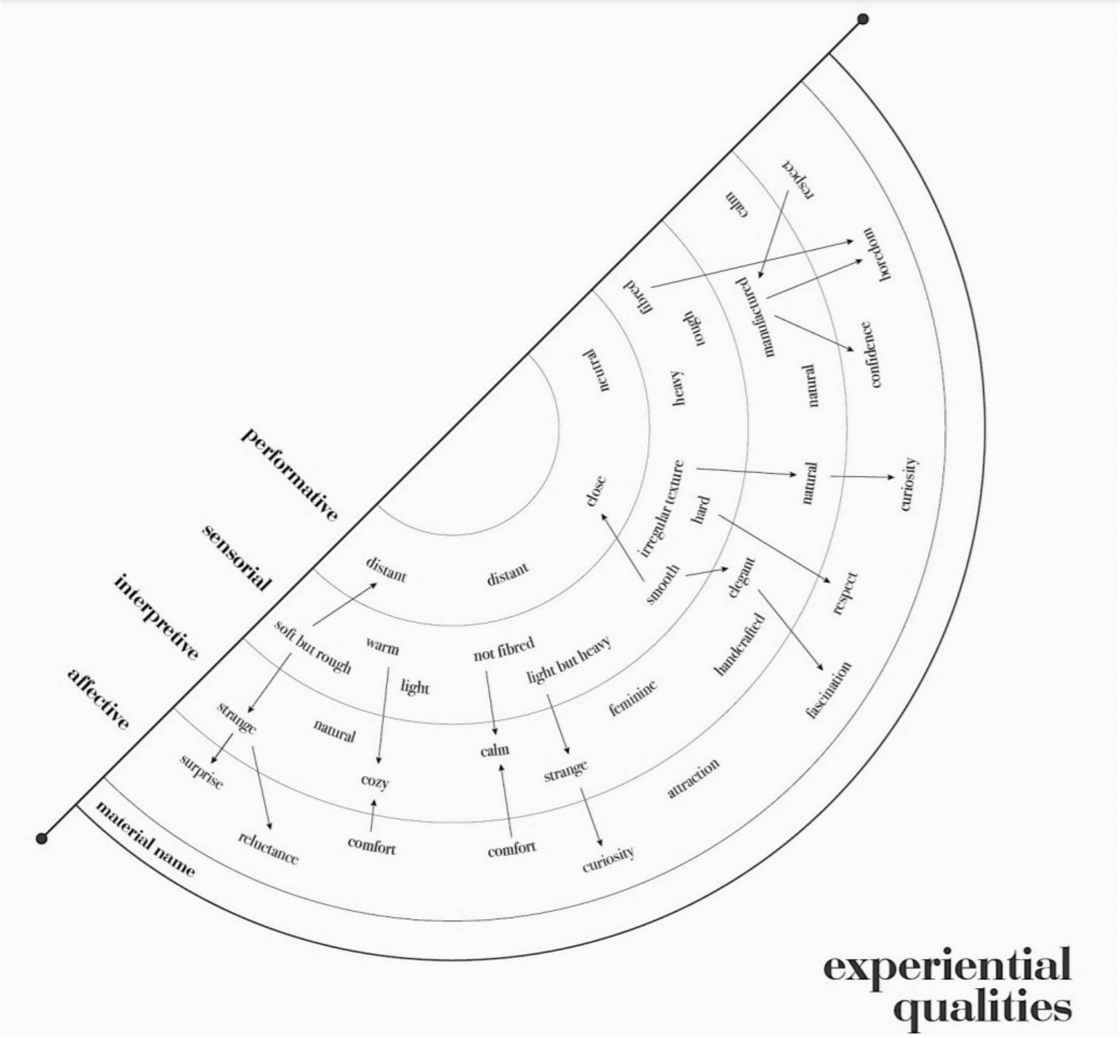


Figure 13
Experiential Qualities of Materials (Serena & Elvin, 2018)

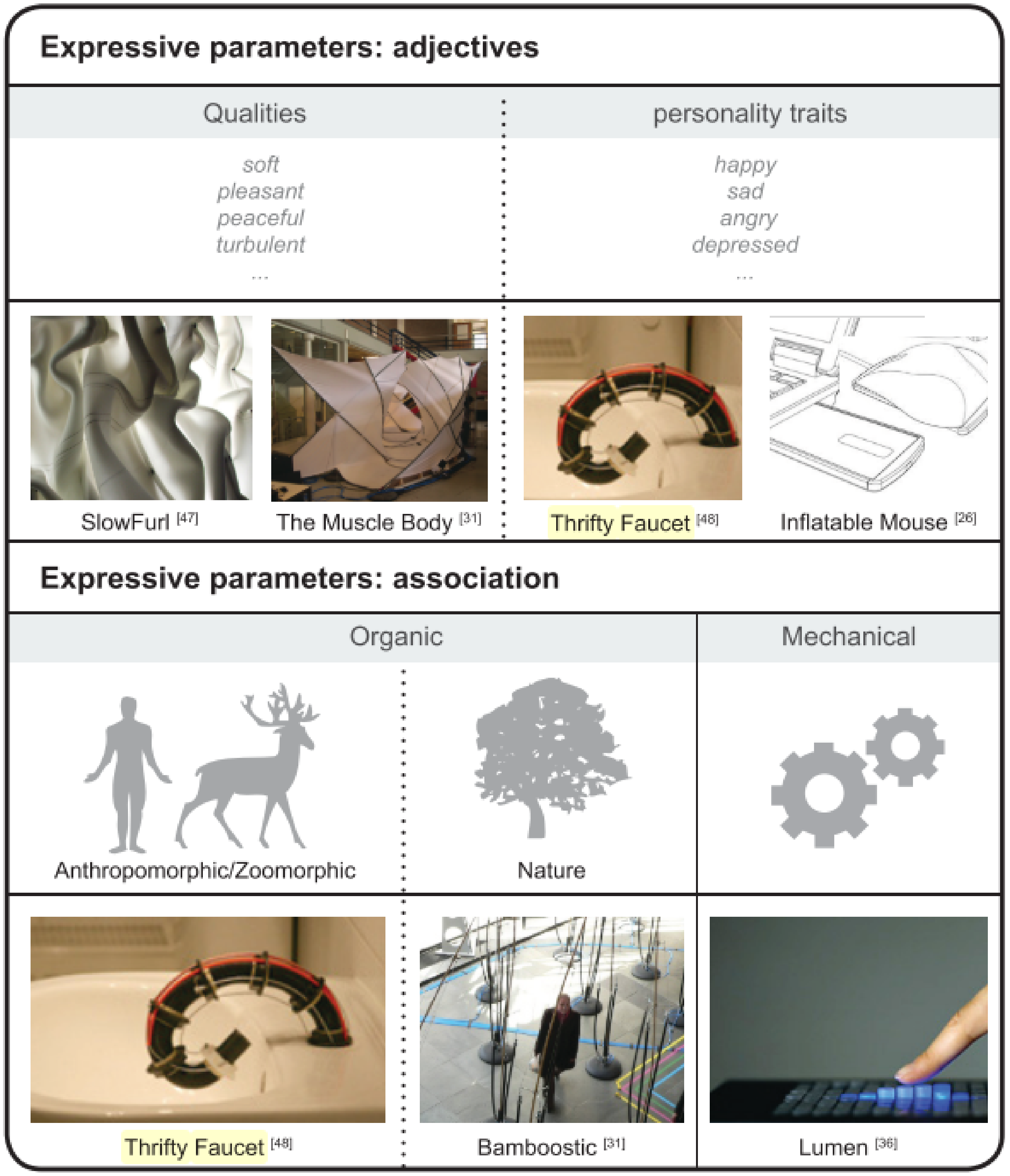


Figure 14
Expressive Parameters of Shape Change (Rasmussen et al., 2012)

2.3 GUIDELINES FOR MATERIAL SELECTION

This project explores how the parameters of shape changing materials presented: spatial, temporal, and expressive affect the material experience of livingness of shape changing materials. In order to properly study these parameters, a shape changing material must be selected that is versatile and controllable enough to precisely tune these parameters. The following criteria describes the necessary guidelines the material must meet in order to be selected as the shape changing material to study:

● Needs

- Material should provide control over the kinetic parameters (speed, acceleration, delay)
- Material should have a high range of its kinetic parameters (low vs. high speed)
- Material can achieve a variety of forms
- Material does not require custom, complex equipment to fabricate
- Material movement is reversible

● Wishes

- Material should be scalable
- Material allows for modular design

Figure 15
Liquid to Air: Pneumatic Objects by Christopher Guberan

CHAPTER THREE

SHAPE CHANGING MATERIALS

This chapter provides an overview of the various shape changing materials available and the active and interface elements used to create shape changing interfaces. Based on the exploration of these materials, pneumatic materials are selected as the best performing active element due to its controllability and speed with 3D printed textiles selected as the interface element for its programmability potential and familiarity.

3.1 OVERVIEW OF SHAPE CHANGING MATERIALS

Figure 16
Ego kinetic installation by Studio Drift

New advancements in shape changing materials allows for the creation of more dynamic, interactive interfaces. Shape changing materials can be described as materials that exhibit a mechanical change in form or shape due to external stimuli (Coelho & Zigelbaum, 2011). The source of the external stimuli can come from a user interacting with the material or from a controlled source. Overall, a shape changing material in HCI can be defined by two characteristics: the active element and the interface element. The active element refers to the material that reacts to the external stimuli. The interface element refers to the material the user perceives and interacts with. In many papers, the active material and the structure are one and the same, as seen in Christopher Guberan's Liquid Pneumatic Objects or in bioLogic's active living elements (Yao et al., 2015). Many times though, an external structure is used to communicate the shape change. This can be used to animate materials that we often perceive as being static providing an enhancement to the original interactions we are used to as can be seen in animated textile projects such as studio drift's Ego kinetic sculpture (Fig. 16).

In the following sections we will explore the active elements that have been developed due to recent advancements in material science and discuss the important parameters of interface elements that allow designers to take control of their material to achieve the incredible results that can be found today in shape changing material research.

3.2 ACTIVE ELEMENTS

Developments in material science has brought about a range of new shape changing materials for use in product design. These materials range from DIY, readily available materials such as Shape Memory Alloys (SMAs) to engineered living microorganisms that can react to environmental input. These materials serving as active elements in shape changing interface have been transforming the way people interact by allowing new types of responsive, organic interactions between humans and computers. The following will discuss some of the most popular and interesting active elements available including:

Heat sensitive materials

Liquid sensitive materials

Pneumatic materials

Mechanically actuated material

This is not an extensive list of active elements, but it is mainly meant to cover the most relevant materials related to this project due to their availability and use context. In reality, many other environmental inputs have the potential to cause a shape changing effect on a material depending on the material's underlying properties creating an endless possibility of active materials still left to research in the future.

Figure 17
Programmable Materials by MIT Selft Assembly Lab

Heat Sensitive Material

Heat sensitive materials such as SMAs are sensitive to variations in temperature and induce shape change when heated. The stimuli can come from an external heat source, or more commonly, by running an electric current through the material. One of the main advantages of SMAs is its compact size that allows it to be seamlessly integrated into soft materials such as textiles. One of the most relevant example is of the TU Delft caterpillar locomotion project that uses SMAs to control the movement of the soft, fabric caterpillar-like prototypes (Fig. 18) (Atmopawiro, 2019). Similar to the caterpillar project, ClothTiles proposed a combination of 3D printed joints printed directly on textile that when combined with SMAs are able to create an integrated mechanism to create movement in textile clothing (Fig. 19) (Messerschmidt & Matthies, 2021). SMAs have a controlled and fast forward state when heated, yet a slow uncontrolled backwards stage during cooling. To improve the reversibility of the material, ModiFiber proposes a Two-Way Morphing Soft Thread Actuators created by applying a silicon coating to the actuator. This gives the actuator elasticity to quickly return back to its original shape after actuation (Fig. 20) (Forman et al., 2019). SMAs are best suited for smaller size applications due to their high work per unit volume, yet are not well suited for scalability (Coelho & Zigelbaum, 2011).

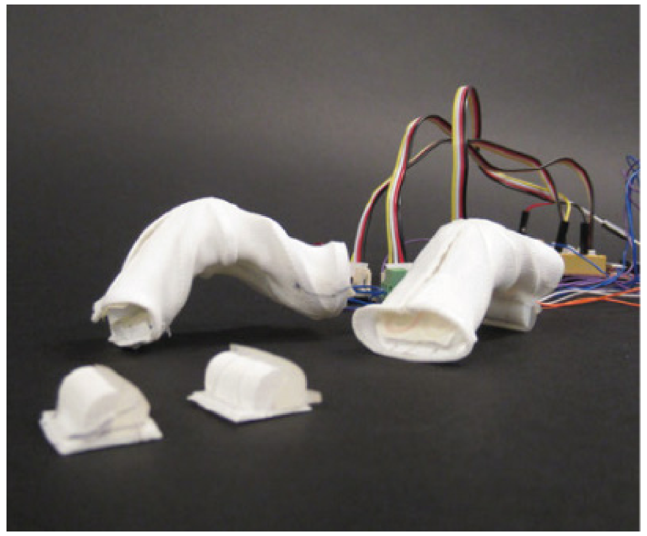


Figure 18
A caterpillar locomotive device (Atmopawiro, 2019)

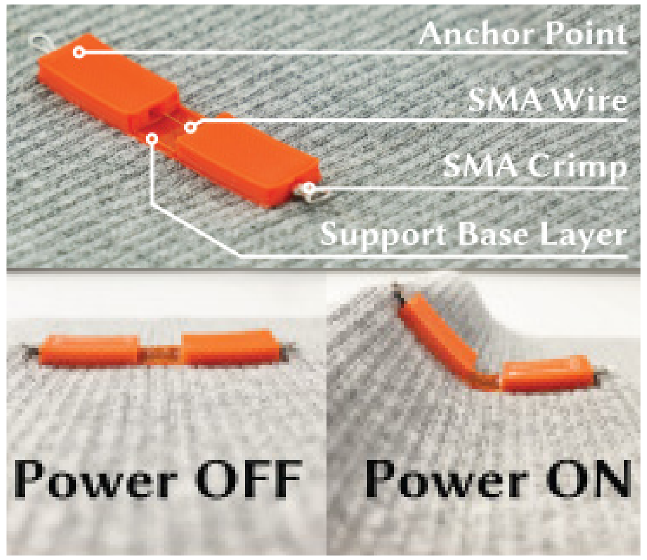


Figure 19
ClothTiles 3D printed and SMA textile actuators (Messerschmidt & Matthies, 2021)

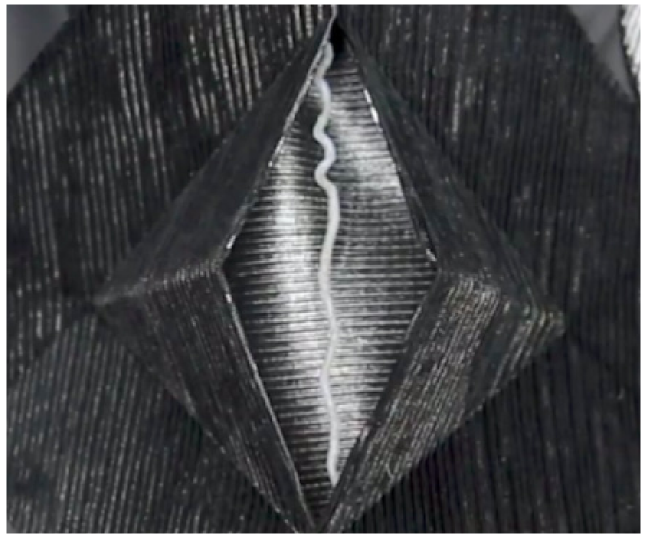


Figure 20
ModiFiber: a reversible SMA actuator (Forman et al., 2019)

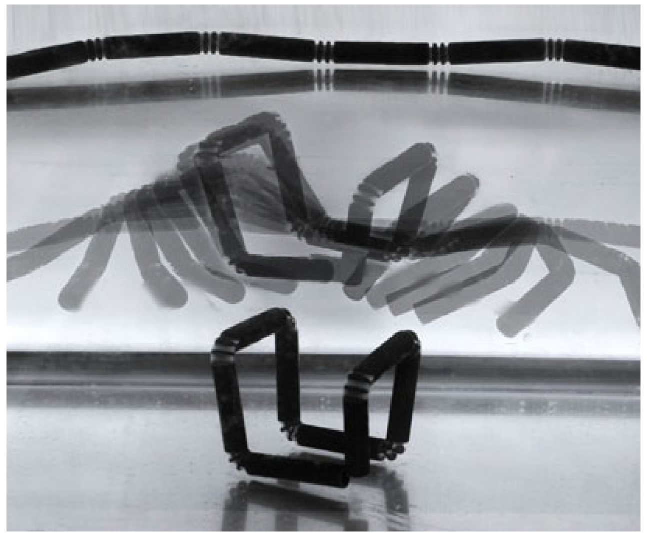


Figure 21 4D printing shape changing actuators by MIT Self Assembly Lab (Tibbits, 2014)

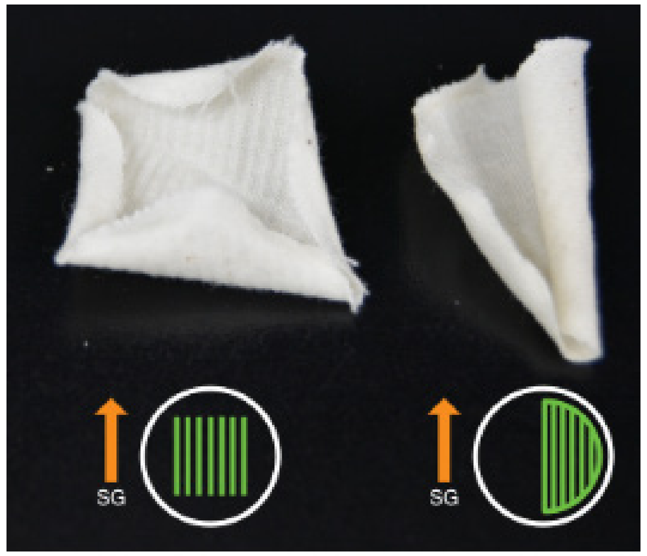


Figure 22 Hydrogel embedded textiles for shape change design (Rivera et al., 2020)

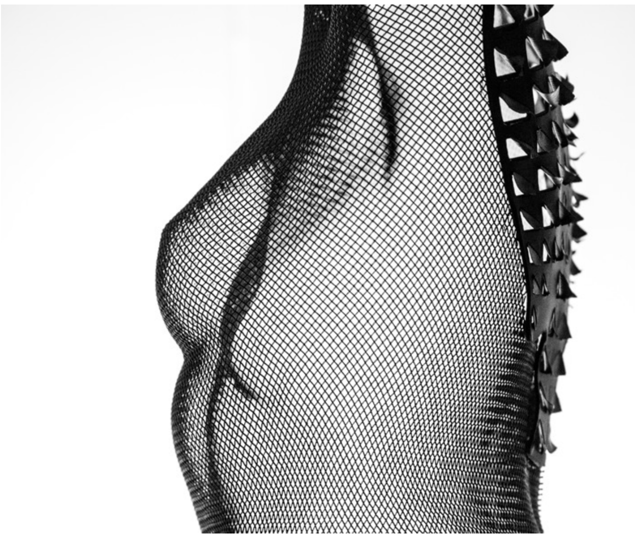


Figure 23 bioLogic water sensitive living actuators (Yao et al., 2015)

Liquid Sensitive Materials

Liquid sensitive materials create shape change by swelling or contracting when expose to liquids such as water or due to changes in hydration or humidity in the environment. With materials such as hydrogels, the placement of the hydrogel can be intentionally applied along a shape changing medium to vary the deformation. This has been shown to work in projects such as the hydrogel-textile composite, where textiles are used as the interface element and change shape when exposed to changes in humidity (Fig. 22) (Rivera, Hudson Abstract, Forman, & Yao, 2020). In MIT's Self Assembly lab, water/humidity has been used to initiate the shape change or self assembly of a material to its desired final form by dipping the material in water (Fig. 21) (Tibbits, 2014). In their 4D Printing project, a variety of water sensitive multimaterial 3D printed structures were created using a hydrophillic material that expands when exposed to water creating a variety of complex 3D structures. Liquid sensitive materials show advantages in their ability to mimic nature since shape change affected by hydration is also commonly found in living organisms such as plants and flowers. Since some living organisms have been found to change shape when exposed to water, some researchers have been able to exploit these qualities for material design. The bioLogic project shows how a biological responsive organism can be integrate into materials to induce shape change when exposed to water (Fig. 23) (Yao et al., 2015). Disadvantages include difficulty in controllability of its kinetic parameters specially in the reversibility of the shape change as this parameter is dependent on the material's ability to dry in the environment.

Pneumatic Materials

Pneumatically actuated materials consist of an elastic material that expands due the internal air pressure created from an external source. The external source can often come from a closed loop source such as a syringe or an open loop source such as an electronic air pump or compressor. Compared to other forms of actuation, pneumatic actuation has several advantages over other stimuli such as exhibiting a "large workload, controllability, reversibility, and fast actuation" (Siéfert et al., 2018). These advantages are beneficial to this study as it allows complete control over the kinetic parameters of the shape changing actuation. Disadvantages of pneumatic actuation include the need for an external air source, difficulty in fabricating air tight structures, and noise from air source if using an open loop system.

The use of pneumatic actuation in shape changing material has been commonly studied in the soft robotics field in the creation of soft pneumatic hands, orthotics, and locomotion (Fig. 24) (Scharff et al., 2017). This is achieve by inflating the internal channels along an elastic actuator that causes an overall shape change in the form of the actuator. The focus of soft robotics is often on improving the functional performance through optimizing the geometry of the actuators.

In the field of pneumatic user interfaces, the focus is often placed on form finding through variations in the geometry. This is specially evident in the shape morphologies exploration conducted by MIT's projects PneUI (Yao et al., 2013) and Aeromorph (Fig. 25) (Ou et al., 2016). The PneUI proposed a composite material fabrication method to create basic inflatable geometries. AeroMorph improved on this previous work by creating a digital fabrication workflow that allowed for the simulation and creation of complex shape change inspired by origami techniques. Advancements in 3D printing have also allowed for the creation of complex liquid printing inflatable structures that can achieve even larger inflation (Fig. 26) ("Liquid Printed Pneumatics — Self-Assembly Lab," 2017). A different approach was also taken by the Sticky Actuator project (Niiyama et al., 2015) and the MorphIO project (Nakayama et al., 2019), where custom modular inflatable actuators are created that can be attached to various inanimate objects to make them come to life.

Figure 24
TU Robotic Hand project (Scharff et al., 2017)

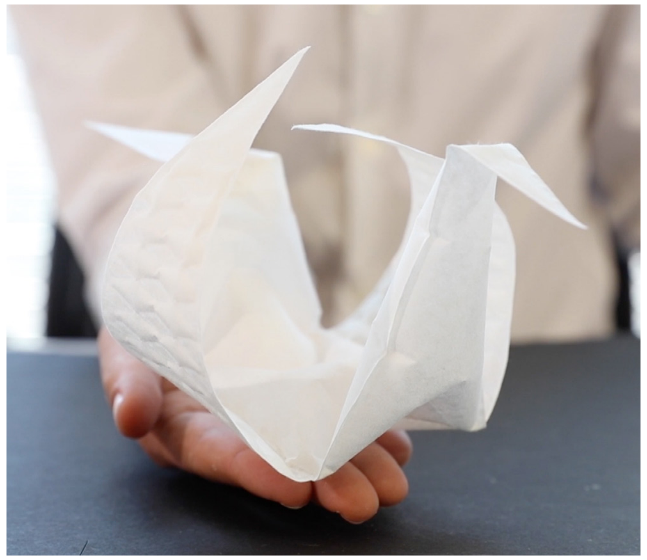


Figure 25
Aeromorph heat sealed shape changing textiles (Ou et al., 2016)

Figure 26
Liquid to Air: Pneumatic Objects by Christopher Guberan

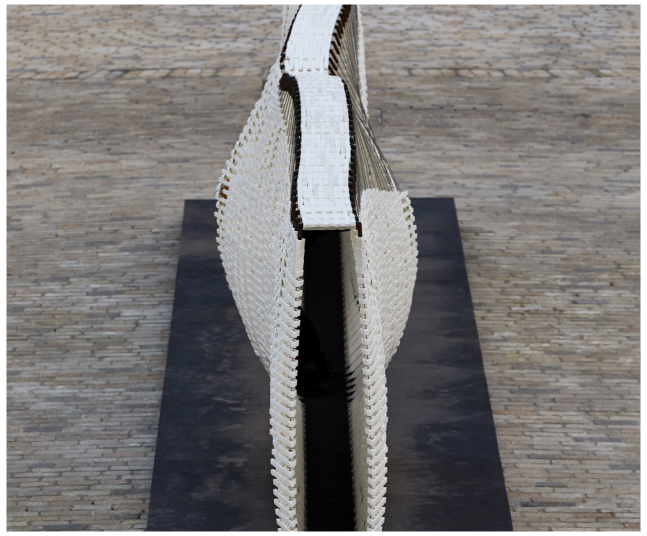


Figure 27
Disobedience by Studion Ini

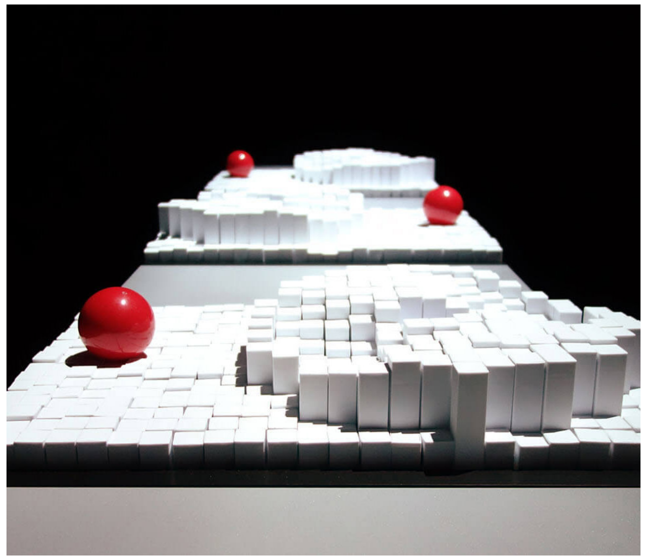


Figure 28
Transform shape changing tabletop (Ishii, 2015)

Figure 29
Shylight by Studio Drift

Mechanical Materials

Mechanical actuation refers to the use of motors to create various types of movements through direct connection to the shape changing interface or through the use of wires to conceal the actuation. Its scalability and controllability are its most unique qualities that make it ideal for large scale design such as architectural exhibits. This can be seen in the large scale immersive exhibits of Studio Ini such as Urban Impact or Disobedience (Fig. 27). Smaller scale projects in HCI research have also been created using mechanical actuation. Thrifty faucet uses a flexible tube with servo motor driving wires to create life-like complex movements (Togler et al., 2009). Interactive tabletop interfaces such a transform use a multitude of motors to create a large matrix of blocks that produces a deformable surface (Fig. 28) (Ishii, 2015). Disadvantages of mechanical actuation include associations with mechanical movement qualities such as jerky or repetitive movement, and the need for an external source. Despite the disadvantages of associating mechanical movement with non-living objects, art installations such as Studio Drift's Shylight (Fig. 29) showcase the opposite phenomenon as mechanical actuation is actually used to make the flower-like textile come to life in biomimetic movements.

3.3 INTRODUCTION TO PNEUMATICS

Due to pneumatic actuation's advantages of exhibiting large workload, controllability, reversibility, and fast actuation, pneumatic shape changing materials will be studied for the remainder of the project (Siéfert et al., 2018). Pneumatics is the study of how air and other gases can be used to power or move objects. Air can be used as a means of energy transfer, such as converting pressurized air into the movement of an actuator. When working with pneumatic shape changing materials or actuators, it is critical to understand how the properties of air used in the system affect the spatial temporal qualities of the material. Some important parameters to consider when working with actuators include volume, pressure, flow rate, flow direction, airtightness, closed loop vs. open loop pneumatic sources, and sensing.

Volume and Pressure

Gas molecules can adapt themselves to a container by spreading apart or coming closer together. In a gas, volume and air are inversely proportional according to Boyle's law (P1V1 = P2V2). This means that when a certain volume of gas is transferred to a smaller volume container, the pressure will increase and vice versa. This principle also applies to pneumatic actuators. The deformation of an actuator, which is determined by how much it inflates, is directly related to the pressure. Thus, a higher pressure will cause an actuator to reach a higher deformation. This behavior is similar to inflating a flat bike tire. At a low pressure, the tire is flat and flexible. At a higher pressure, the tire changes shape into a round tube with sufficient stiffness to support you in your ride. As seen in soft robotics, the deformed shape of an actuator is often characterized by the pressure applied to the actuator. Air sources will often have a maximum air pressure that they can produce or have a pressure regulator that allows the user to vary the pressure manually. In literature, it is common for researchers to test the performance of a pneumatic actuator by measuring how the angle of deformation changes with different applied pressures.

Flow Rate

While volume and pressure determine the spatial qualities such as the deformation of an actuator, flow rate determines the temporal qualities or movement of the actuator. Flow rate, or volumetric flow rate, is a measure of the amount of air passing through an orifice per unit of time. There is a direct relation between the flow rate and the velocity of the actuator at a constant pressure. Thus, if the pressure is maintained constant, a higher flow rate will cause a higher velocity movement in the actuator end. In shape changing material research, it is quite rare for researchers to measure the change of speed of the actuator while varying the flow rate as the focus tends to be on the overall deformation of the actuator and not the speed of movement. For the purposes of this report, controlling the flow rate will become important at a later stage as having control over the movement speed of the actuator is essential to studying the full scope of its spatial temporal qualities.

Flow Direction

Flow direction refers to whether the air flows towards or away from the actuator. When it comes to pneumatic actuators, the flow direction controls the inflation (towards actuator) or deflation (away from actuator). In shape changing materials, this is referred to as forward/reverse movement. A quality of pneumatic systems is that the forward and backwards movement can easily be controlled only by changing the air flow direction, which is difficult in other shape changing materials such as SMAs or hydrogels. Most SMAs and hydrogels have a controlled forward direction shape change, yet reversing this shape change requires an additional mechanism such as covering the SMA string in silicon or heating up the hydrogel to evaporate the moisture (Forman et al., 2019). Pneumatic materials, on the other hand, benefit from an easily reversible mechanism making it superior in the controllability criteria. This can be done by pushing/pulling a pneumatic syringe in a closed loop system or with a combination of an active air pump and vacuum in an open loop systems.

Closed Loop vs. Open Loop Pneumatic Sources

Pneumatic actuators require an energy transfer to be activated in the form of air. The source of the air can come for a closed loop system, which means that the air is fully contained within the design system and the same air is transfer back and forth between actuator A and actuator B. In a use case scenario, a closed loop system can allow for the air transfer to occur from user interaction when the user presses down on actuator A causing the air to flow to actuator B. Opposite to this is the open loop pneumatic sources such as an air compressor or an air pump. In this scenario, the source collects air from the outside and pumps it to the actuator thus new air is cycled through the system each time. Using two air pumps, one as a pump and one as a vacuum (this can be achieved by simply reversing the connection of the pneumatic tubes for the vacuum pump), can allow for digital control of the inflation/deflation of the actuator using a microcontroller (E.g. Arduino).

Airtightness

When fabricating inflatable structures, one of the main complications shown in literature is how to keep the structure and its connections airtight without any air leakage. If there are air leaks in the structure, this causes the inflatable to lose pressure over time, which is often not ideal as it requires a constant inflow of air and decreases the performance of the actuator. This complication is most notable when using additive manufacturing to fabricate inflatables as it is difficult to fully seal the material in between the printed layers. If the inflatable has air leaks, then it will require an open loop air source such as an air pump or air compressor. If the inflatable is airtight, then it opens the possibility for a closed loop system that does not require an active air source opening the use case possibilities of the actuator.

Sensing

Projects such as Aeromorph, MorphIO, and TU Delft Robotic Hand project showcase how the pneumatic qualities of actuators can actually be exploited as a sensing mechanism for interaction design (Fig. 30) (Nakayama et al., 2019; Ou et al., 2016, Scharff et al., 2017). By measuring the pressure inside an inflated actuator, an unexpected change in pressure that is not caused by the air source can indicate that an user is interacting with the actuator. For example, in the MorphIO project, this is showcase with a bellow actuator that increases in length when inflated. If the actuator is compressed by the user, the increased in air pressure as seen in the graph would indicate the amount of pressing done by the user. Adding sensing capabilities to your design opens the possibilities to creating more responsive interfaces, thus, increasing the livingness of the shape changing material.

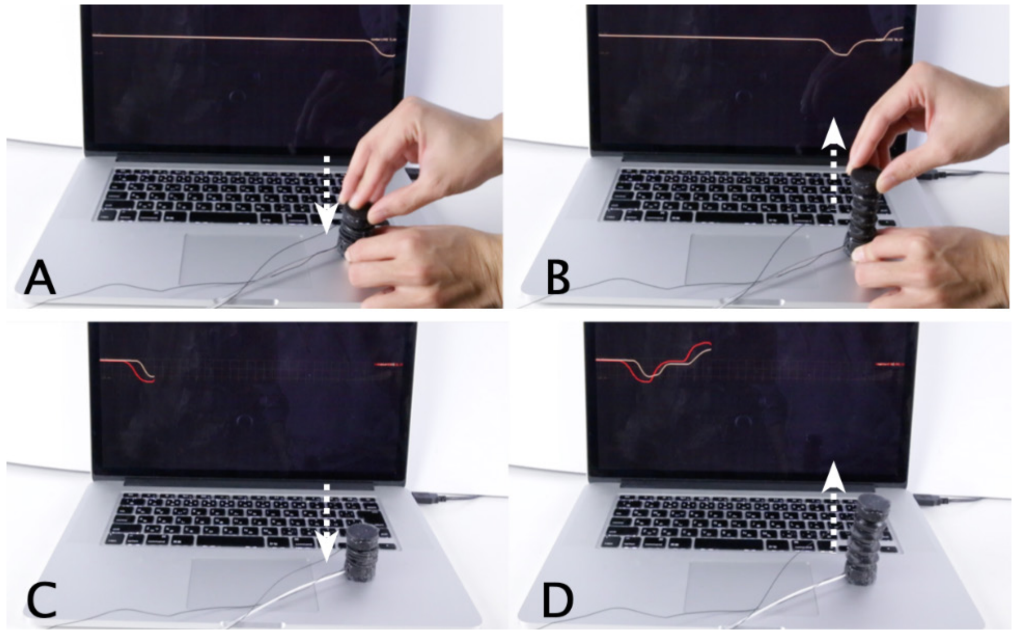


Figure 30
MorphIO pneumatic sensing capabilities (Nakayama et al., 2019)

3.4 INTERFACE ELEMENTS

With pneumatically actuated materials selected as the active element, it is now critical to explore the parameters of interface element. Interface elements are the structure or material that is animated when the active element is actuated. This element can essentially be any material in our world ranging from textiles to 3D printed material to the leafs from a tree. The important aspect of an interface element is that often times the user will already have a preconceived notion on how this material looks, acts, and feels. When adding into the equation the ability to induce shape change due to the inclusion of an active element, it creates an entirely new experience for users to explore. Designers and engineers are able to program these new types of interactions by computationally selecting where the active element is applied on the interface element to create highly complex forms and movements. This type of material that allows computational form creation and movement has been coined Programmable Materials.

Programmable Materials

Programmable materials combine the fields of shape changing materials and computational optimization and simulation to create highly complex shape changing structures. The MIT Self Assembly lab is one of the pioneers in this technology where they explore new manufacturing methods such as 4D printing that can allow for unconventional method of form creation. The Liquid Printed Pneumatic Objects, for example, propose a new way for 3D printing highly flexible, air tight structures that can then produce beautiful organic shapes when inflated that can act as household objects such as lamps. The Active Shoes project shows a different use of 3D printing, where the 3D printed material is directly deposited in onto pre-stretched fabric on a flat plane that can deform into the 3D form of a shoe when released from the printing bed. By simply modifying the 3D design of the print for both of these materials, different forms and movements can be achieved with this programmable materials. Programmable materials, therefore, provide an endless array of possibilities that can easily be controlled by the designer digitally (Fig. 31).

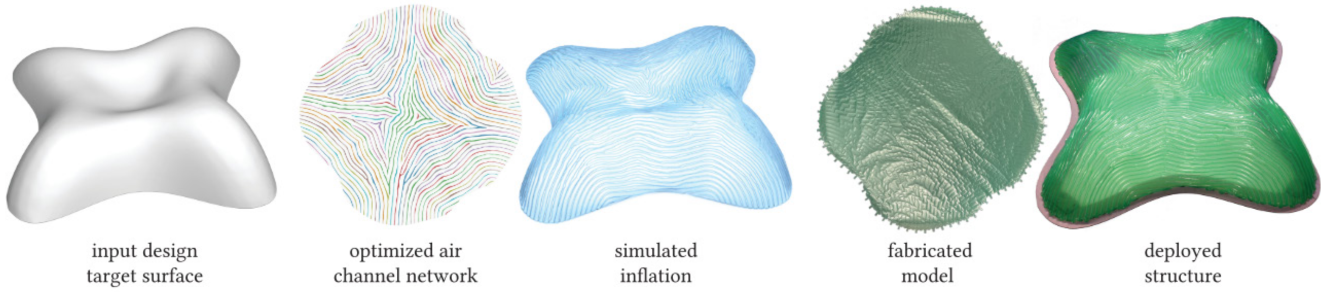


Fig. 1. Inflatables are composed of two thin sheets of inextensible material, fused together along carefully selected curves to form a network of channels that can be inflated with air. Our method optimizes the layout of these curves so that the inflated structure best approximates the desired input shape.

Figure 31
Computation inverse designed inflatables (Panetta et al., 2021)

Auxetic Materials

The rise of programmable materials using digital tools has paved the way for researchers to explore theoretical forms and shapes more difficult to produce with conventional manufacturing methods. Auxetic structures allow for the creation of curvatures shape change that are otherwise impossible with regular materials due to the unusual characteristics of a negative Poisson's ratio. In architecture, this technology has been used to create otherwise impossible curvatures from simply fabricating a 2D sheet. (Fig. 32 & 33) (Naboni & Mirante, 2015). If an active element is added to a auxetic structure, the state of shape change can then be controlled by the designer directly. This was shown by a TU Delft research project conducted by Lisanne van Leijsen on Pneumatic Metamaterials where 3D printed auxetic, flexible, and hollow structures were fabricated that would then create an unexpected expansion in size when inflated with an air source. This project proved that even using readily available technology such as 3D printing, designers can now incorporate auxetic structures to explore shape changing interfaces.

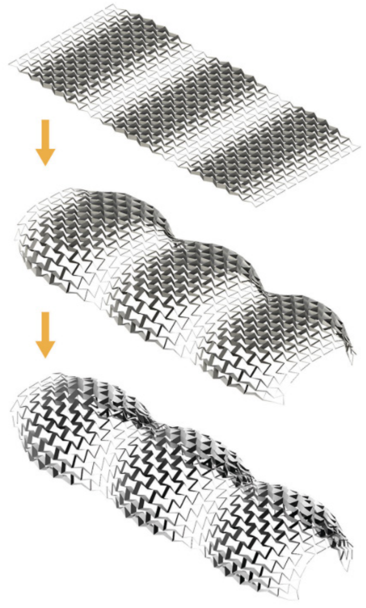


Figure 12: from top: planar structure, halfway bent structure, bent structure.

Figure 32
Diagram of auxetic curved patterns for architecture (Naboni & Mirante, 2015)

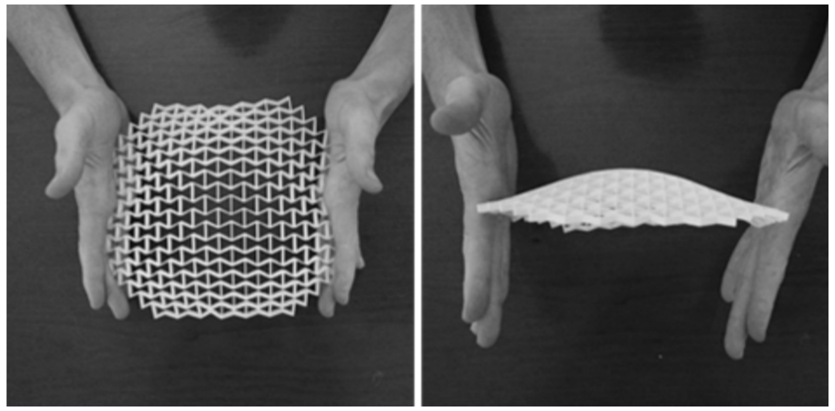


Figure 33
Physical prototype showcasing shape change of auxetic structure (Naboni & Mirante, 2015)

3.5 TEXTILE AS THE INTERFACE ELEMENT

As can be seen from some of the previous examples in this chapter, textile is a very popular material for use as interface element in shape changing interface design. Textiles offer a wide range of organic form and movement possibilities due to their malleability and fluidity. Additionally, they have become an essential part of product design found in the clothing we wear, the products we use, and the environments we inhabit. Due to our rich history with this material, humans are familiar with common performative interactions with textiles such as folding and stretching. This familiarity makes it ideal for creating shape changing interfaces as adding active elements can expand our interaction with an already highly familiar material. When studying the user experience and emotional response of shape changing materials, textiles are often used as the interface element for this very reason. For example, The Textility of Emotion study shows studied the emotional response of participants with an exhibit of 5 textile samples with varying bioinspired textures that move in synchrony with the breathing of different animals (Davis, 2015). Other studies have also used textile as a cover for the underlying material causing the shape change in order to abstract the form and interaction (Dong, 2019; Hornbaek et al., 2014) Due to textile's great potential for use shape changing interface design, this report will continue exploring shape changing interfaces using textiles as its interface element.

Smart Shape Changing Textiles

Smart textiles differ from your ordinary fabric in that they can sense and/or react to their environment based on different stimuli. This is often achieve with the implementation of electronics and active + sensing elements integrated in the fabric. For this project, it is of special interest to consider smart textiles that use active elements to change their shape. A common example of this is the use of SMA fibers that can be sewn directly onto textile. When the SMA fiber is heated up, it will cause a contraction in the fiber that pulls the textile with it according to the sewing pattern inducing a shape change and adding additional stiffness to the fabric. These shape changing textiles have been widely explored for uses in mimicking the locomotion of caterpillar, creating adaptable clothing, or even creating functional fiber robotics (Fig. 34) (Atmopawiro, 2019; Buckner, Bilodeau, Kim, & Kramer-Bottiglio, 2020; Messerschmidt & Matthies, 2021). Although many other examples of smart textiles focus on sensing abilities, specially for health wearables, these type of smart textiles will not be covered in this report as the focus of the material exploration is on shape change output and not the sensing input.

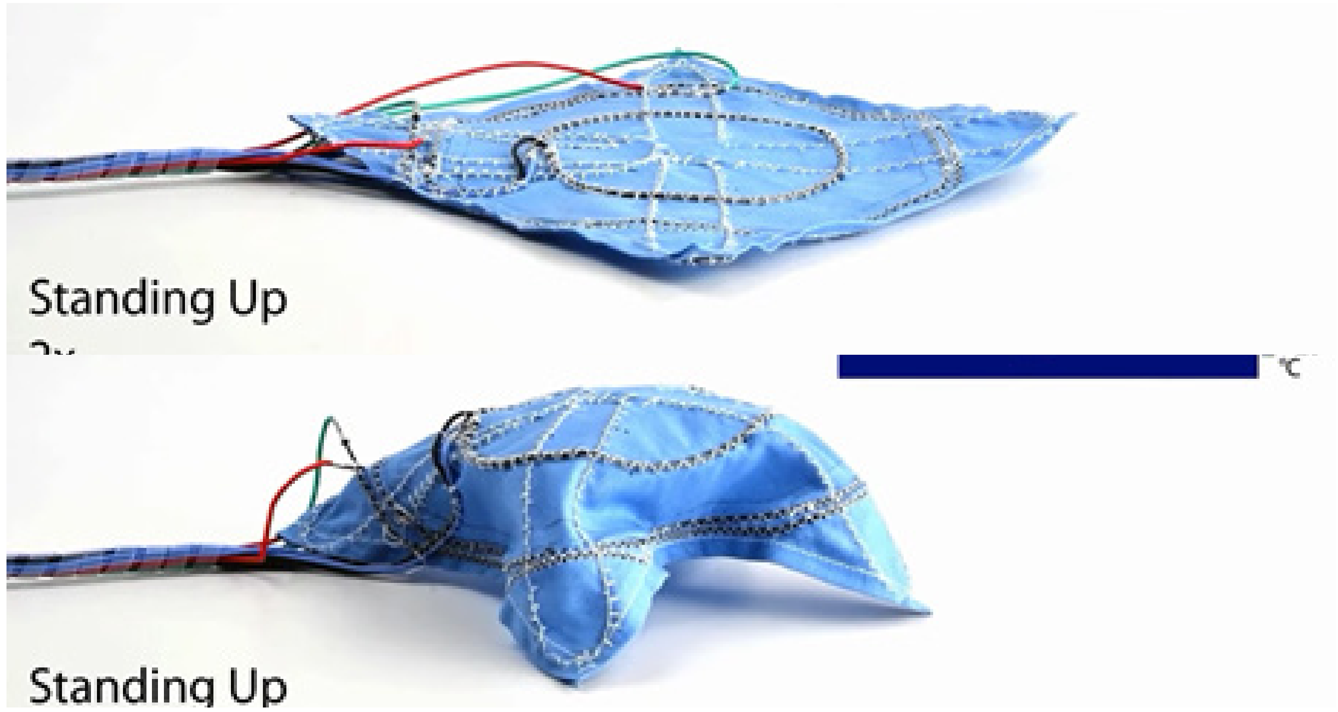


Figure 34
Robotizing textiles with SMAs (Buckner et al., 2020)

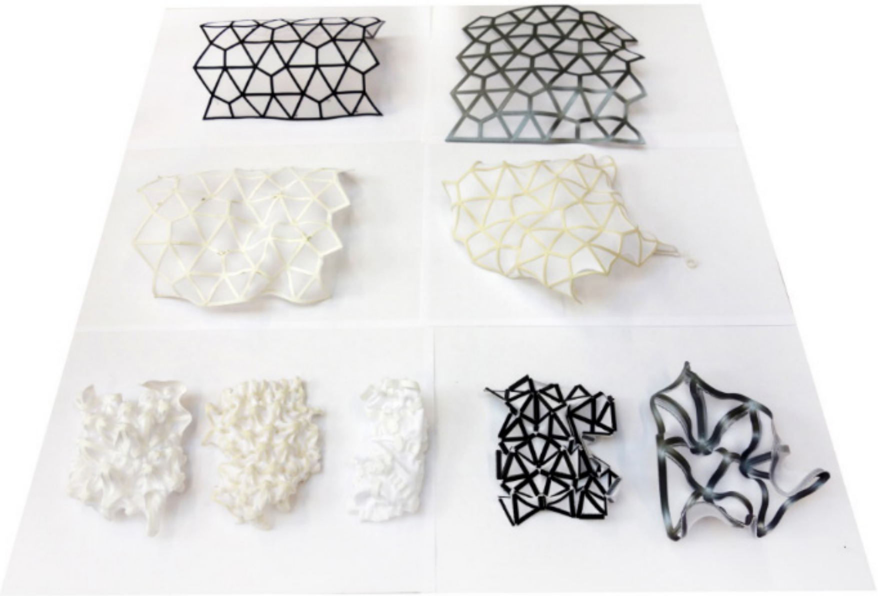


Figure 35
Material form finding using 3D printing on textiles (Kycia, 2018)

Programmable Textiles

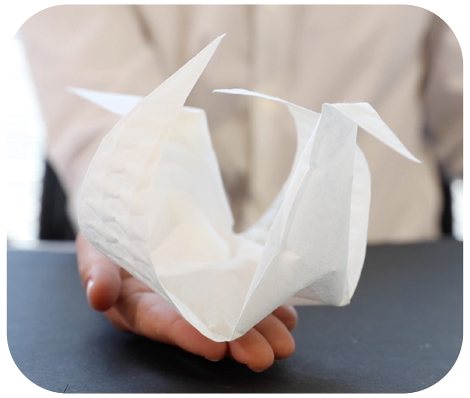
In the field of computationally design shape changing textiles, the use of 3D printing on textiles, coined 4D textiles due to its time dependency, has been of great interest. Complex 3D geometry can be achieved shapes by pre-tensing the textile on the printing bed, printing a 2D pattern on the textile, and releasing the tension once the print is completed. The energy stored in the textile causes a deformation in the material due to the additional rigidity of the printed material. The 3D printed pattern has a great influence on the final form that the textile will take. 4D textiles have been investigated as a form-giving tool (Fig. 35) (Kycia, 2018), computational simulations of the possible active forms (Agkathidis, Berdos, & Brown, 2019), and self-assembly applications ("Active Shoes — Self-Assembly Lab," 2013). Other student projects such as the Conductive Origami and Outline Stroke (Fig. 36) show how 3D printing can also be use on stiffer fabrics such as cotton and canvas, not to create deformations due to the pre-tension on the printing bed, but to add additional structure and stiffness to the textile to allow it to bend into 3D forms to create products such as lamps and vases. Using 4D textiles, therefore, shows great promise in its ability to achieve a variety of shape changes and additionally will follow on the footsteps of the caterpillar locomotion research from the faculty (Atmopawiro, 2019).

Figure 36
Outline Stroke student project by Stav Rguan

3.6 PNEUMATIC TEXTILES

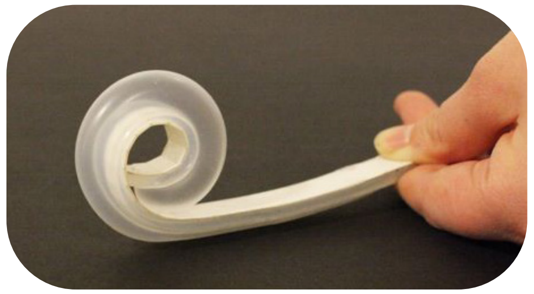
The combination of pneumatic actuation with textiles creates an ideal medium for exploring the expressive qualities of shape change due to the controllability of pneumatics and the emotional connection of people with textiles (Fig. 37). Some proposed techniques to fabricate pneumatic textiles include heat sealing of TPU coated fabric (Ou et al., 2016), computationally designed textiles with uniform internal inflatable ("Knitflatable Architecture - Yuliya Šinke Baranovskaya," 2015), computational designed textiles with interwoven tubing (Kurumaya, Nabae, Endo, & Suzumori, 2019), and 3D printed pneumatic structures on fabric (Papakonstantinou, 2015).

Of special interest is the 3D printed pneumatic structures on fabric as they allow the possibility of complex computational design exploration, ease of fabrication, and technical novelty. In the FabricFlation project, the pneumatic actuation was only briefly explored and was not able to achieve large enough deformations to induce expressive qualities since the pneumatic muscles had to be printed flat on the fabric. The inability of the material to induce large deformations was mostly due to the difficulty in 3D printing airtight, yet flexible complex structures specially when printing directly on textile. To solve this problem, I propose using separate, modular pneumatic actuators onto the 4D textile medium similar to the Sticky Actuators and MorphIO actuators that can be attached to various material mediums (Nakayama et al., 2019; Niiyama et al., 2015).



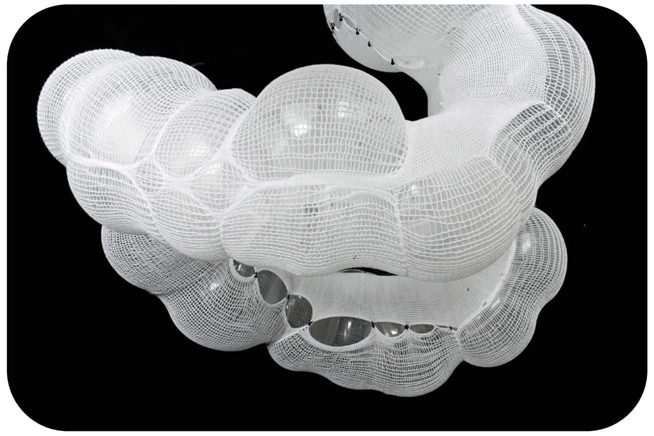
Heat Sealed Fabric

Aeromorph



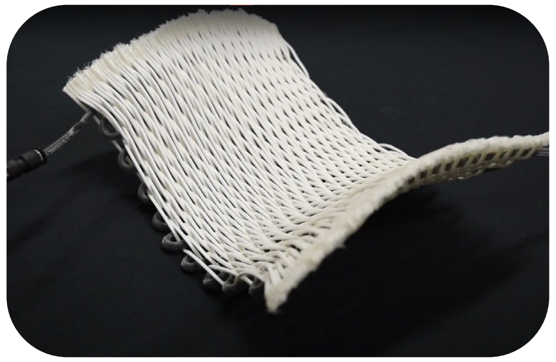
Multimaterial Silicon Composite

PneUI



Computational Fabric with Uniform Inflatable

Knitflatable



Computational Fabric with Interwoven Tubing

Active Textile McKibben Muscle

Modular Pneumatic Actuators

MorphIO/Sticky Actuators

4D Textiles Inflatables

FabricFlation

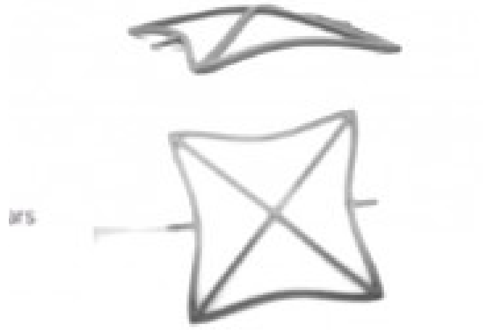


Figure 37
Example of pneumatic textiles and soft materials in literature

CHAPTER FOUR

MATERIAL EXPLORATION

This chapter introduces the initial exploration and prototypes of pneumatic textiles. Various fabrication methods based on previous research are tested ranging from low fidelity balloon models to 3D printing inflatable structures showcasing the main findings and complications encountered along the way. The chapter concludes with a material proposal and scope to explore during systematic tinkering.

4.1 MATERIAL FABRICATION TECHNIQUES

During the literature review, multiple fabrication methods were identified as shown in the Figure 37 showcasing the various pneumatic textile projects. Due to capabilities in the Applied Labs as well as my personal ambitions of experimenting with methods that had potential for computational modelling in the future, the following two fabrication methods were explored:

Fabric Inflatables: using heat-sealing fabrics like the Aeromorph project that allows to create inflatable structures. This process has been thoroughly documented and can easily be replicated yet requires a custom heat-sealing machine for more complex designs.

3D Printing Pneumatic Textiles: Using 3D printed flexible printing materials to create pneumatic actuators that can be printed directly on textile or attached to textile. This process combines some of the same principles showcased in the Fabricflation and pneumatic chiral structures project.

For this phase, these two techniques were freely explored by creating rapid prototypes and tests to quickly understand the possibilities of pneumatic textiles and select a fabrication technique and material. The main insights from these first prototypes are then used to create the material proposal used for the remainder of the project. In Chapter 5, a more systematic approach of studying the material is presented to gain a deeper understanding on the parameters affecting the selected material and its shape change capabilities.

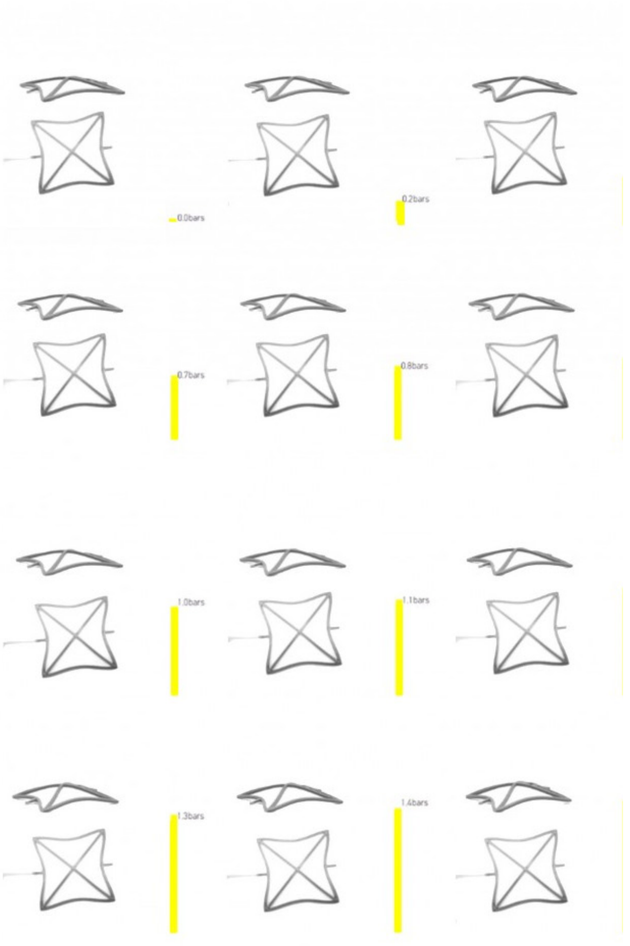


Figure 38
Fabricflation inflatable 3D printed textiles (Papakonstantinou, 2015)

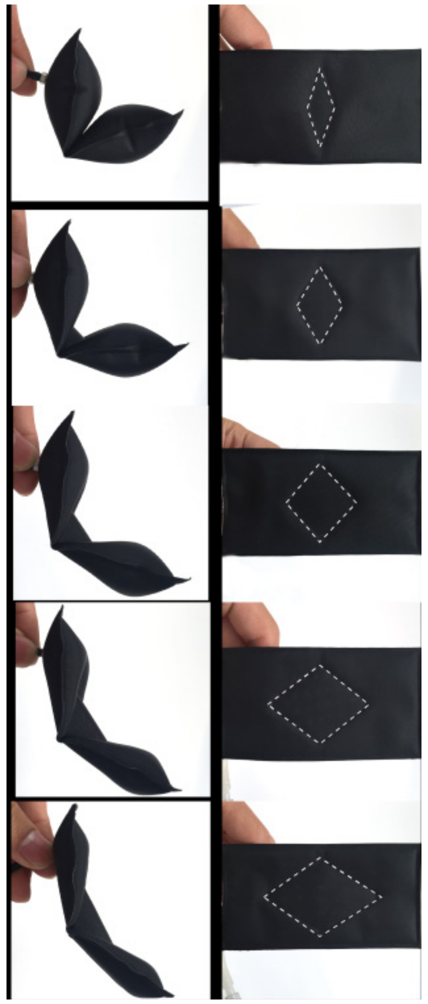


Figure 39
Aeromorph inflatable bending actuator (Ou et al., 2016)

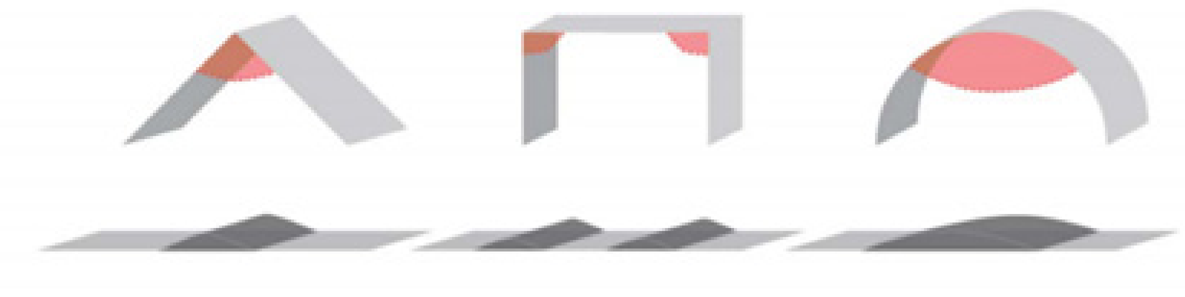


Figure 40
Basic hinge design for inflatble actuators

Figure 41
Bending actuator built with balloons and textile

Low Fidelity Inflatables

The easiest method to understand how pneumatics can affect the shape change of a textile structure is to study it using simple inflatable structures. The first attempt at understanding pneumatic shape changing materials was to use readily available materials such as balloons, cardboard, and scrap textile. The Aeromorph project proposes a "hinge mechanism" to induce shape change where essentially two inflatable pouches bend along a center hinge when inflated (Ou et al., 2016). This idea was quickly replicated using a set of a balloons and cardboard as the stiff layer to replicate the hinge mechanism.

The first step was to create a simple curling shape morphing prototype using the principles of the mechanical hinge. The material would then curl towards the inflated side as the flexible material expands more one side thus pulling on the fabric and creating a curling motion. The fabrication of the actuator consisted of a two-layer stiff textile with openings to insert balloons, a strip of cardboard with 2 bends acting as the hinge. All adhesion was done using hot glue and the inflation was done using a medical hand pump. As can be seen in Figure 41, this was sufficient to create a quick, bending actuator displaying the basic pneumatic actuator principles.

Actuating a Textile Sheet

Next step was to take the curling actuator created and produce a shape change on a larger textile sheet from 2D to 3D. To create this, a cardboard skeleton was glued to a 15 x 20 cm textile sheet and glued to the curling actuator, which helped in guiding the deformation of the textile. The cardboard skeleton was used to give the textile some added stiffness to produce a simple “U” curve. The idea is that by simply using a single actuator, a large shape change can occur on the overall structure due to the added stiffness of the cardboard skeleton. The prototype proved that a 2D textile could be transformed into a 3D curve with a singular pneumatic actuator. The current structure though did not create an even curve and the parallel skeleton structure on the edges actually prevented the shape from curling properly since they were too stiff.

Figure 42
Textile sheet actuator prototype

Variations in Skeleton Structure

Quick changes to the skeleton structure were also tested, which resulted in some minor changes in the deformation of the textile (difficult to see in the Figures, but can be clearly be felt with touch). The bottom skeleton structure shows that a simple change in the angle of the skeleton can cause the structure to curl into a «mountain»-like shape as opposed to a curve. This brings up the possibility of designing a singular, simple pneumatic actuator that can create a variation in shapes of the textile only with variations in the skeleton structure attached to the textile. This principle will later become a guiding idea for the systematic tinkering of the material in the next chapter.

Additionally, it was found that by adding the skeleton structure in perpendicular patterns, the deformation becomes more stable and controlled. It can be concluded that the number of skeleton «ribs» and/or actuators defines the resolution of the curve (More ribs and/or actuators = smoother curve) at the expense of making the textile structure more rigid. Specially when using cardboard, an increase in the density of the skeleton structure will add significant additional stiffness to the textile, which might detract from the unique soft and organic qualities of using textile as an interface element. In the next prototypes, it will be critical to explore more flexible material that can provide the necessary structure without the rigidity of the cardboard.

Figure 43
Textile sheet actuator with skeleton structure prototype

TPU Heat Seal Textiles

The next step was to test the performance of the Aeromorph heat-sealed textiles, which appear to be highly promising based on the results shown in their paper (Ou et al., 2016). Using their diamond shaped hinge geometry guideline, an initial bending prototype was manually created by layering 2 sheets of TPU coated fabric and selectively heat sealing the edges of the desired shape and the diamond shaped hinges. According to the paper, the diamond shaped hinges allow for a greater range of control over the bending motion both physically, but also in their digital simulations. The initial bending actuator was successful when inflated with a medical hand pump, therefore, two other designs from the Aeromorph were replicated to assess their performance and ease of fabrication. The three prototypes created were: a unidirectional bending actuator, a multidirectional bending actuator, and a curve bending actuator.

This manual method is simple and quick to prototype shape changing textile but becomes difficult when attempting to create more complex structures. For example, when making the multidirectional bending actuator, it was difficult to manually place the hinges on the correct location on the textile. As a result, the actuator does not bend into a box shape as expected, but still creates its own unique shape. As for the curve bending actuator, it became quite difficult to manually add multiple hinges at such close distance with such precision, thus, the final curvature showed some imperfections.The AeroMorph paper suggest that this process can be automated by creating metal templates of the heat seal design or a CNC router with a heat sealing tip to digitally fabricate these structures.

Other processes of heat sealing were also tested, yet they showed little success:

1. Heat sealing 2 layer textile with the tip of the nozzle of the 3D printer. The nozzle did not seem to be hot enough or make sufficient contact for heat transfer with the fabric for this method to work. This method could be re-tested by increasing the nozzle temperature or slowing down the nozzle movement.

2. Introducing a 3D printed TPU template on the inside layer of the fabric. An additional layer of fabric then needs to be heat seal manually along the edges created by the printer. This method worked in terms creating a seal, but the TPU (2mm height) was too stiff to allow for bending movement. When tested with a smaller height, it was found that the textile stuck to itself, therefore, this method is not recommended.

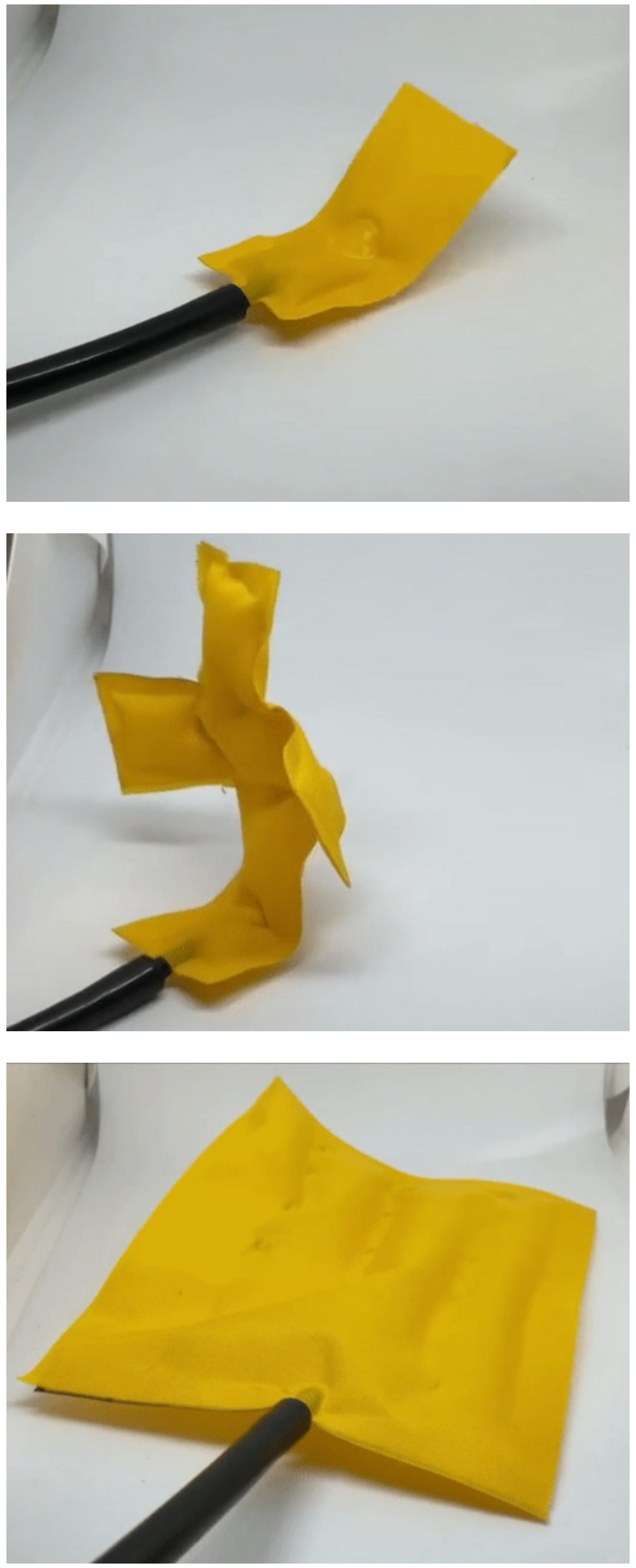


Figure 44
Heat sealed textile inflatable prototypes

4.2 3D PRINTED PNEUMATIC TEXTILES

Inspired by the work of Christopher Gurean's Active Shoes and Agata Kycia's 4D textiles, it was interesting to explore the possibility of combining 3D printing and textiles to create shape change not because of the pre-tension applied when printing, but because of the inflation of hollow 3D printed structures ("Active Shoes — Self-Assembly Lab," 2013; Kycia & Guiducci, 2020). This method would combine 3D printing within textiles with pneumatic hollow structures similar to the Pneumatic Chiral Structures created by Lisanne van Leijsen. The chiral structures showcased the ability of the arms of the chiral to expand when inflated. When patterned into a larger structure, the chiral structures create a surprising in-plane expansion of the material.

Combining 3D printing within textiles with pneumatic actuation would create a novel approach to shape changing textiles that has not been explored in detailed in the past. The closest exploration of this method is the Knitflation project, which briefly explored the ability of incorporating 3D printed pneumatic actuators into 4D textiles to create adaptable architecture (Šinke, 2015). This project showed that the potential of exploring this direction but did not manage to fully characterize the material. Additionally, the deformation showcased in the protypes showed little deformation when compared to other pneumatic actuator projects allowing for improvement of the 3D printed actuators from a technical perspective.

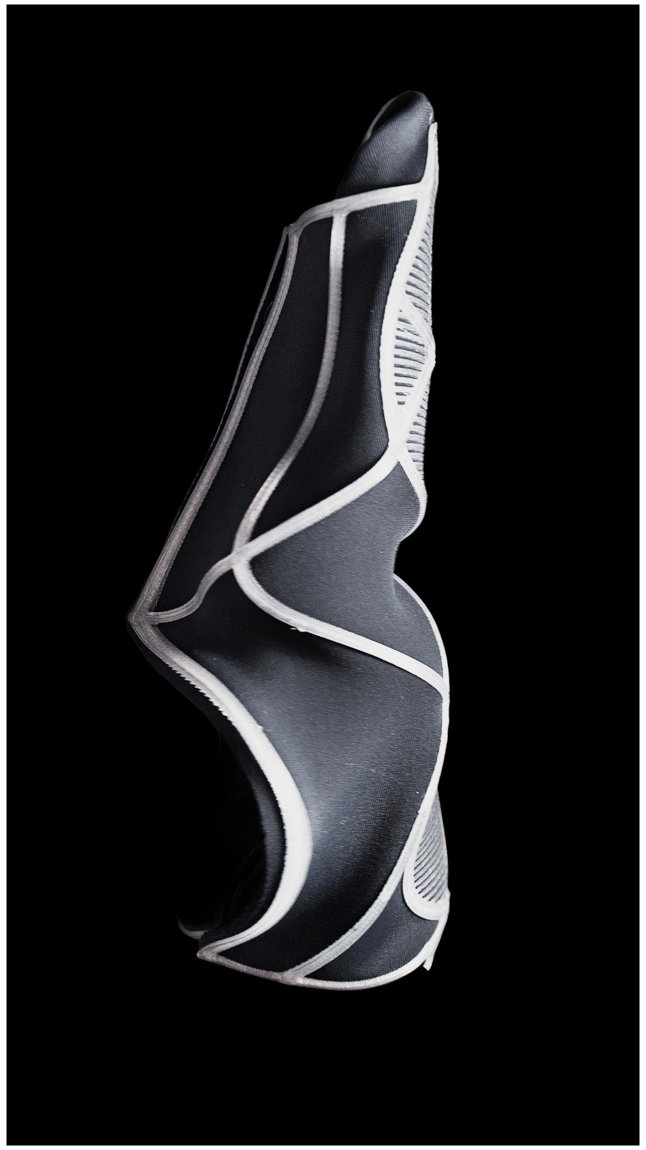


Figure 45
Active Shoes by MIT ("Active Shoes — Self-Assembly Lab," 2020)

Figure 46
Self forming textile structures (Kycia & Guiducci, 2020)

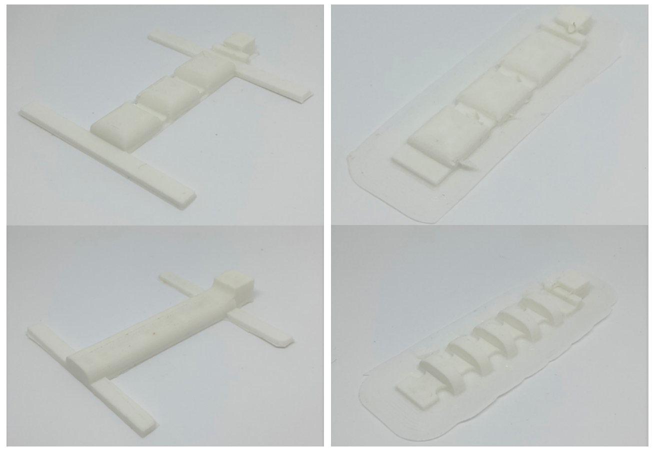


Figure 47
Initial 3D printed actuator prototypes

Figure 48
Pneumatic soft robotic hand (Scharff et al., 2017)

Initial 3D Printed Prototypes

The first attempt to test this idea was to transfer the concept from the low fidelity inflatables and the TPU heat sealed textiles into the a 3D printing structure. The first prototype of the 3D printing structures included a hollow inside with inflatable pockets and a "skeleton" structure replicating the design of the balloon + cardboard prototypes. The idea was that when attached to a piece of textile, it would create a curve bending textile similar to the previous prototypes created. The prototype was printed with TPU 95A flexible material (as was recommended in the pneumatic chiral structures paper) on an Ultimaker 3. It was found that despite the promising results from the chiral structures, the prototype created was stiffer than expected and showed minimal deformation when inflated. This is was due to the high wall thickness used in this prototype (1,2 mm) and the geometry of the actuator.

As this is a new material, the design from the balloon + cardboard prototype cannot be replicated exactly, and a new design needs to be created that fits the material properties better. To improve the performance of the 3D printed actuators, TU Delft's soft robotic hand project was taken as inspiration to design a more flexible inflatable structure. By studying the geometry of the robotic fingers, it was identified that the bellows or inflatable pockets need to be significantly larger and the gaps in between the bellows should be thinner to act as a hinge as can be seen in Figure 48.

As seen on Figure 47, the samples were improved based on the soft robotic finger design to improve the bending deformation. While the first three samples showed minimal actuation due to their high stiffness still, the prototype mimicking the soft robotic finger geometry did show significant deformation. Despite the success of the robotic finger like actuator, the actuators were not fully airtight, therefore, they had loss of pressure due to air leakage which affected their deformation. This issue proves to be a grand challenge of 3D printing inflatables and will be further addressed in the Chapter 5.

With the first successful 3D printed actuator created, Other questions about the material possibilities arose:

1. Can the actuators be printed directly on textile?

2. Can multiple "branches" of the actuator be printed together to create more complex movements?

3. Can the actuators create in-plane deformation on the textile similar to chiral structures?

Printing Directly on Fabric

Using the actuator samples from the initial prototypes, an attempt was made to print the structure directly on fabric. Lycra fabric was used as it is commonly utilized in 4D textile research due to its stretchability when pre-tensing the textile. For the purposes of this test, the textile was placed on the printing bed using binder clips, but not pre-tension to avoid deformation when removed from the bed. On the printing settings, the printing head was offset by the thickness of the fabric (0,3mm) and the actuator was printed directly on the fabric. The print was completed successfully, yet the actuator had noticeable gaps in the structure causing air leaks compared to when printing the traditional way on the printing bed. Additionally, the adhesion of the actuator to the textile was less than ideal as it was quite easy to remove the actuator from the textile by hand with little force. Both the poor print quality of the actuators when printing directly on textile and the poor adhesion of the 3D print to the textile are two main issues that need to be address in order to successfully produce this material.

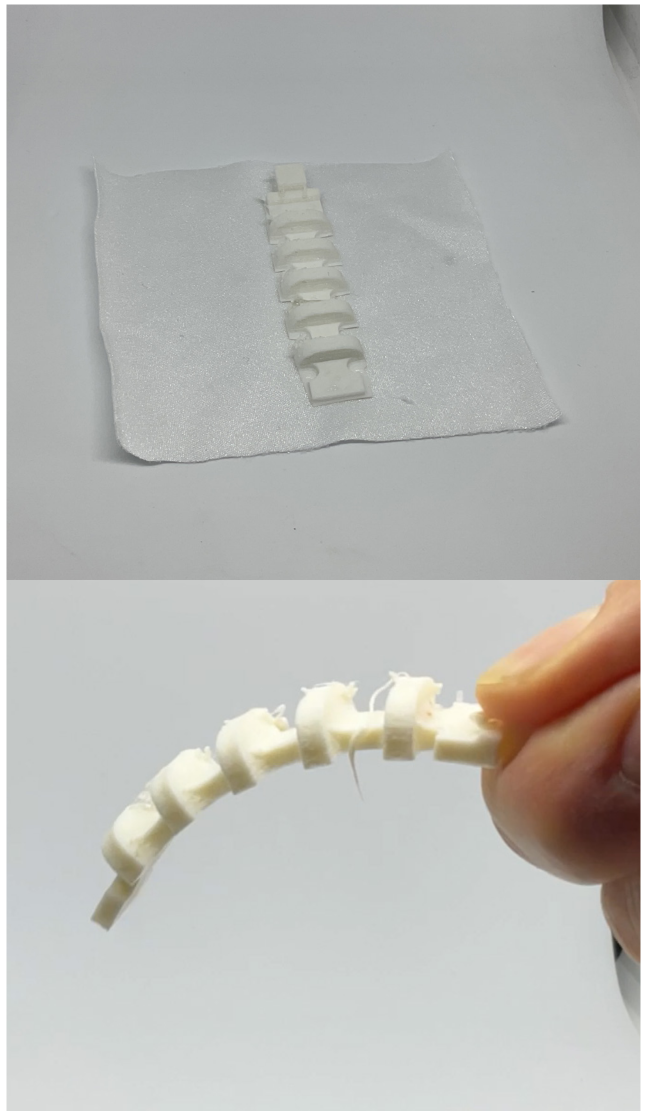
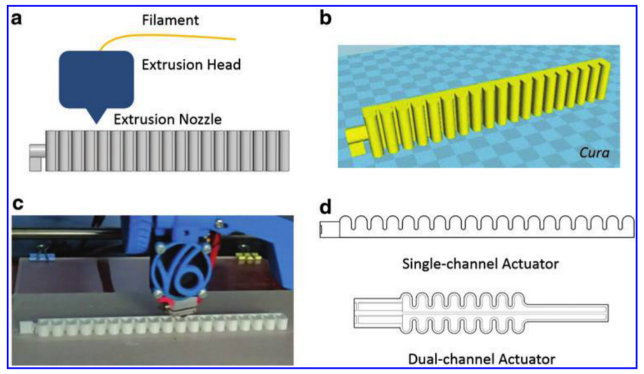


Figure 49
Actuator printed on textile (it detached from fabric during actuation)

Improving the Actuator

Using the actuator Sample 4 from the previous test, an attempt was made to print the structure directly on fabric. Lycra fabric was used as it is commonly utilized in 4D textile research due to its stretchability when pre-tensing the textile. For the purposes of this test, the textile was placed on the printing bed using binder clips, but not pre-tension to avoid deformation when removed from the bed. On the printing settings, the printing head was offset by the thickness of the fabric (0,3mm) and the actuator was printed directly on the fabric. The print was completed successfully, yet the actuator had noticeable gaps in the structure causing air leaks compared to when printing the traditional way on the printing bed. Additionally, the adhesion of the actuator to the textile was less than ideal as it was quite easy to remove the actuator from the textile by hand with little force. Both the poor print quality of the actuators when printing directly on textile and the poor adhesion of the 3D print to the textile are two main issues that need to be address in order to successfully produce this material.



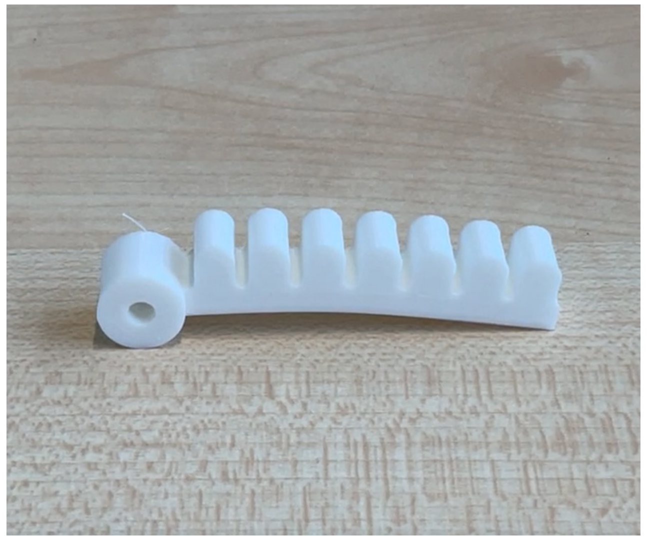


Figure 50
Improved actuator with new printer settings

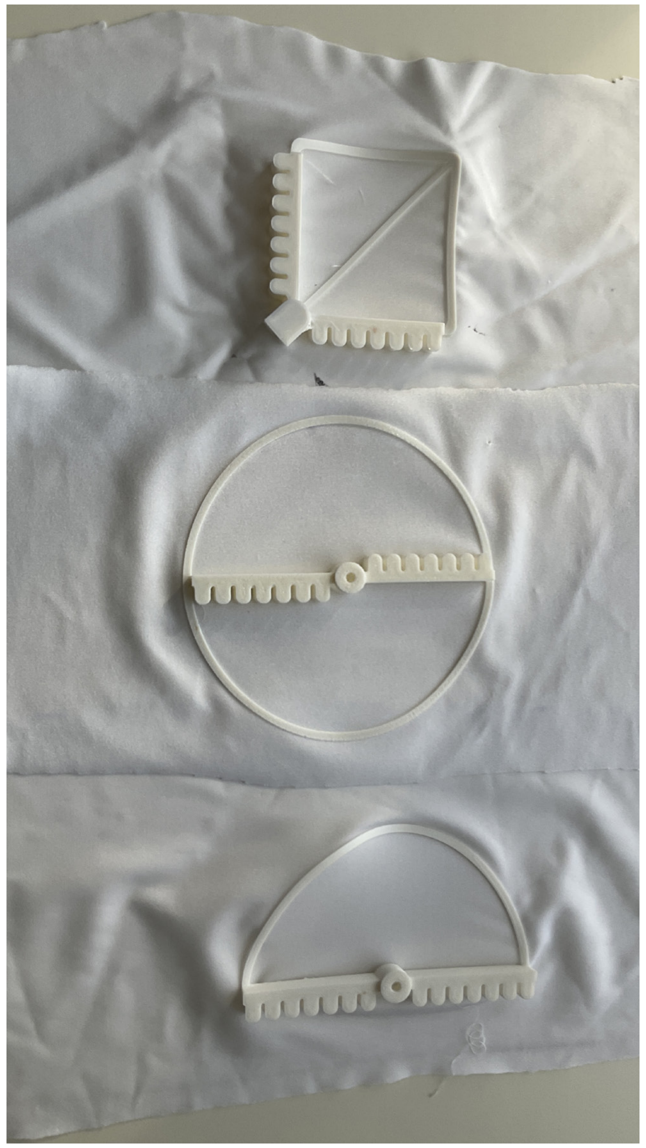


Figure 51
Actuators printed on textile prototypes

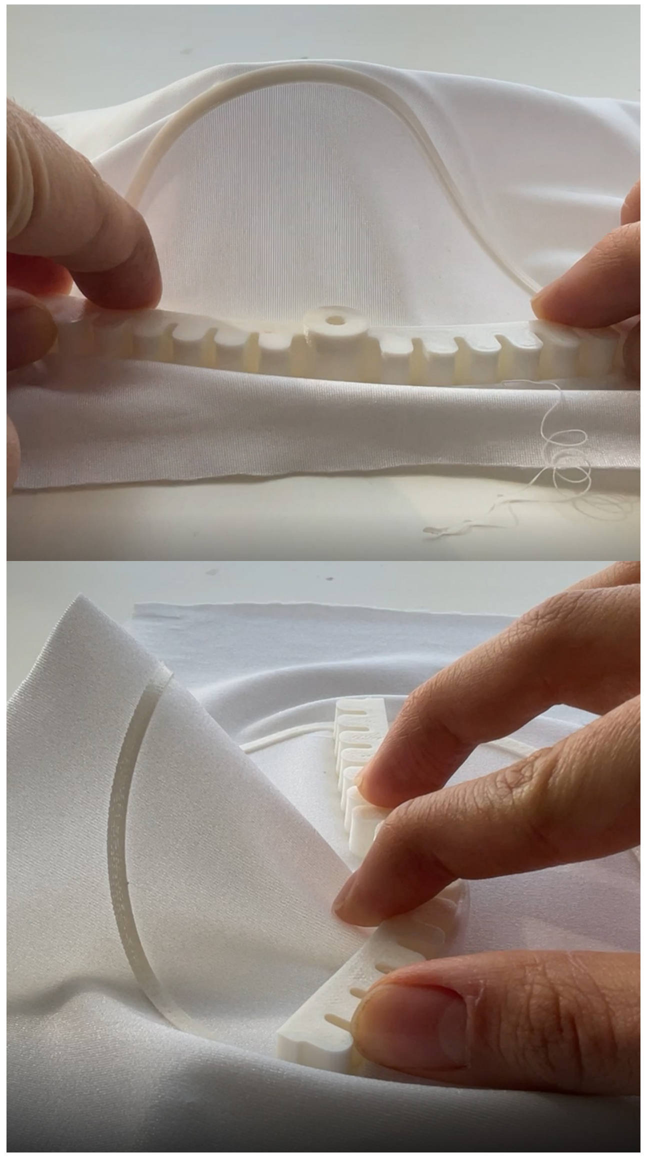


Figure 52
Example of expected actuation (actuators were not airtight)

Printing the Improved Actuators onto Textile

Following on the success from the bellow actuator printed with Ultimaker TPU 95A, the idea arose to use the deformation of the bellow actuator to create a larger deformation on the overall structure of the textile. This is done by combining the design of the bellow actuators with a patterned 2D design serving as the structure or skeleton of the textile, which is then directly printed onto the fabric. This additional 3D printed structure serves a similar purpose to the cardboard skeleton created for the low fidelity balloon prototypes as it helps transfer the deformation from the actuator to the textile. Since the actuators show improved performance when printed sideways, this would create an in-plane deformation on the textile if they are printed directly on the textile. These designs would essentially function on the principle that the actuator would deform causing the 3D printed structure to buckle out-of-plane and create different 3D forms. The prototypes exploring this principle are shown in Figure 51 and 52.

This differs from the previous attempts at actuating textile as now the bellow actuators (active material) are indirectly actuating the textile (the interface material) as the shape change is transfer through the 3D printed "skeleton" structure. This idea is promising as it takes advantage of the stretchability and tension of the lycra to transform small in-plane deformations of the actuators into larger 3D shapes on the textile. Additionally, having the actuator indirectly actuating the fabric allows for a more surprising interaction as the shape change becomes harder to predict. With the active material interacting with the interface material indirectly as shown in these prototypes, it opens up the possibility of separating the two materials during fabrication in order to address the airtightness and textile adhesion issues found in the previous prototypes.

Separating the Actuator and Textile

Despite the many attempts to print well performing prototypes directly onto textile, it was found that printing the actuators directly on the textile increased the chance for imperfections in the print causing an increase in air leakage thus reducing the deformation performance. Additionally, it was noted that the adhesion of the 3D printed material on the textile was also of poor quality now. Although it would be ideal for the 3D printed inflatables to be fully integrated into the textile, these complications suggest that the materials need to be fully understood and characterised separately before they can be integrated with each other. Therefore, the 3D printed actuator and 3D printing within textiles will be explore separately and combined to create a hybrid shape changing material to simplify the problem

Connecting the Actuators to the Textile

With the actuators and the 3D printed textile being separate components, a method of connecting and transferring the shape change from the actuator to the 3D printed textile must be created. To solve this a physical connection point can be created with the 3D printed material on both the actuator and the 3D printed pattern on the textile or some temporary adhesive such as Velcro can also be used. For the next prototype, attachment points were created on at the ends of the actuator that allow the actuator to easily click onto the textile as shown in Figure 54. As previously noted, it is best if the actuator is not fully attached to the textile as the tension of the textile will reduce the deformation performance. Instead, by only attaching the actuator at two points, a simple mechanism is created that causes the two attachment points on the textile to come together as the actuator deforms and the 3D printed pattern on the textile to deform out-of-plane as the points come closer together to each other.

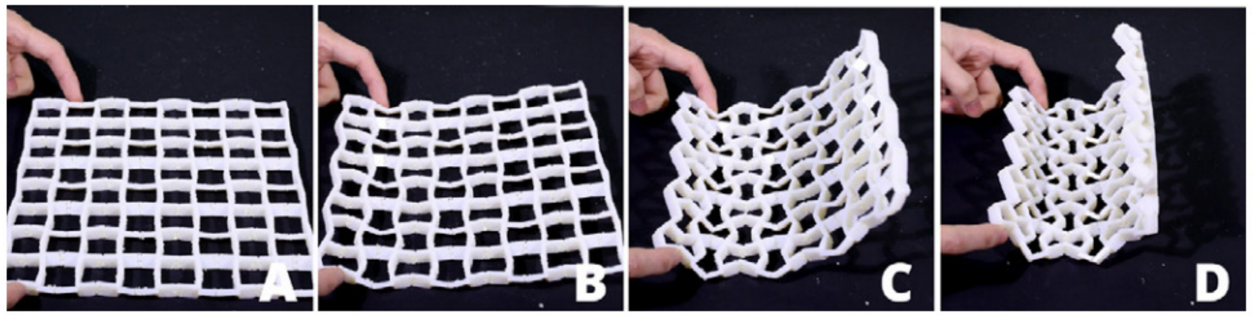


Fig. 18. A 2D tessellation of spatial transformation of bending and basic units. This tessellation creates a bending sheet.

Figure 53
KinetiX actuated metamaterials (Ou et al., 2018)

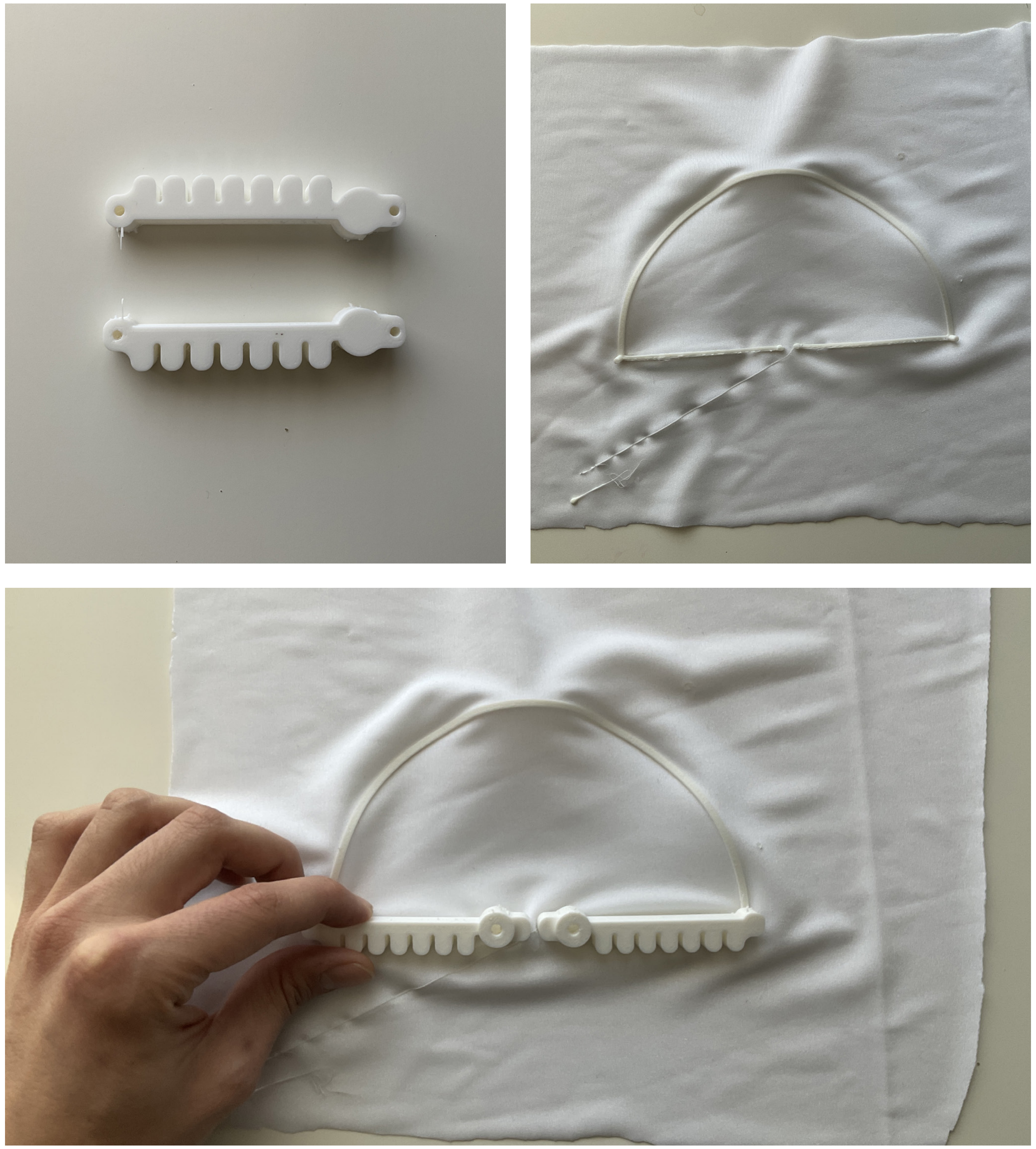


Figure 54
Separating the actuators from the 3D printed textile

4.3 PROOF OF CONCEPT PROTOTYPE

The initial material exploration on 3D printed textiles provided the following insights:

Combining pneumatic structures with textile directly during the printing process is difficult due to the fragility of maintaining airtightness in the actuators and poor adhesion to the textile.

The actuated shape of the textile is influenced by the 3D printing pattern printed on the textile and the location of the actuator.

Actuators are able to create both in-plane and out-of-plane deformation depending on the location placed on the textile.

Multiple actuation points on the textile has the potential of creating more complex textile deformations.

Based on the insights from the initial exploration, the following proof of concept prototype is presented that will be further explored systematically in the next chapter. The proof-of-concept prototype consists of three component:

1. **A TPU pneumatic actuator**
2. **A TPU 3D printed pattern**
3. **A mesh fabric**

This basic prototype showcases a circle 3D printed pattern with an internal cross structure for additional stiffness that is directly printed on the mesh fabric. The TPU pneumatic actuator contains attachment points at the end of the actuator that click onto the 3D printed pattern on the fabric. When the actuator is inflated, it creates an in-plane or out-of-plane deformation depending on its orientation on the fabric that causes the two attachment points to come together and deform the textile into a 3D shape. The textile has a 3D printed pattern that determines the final actuated shape based on parameters such as outline shape, material width/thickness, and pattern density. The material proof-of-concept is demonstrated physically with the prototype shown but can also be simulated digitally. The proof-of-concept showcasedhas new modifications to the actuator and textile parameters that will be covered further in the next chapter.

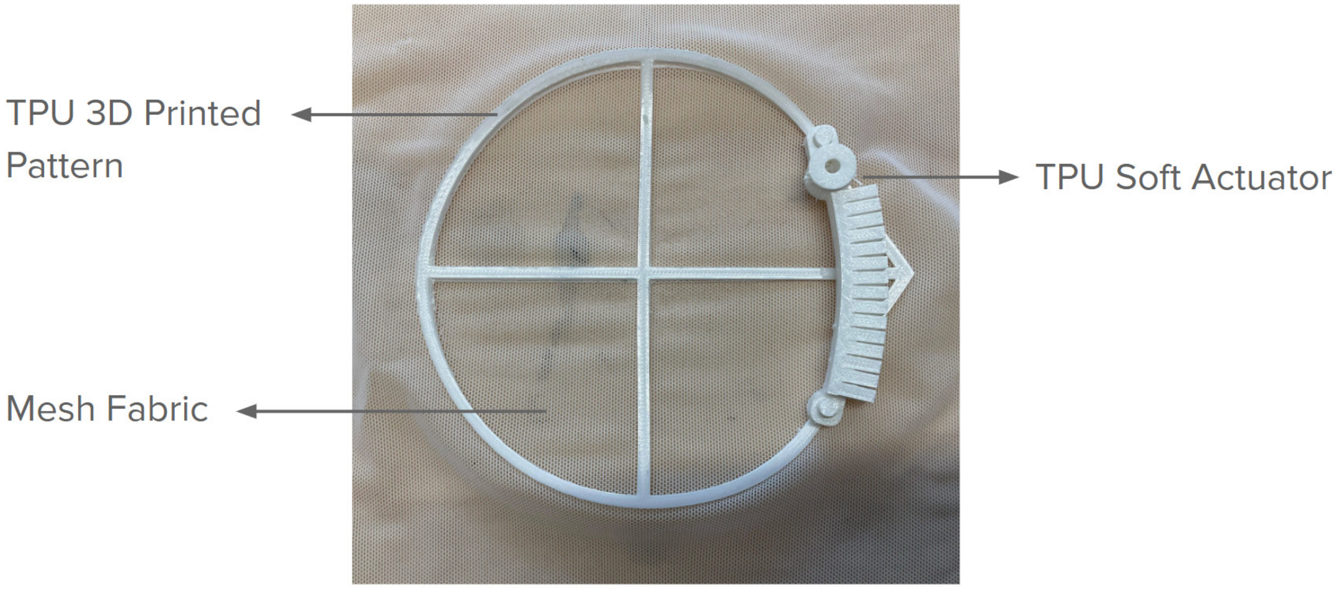


Figure 55
Overview of material components

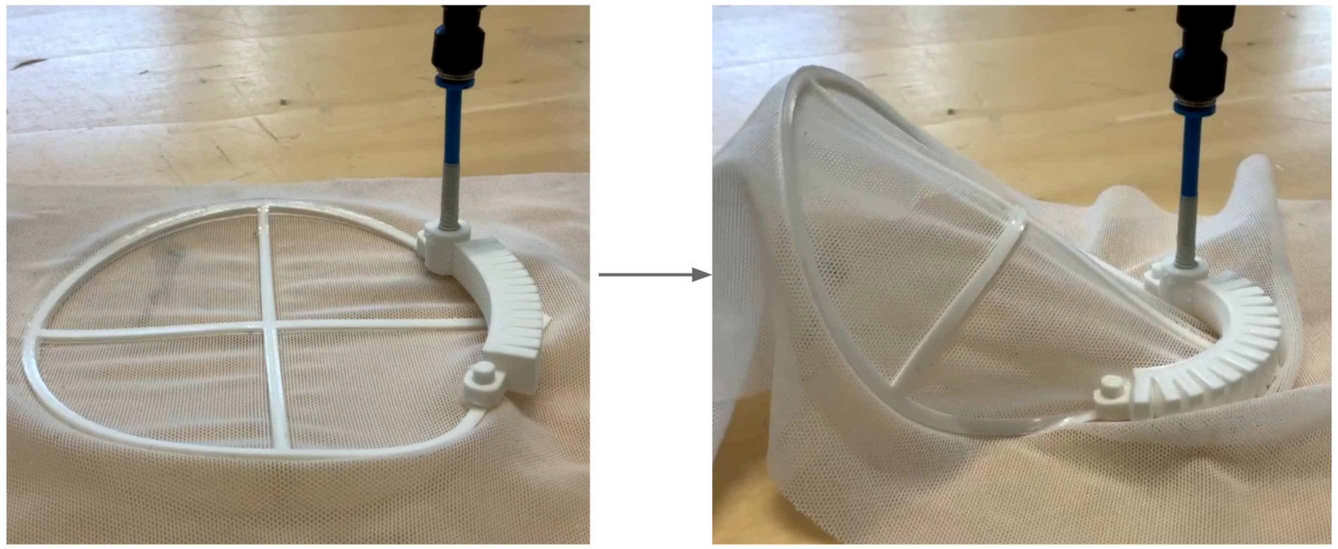
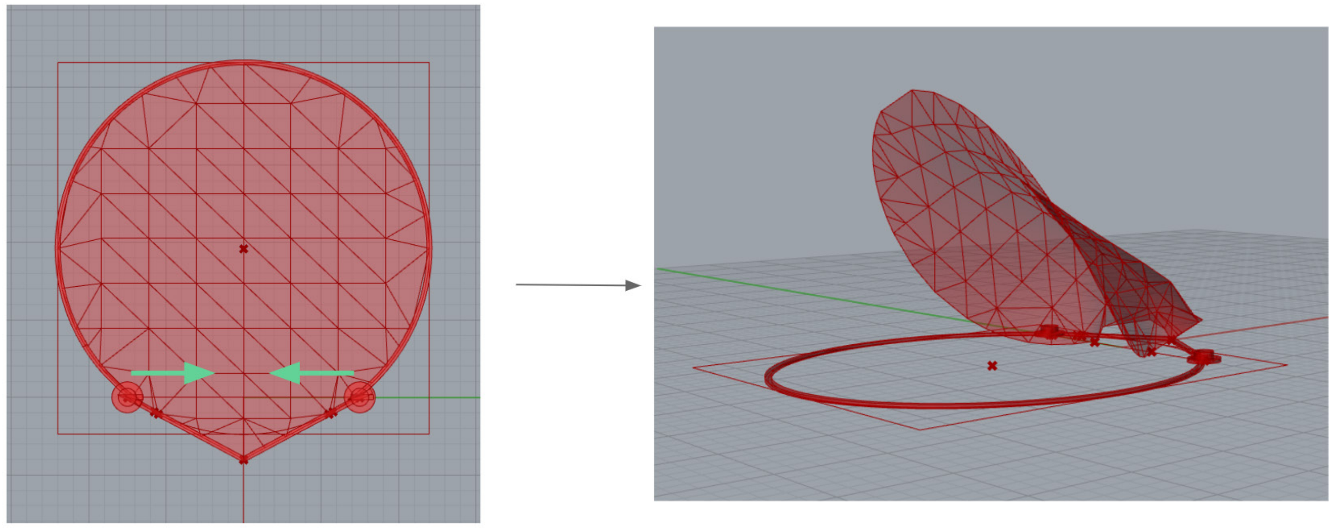


Figure 56
Proof of concept prototype



Parametric Design

Simulated Active Form

Figure 57
Proof of concept prototype simulated using Grasshopper

Computational Design Potential

Similar to simulating the deformation on 4D textiles due to pre-tensioning of the textile, a test was done using Grasshopper to prove that the proof-of-concept material has potential for computational design. This simulation uses an inner mesh that represents the fabric with an applied parametric shrinkage tension (meaning the edges of the mesh want to contract in length). The outline of the structure represents the 3D printed portion as is modelled by dividing the curve to into multiple rod component with a fixed length that can bend to create complex curves. The shape change in the simulation is actuated by moving two points of the structure closer to each other causing the structure to buckle and change shape. The moving of two points simulates what happens when the bending actuator is inflated and brings the two attachment points closer together. Based on the simulation of the basic circle design, it can be seen that the proof-of-concept has the potential for computational simulation in future work of the material. In Chapter XX, a more detailed digital simulation is presented using the final shape changing material.

Now that the material to research has been finalized, the next chapter will provide a more systematic exploration of the material and determine the best methods for fabrication to allow future designers to replicate the work in the future.

CHAPTER FIVE

UNDERSTANDING THE MATERIAL

This chapter expands on the material proposal from the previous chapter by systematically exploring the parameters of the actuator and the 3D printed textiles separately. The parameters include both material qualities and fabrication processes. The chapter begins with an introduction into the material taxonomy followed by the systematic tinkering research, which is summarized into multiple key insights that come together in the final section to create a guide for successful fabrication of the material.

5.1 MATERIAL TINKERING PROPOSAL

Figure 58
Inflatable prototype from Fabricflation project (Papakonstantinou, 2015)

As shown in the initial material exploration and in both the Pneumatic Chiral Structures and Fabricflation project, printing pneumatic actuators using TPU filament, specially when combined with textiles, has some complications. The first prototypes created showed difficulty in balancing the airtightness and deformation of the actuator in addition to having adhesion issues with the textile. For this reason, the proof-of-concept prototype presented in Chapter 4 proved that by separating the actuator and the 3D printed textile, it is possible to:

1) Optimize the components individual for best performance and ease of fabrication.

2) Study the material from a computational modelling perspective in which parameters can be tweak to achieve different 3D forms

Figure 59 showcases the how the fabrication of the 3D printed pneumatic textiles has been broken down into separate components by separating the active element (actuator) from the interface element (3D printed textile). Studying the components individually can still provide insightful information into the fabrication of these materials, but it loses one special quality about the material proposed by Fabricflation: integration into the textile. Integration of the active element directly onto the textile does pose some additional opportunities for more integrated wearable applications, yet the two components must first be studied separately before this direction can be explored. As shown in Fabricflation, their brief exploration of integrating the 3D printed actuator directly on the textile proved that further research is still needed to optimize the deformation and airtightness of the actuators. The material tinkering shown in this chapter contains a more structured, guided exploration of the parameters with the final goal of understanding how to optimize the fabrication and performance of both the actuators and 3D printed textiles. With a thorough understanding of these materials individual, a future research project can then use the recommended techniques to create the integrated 3D printed pneumatic textiles.

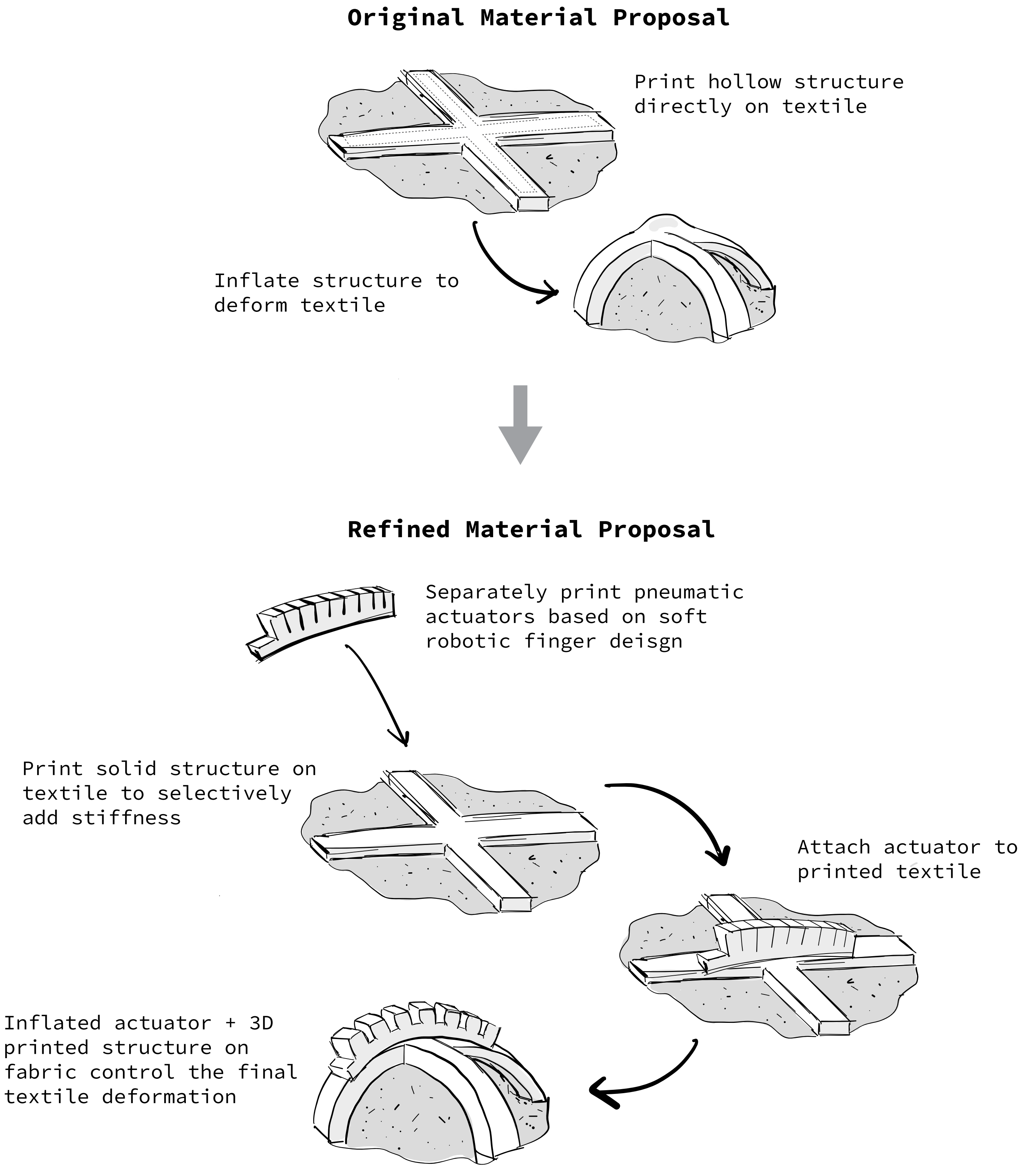


Figure 59
Material proposal overview

5.2 MATERIAL TAXONOMY

Figure 60
Material Taxonomy for Pneumatic Textiles

The material taxonomy defines the ingredients, processes, structures, and other parameters that can be explored within a material. The 3D printed pneumatic textiles explored in the material tinkering is a shape changing material that consists of two components: 3D printed pneumatic actuators and 3D printing within textiles. The material taxonomy reflects this matter by including some categories that apply only to one of the individual components. Although the material tinkering proposal defines each of the components and how they interact with one another, it is critical to note that the material ingredients of the actuator and textile have not been fully defined yet in the material taxonomy. This can differ from other material taxonomies in MDD where a very specific material is being studied. This openness in the scope of the ingredient of the materials is important as it allows for exploration of other materials that might be best suited for shape changing applications. The material taxonomy for the 3D printed pneumatic textiles is shown in Figure 60. A new section was added to the taxonomy, the pneumatic parameters, which includes other considerations that are required when fabricating a pneumatic system.

Systematic Tinkering Overview

From the material taxonomy, the most critical parameters were tinkered with to understand how changes in the material of both the actuator and the 3D printed textile affected the shape changing behavior. The first goal of the systematic tinkering was to develop a reliable fabrication process to create both the actuator and the 3D printed textile. This is due to complications in the fabrication process found during the initial material exploration phase such as difficulty with airtightness and adhesion of 3D printed material to textile. The second goal of the systematic tinkering was to maximize the shape change deformation and variety of forms possible when combining the actuator and 3D printed textiles together. The systematic tinkering section presents the actuator and 3D printed textile tinkering separately to fully understand the components from an individual level and later explores how they influence each other.

To help achieve the goals stated, the following research questions were asked during tinkering:

[1] WHAT IS THE BEST 3D PRINTING PROCESS TO CREATE THE ACTUATORS AND 3D PRINTED TEXTILES?

[2] HOW DOES THE USE OF DIFFERENT MATERIAL TYPES AFFECT THE PERFORMANCE OF THE ACTUATORS AND THE 3D PRINTED TEXTILES?

[3] HOW DOES THE GEOMETRY AND SIZE OF THE ACTUATORS AFFECT ITS SHAPE CHANGING PERFORMANCE?

[4] HOW DOES VARIATION IN PATTERN AND 3D PRINTED MATERIAL THICKNESS AFFECT THE DEFORMATIONS OF THE 3D PRINTED TEXTILE?

[5] WHAT COMBINATIONS BETWEEN THE ACTUATORS AND THE 3D PRINTED TEXTILES WORK BEST IN CONJUNCTION TO ACHIEVE INTERESTING SHAPE CHANGING FORMS?

5.3 ACTUATOR FABRICATION

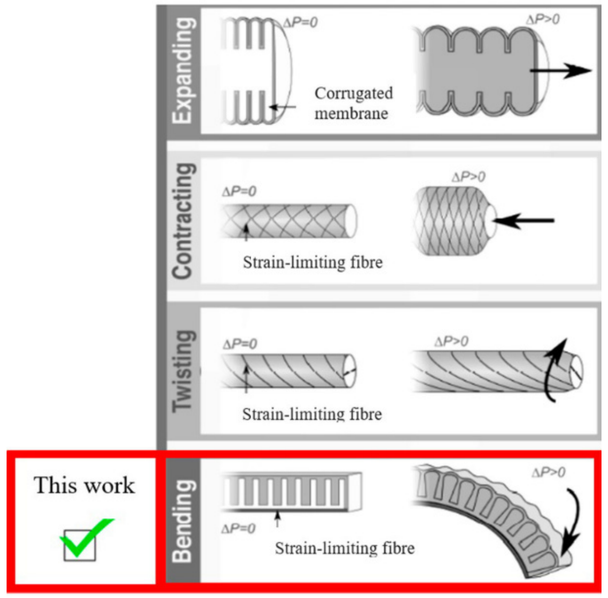


Figure 61
Types of pneumatic actuators (Zolfagharian et al., 2020)

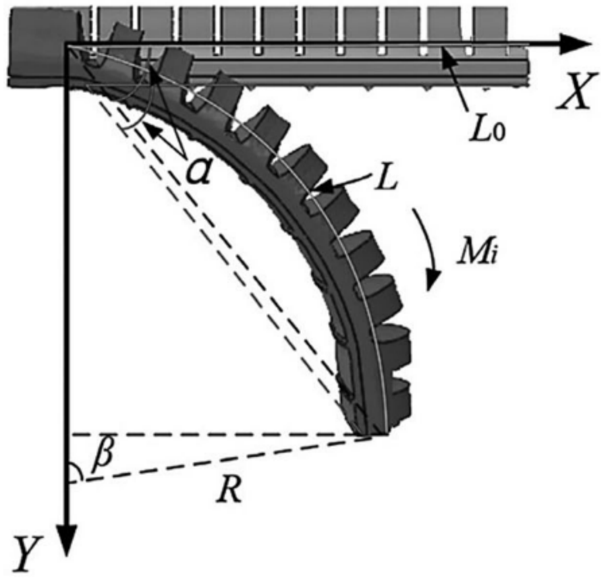


Figure 62
Geometry of bending actuators (Yap et al., 2016)

The tinkering begins with exploring 3D printed pneumatic actuators. Pneumatic actuators provide a high-force, controllable, and reversible method to induce shape change. To maximize the performance of these actuators, literature on 3D printed pneumatic actuator was consulted to understand the basic soft robotic principles underlying it, how geometry influences deformation, possible materials for fabrication, and to select the best printing process possible.

Pneumatic Soft Actuators

Pneumatic soft actuators uses soft, flexible actuators or mechanisms without any traditional mechanical parts. Soft pneumatic robots are created out of a hollow structure made with a flexible material that when inflated changes shape and creates motion. The types of movement possible vary based on the structure geometry of the soft robot. In summary, the basic movements can be condensed into expansion, contraction, twisting, and bending. For this project, bending actuators were selected as they are the most widely studied and they can provide both out-of-plane and in-plane deformation of the textile. Due to time limitations of the master thesis, other actuator types were not explored, yet it is recommended to explore these other types in future projects to obtain a better understanding on how they can contribute to the creation of shape changing interfaces. For more information on how other types of pneumatic actuators are currently being used in shape changing interface research, refer to the MorpheesPlug project (Kim, Everitt, Tejada, Zhong, & Ashbrook, 2021).

Bending actuators work with a simple principle by having a bottom thicker or inextensible layer and a top thinner or extensible layer. When air is pumped into the actuator, the top extensible layer will inflate causing a higher expansion at the top layer than at the bottom layer. This results in the actuator bending depending on the pressure applied. The amount of deformation created by the bending actuator is determined by the following parameters:

The amount of deformation created by the bending actuator is determined by the following parameters:

Material Stiffness

Airtightness

Geometry

Air Pressure

These parameters were explored in the following tinkering process to maximize the performance of the actuator.

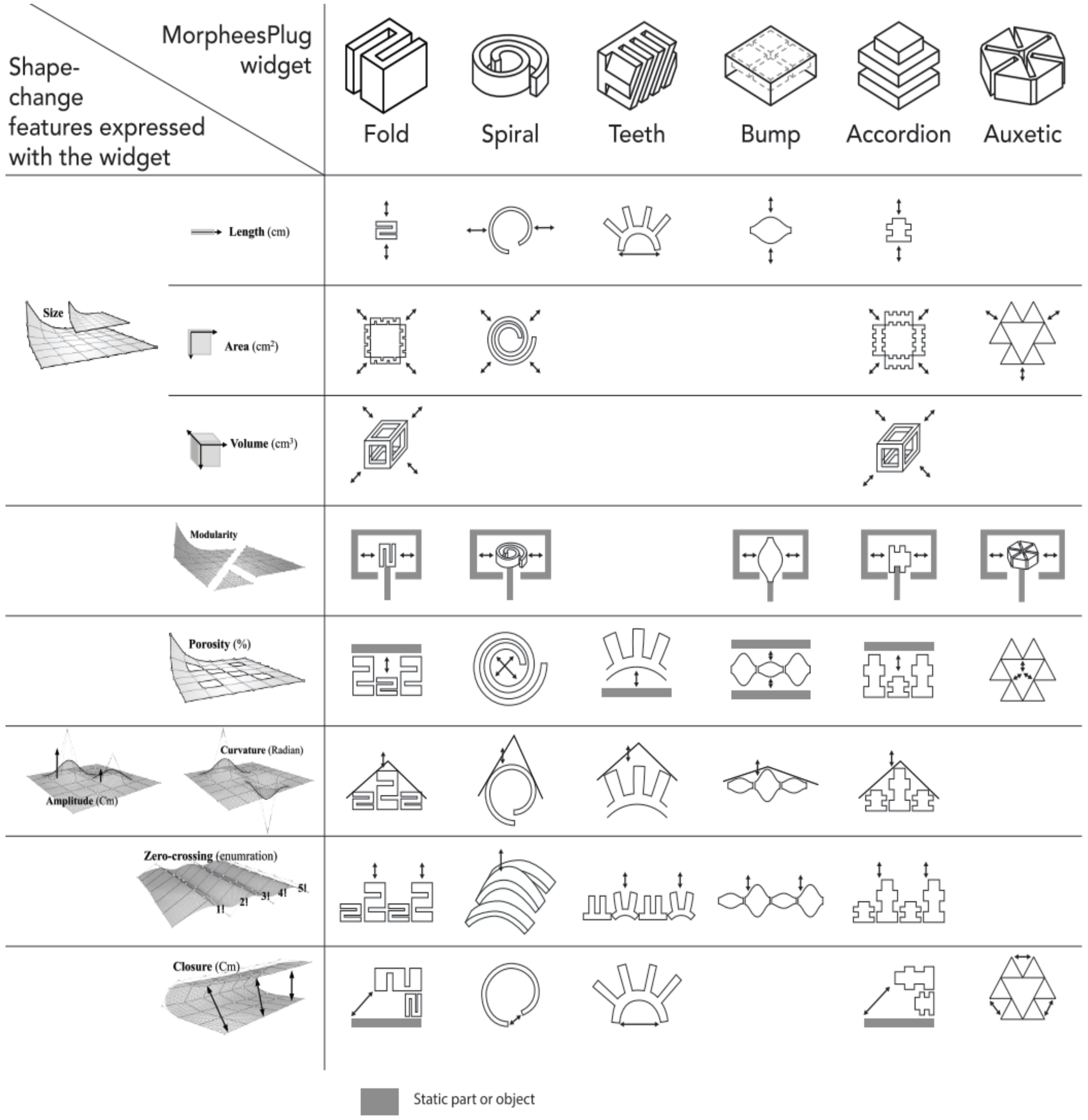


Figure 63
3D Pneumatic actuators for shape changing interfaces (Kim et al., 2021)

5.4 ACTUATOR GEOMETRY

Insight 1

Straight bellow actuators have the highest curvature deformation when inflated.

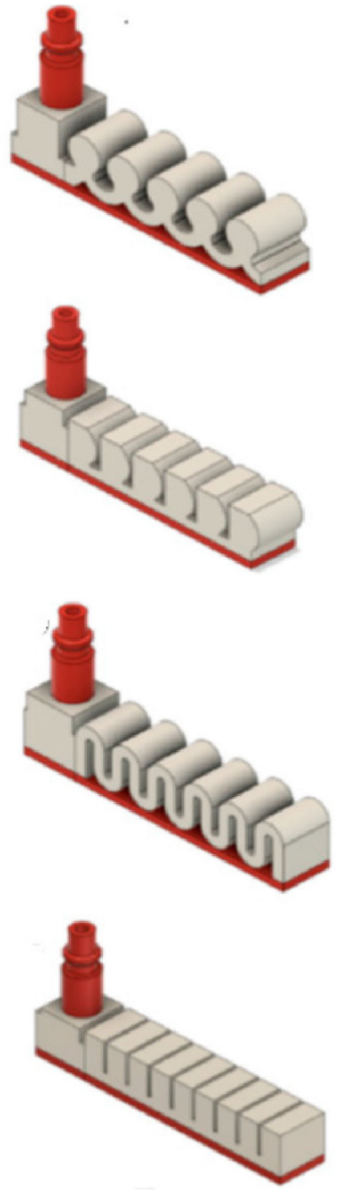


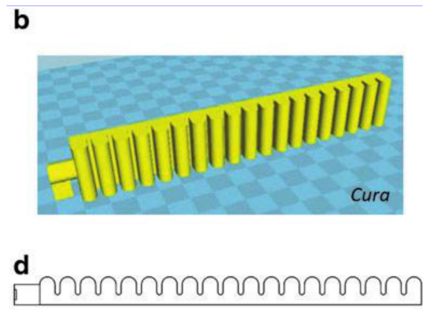
Figure 64
Types of bending actuators (Zolfagharian et al., 2020)

Bellow Shape

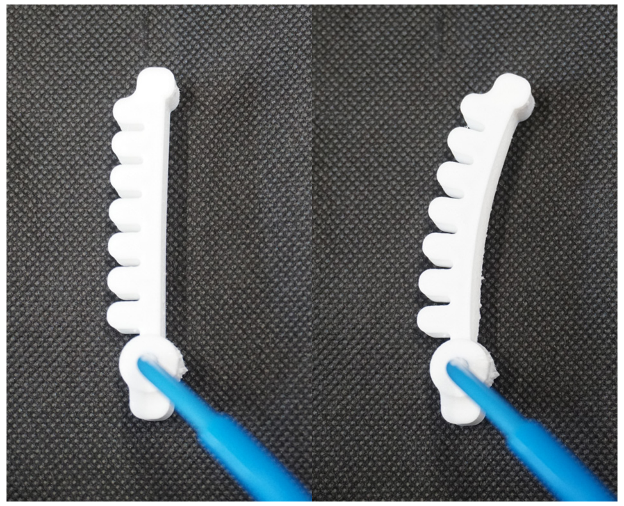
The bellows of the actuator are the small air pockets found in pneumatic actuator that get inflated and maximize the deformation of the actuator. As seen in the initial prototypes, if there are no bellows in the pneumatic actuators, the deformation will be relatively small. By using 3D printing, there are endless possibilities into the geometry of the actuator and its bellows. For example, MorpheesPlug proposes 6 different types of pneumatic actuator geometries that can be created to achieve different types of shape change (Kim et al., 2021). That being said, there are a few geometries for bending actuators reported in literature that have been thoroughly prototyped and tested to define the one with the highest performance. Zolfagharian et al. provides the 4 geometries shown in Figure 64 with the waveform and straight bellows being the best performing ones. Additionally, Yap et al. also proposed the rounded bellow actuator, which inspired the actuator sample during the initial exploration.

These three geometries were printed using Ultimaker TPU 95A with a wall thickness of 0,8mm to compare their deformation with each other. When inflated at 2 bars, the straight bellows actuator proved to have the highest deformation among the three. This result was expected as the straight bellow is able to pack the largest amount of bellows into its geometry thus maximizing the deformation. This is because when the bellows inflate, they push against one another thus causing the actuator to curl more and more

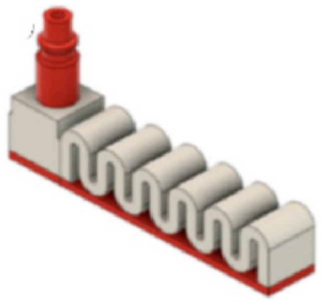
SAMPLE A1: ROUNDED BELLOWS
Material: UM TPU 95A
Wall Thickness: 0,8mm
Dimensions: 80x16x12mm



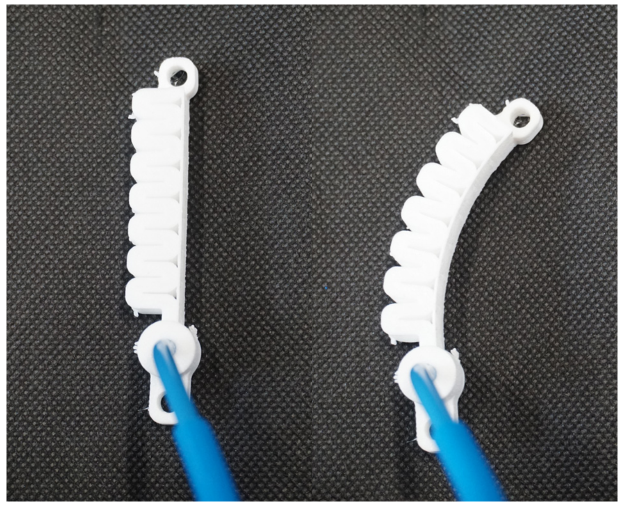
(Yap et al., 2016)



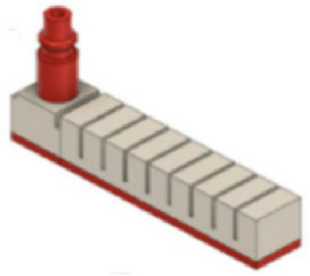
SAMPLE A2: WAVEFORM BELLOWS
Material: UM TPU 95A
Wall Thickness: 0,8mm
Dimensions: 80x16x12mm



(Zolfagharian et al., 2020)



SAMPLE A3: STRAIGHT BELLOWS
Material: UM TPU 95A
Wall Thickness: 0,8mm
Dimensions: 80x16x12mm



(Zolfagharian et al., 2020)

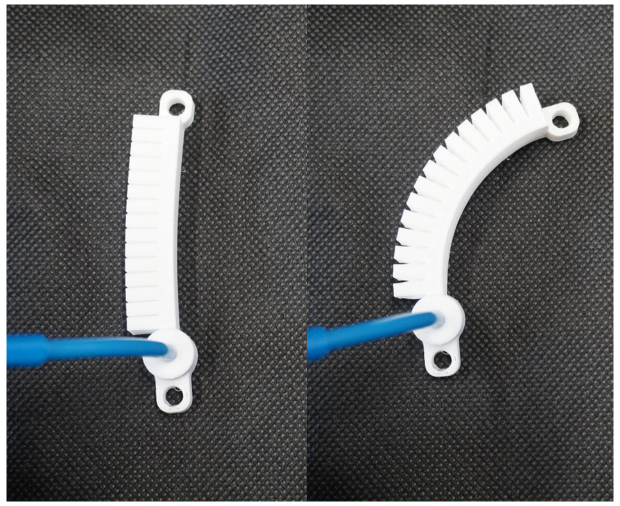


Figure 65
Bellow shape prototypes

Insight 2

A shell thickness of 0,8mm maximizes the performance of the actuator.

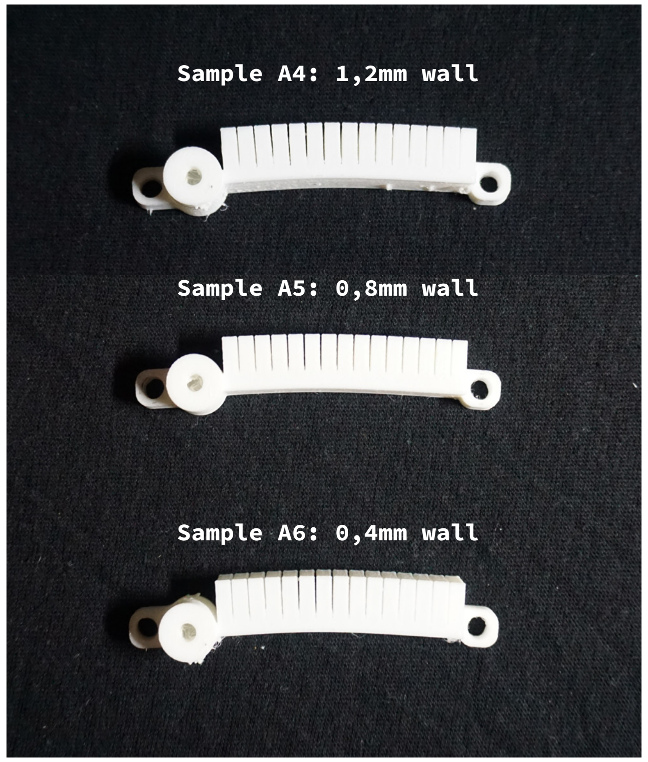


Figure 66
Material wall thickness prototypes

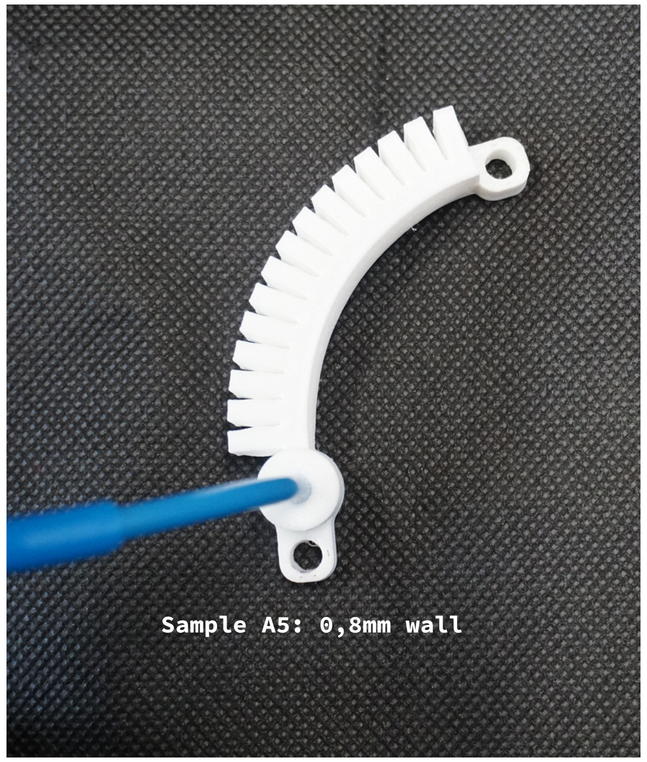


Figure 67
Actuator with 0,8mm wall thickness actuated

Material Wall Thickness

To maintain airtightness in the actuator, a balance between the flexibility of the actuator and the airtightness needs to be maintained. This property is determined by the wall or shell thickness of the actuator. A higher thickness produces an airtight actuator, but its higher stiffness reduces the deformation possible. A lower thickness is often difficult to print without air leaks, yet the actuator remains very flexible. This was tested by printing the actuator with varying wall thickness in multiples of the nozzle diameter (0,4mm) as that determines the minimum sidewall thickness.

The test consisted of the same bellow actuator design printed with varying wall thicknesses of 0,4mm, 0,8mm, and 1,2mm printed with Ultimaker TPU 95A.
The 0,4mm actuator was very flexible, yet had large air leaks preventing from inflating even when using the air compressor.

The 1,2mm actuator was airtight, yet was too stiff to show any significant deformation.
The 0,8mm actuator was the perfect balance as it was flexible and airtight enough to deform when inflated. This confirmed by the recommendations of Kim et al. and Yap et al. and Kim et al. of printing soft pneumatic actuators with 0,8mm wall thickness.

The actuator still had some minor air leaks that prevented it from being airtight. To improved this, the printing settings needed to be adjusted to further improve the printing process.

5.5 PRINTING PROCESS

Although the current actuators samples are able to deform when inflated, they currently require a large pressure source (>2 bars) and still have minor air leaks. Therefore, the next challenge to tackle was to determine the printing parameters that can achieve a successful airtight structure while still maintaining flexibility. It has already been determined that the standard printer settings produce gaps and air leaks in the structure reducing the performance of the actuator. Let's explore the most critical printing parameters to achieve more successful prints.

3D Printing Filament

When it comes to flexible 3D printing materials, there are two main contenders: Ultimaker TPU 95A or Ninjaflex TPU 85A. Ultimaker TPU 95A is specially designed to print successfully with Ultimaker printers and produces more consistent, airtight prints compared to NinjaFlex TPU 85A. That being said, Ninjaflex TPU is significantly more flexible than Ultimaker TPU due to its lower hardness, but it is more difficult to print with due to its flexibility. From testing, it was found that prints made with Ultimaker TPU required a large air pressure only possible with a large air compressor (> 2 bars), which creates limitations for controllability of actuation in the future by using a portable air source. In literature of 3D printed actuators such as the MorpheesPlug project, it is recommended to use NinjaFlex TPU 85A due to its higher flexibility.

Type of Printer

When selecting an FDM printer, there are two types: direct drive and Bowden drive. Direct drive pushes the filament directly into the hot extruder while Bowden drive pushes the filament down a long tube into the extruder. To avoid buckling or other issues when extruding flexible materials, it is recommended to use direct drive. In the case of this project, an Ultimaker 3 was used to print the flexible material despite having a Bowden drive and was successful in the end since it is a small printer having a short Bowden tube. Larger Bowden printers such as the Ultimaker 5 did not work in printing airtight actuators during testing.

Printing Orientation

Printing orientation is critical due to the limitations of FDM printers. As the printer creates layer by layer overlayed on each other, it is critical to minimize the complexity of the print in the vertical direction. Thus, it is easier for the printer to print straight vertical walls to ensure successful prints. The actuators created should be oriented sideways on the printing bed and the overhang distance should be minimized (< 4cm) (Kim et al., 2021).

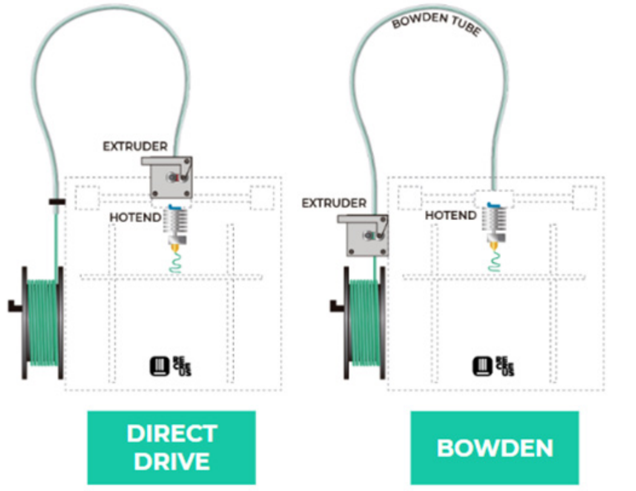


Figure 68
Direct drive vs bowden drive actuator

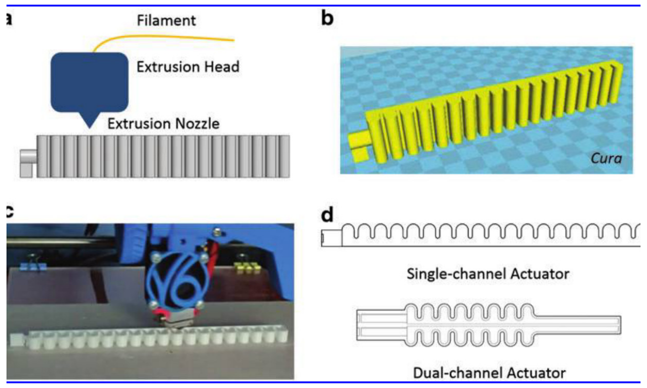


Figure 69
Printing orientation for 3D printed actuators (Yap et al., 2016)

Insight 3

3D printing inflatables require a very slow printing speed (6,5mm/s) to print airtight.

Insight 4

Overextrusion, Outline Overlap, and overhang < 4mm when 3D printing helps to seal gaps during printing to increase airtightness.

Insight 5

Using a needle syringe tip provides a better airtight connection to actuator.

Printer Settings

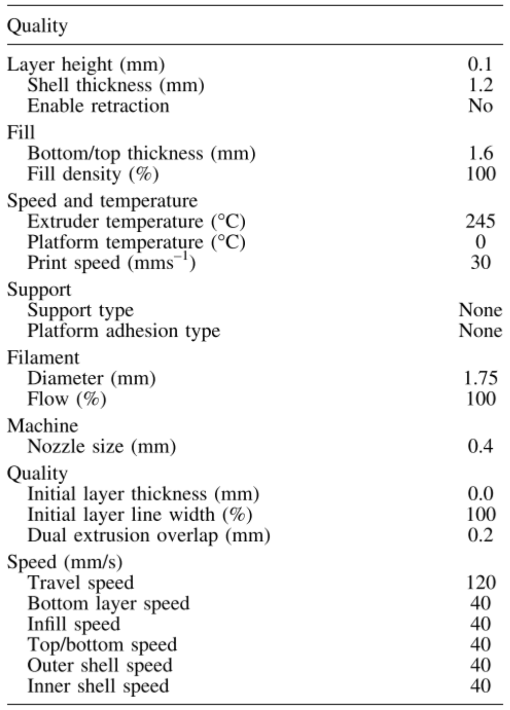
During the initial material exploration and initial tinkering, the recommended settings from Yap et al. were used to improve the airtightness of the actuator. While these settings did improve the airtightness using Ultimaker TPU 95A, it did not produce successful results using the more flexible NinjaFlex TPU 85A as was recommend in the paper when tested on both direct and bowden drive printers. In the midst of the actuator tinkering research, a new paper, MorpheesPlug, was published that showed incredible results with their pneumatic actuators used for shape changing interface design. As seen in Figure 72, these new actuators were able to inflate and expand its walls to a degree not seen before with 3D printed actuators

Based on the promise from their 3D printed inflatable structures, their settings were replicated on the Ultimaker 2 (used in the paper) and Ultimaker 3 using the more flexible NinjaFlex TPU 95A. In both printers, the settings proved to work successfully as their open-source bending actuator was printed fully airtight and could be inflated in a closed loop pneumatic system using a simple medical syringe. An additional tip found in the paper for improving the air source to actuator connection is to print a fully seal actuator, poke a hole on one end of the actuator using a sewing needle, and use a fine syringe needle to connect the actuator to the air source.

These new settings recommend using a much lower speed than other papers. Compared to the other paper that suggests a speed of 40mm/s, the new settings using 6,7mm/s (400mm/min) seem to significantly improve the quality of the prints leading to the elimination of air leaks. Additionally, the overextrusion and outline overlap recommended seemed to seal the gaps between each layer of the print. When inspecting the new 3D prints from close-up, it is difficult to see the 3D printed layers on the surface because of these settings, which help to reduce air leaks.

With the printing process finalized, the possibility of using 3D printing to create pneumatic actuators was finally validated. This new printing process also allows for the use of NinjaFlex TPU 85A to fabricate actuators, which is preferred due to its higher flexibility compared to Ultimaker TPU 95A. The next step was to understand how different parameters in the actuator geometry affect its bending deformation to achieve the best result using the new printing process.

Figure 70
Previously used printer settings with UM TPU 95A (Yap et al., 2016)



Quality	
Layer height (mm)	0.1
Shell thickness (mm)	1.2
Enable retraction	No
Fill	
Bottom/top thickness (mm)	1.6
Fill density (%)	100
Speed and temperature	
Extruder temperature (°C)	245
Platform temperature (°C)	0
Print speed (mms^{-1})	30
Support	
Support type	None
Platform adhesion type	None
Filament	
Diameter (mm)	1.75
Flow (%)	100
Machine	
Nozzle size (mm)	0.4
Quality	
Initial layer thickness (mm)	0.0
Initial layer line width (%)	100
Dual extrusion overlap (mm)	0.2
Speed (mm/s)	
Travel speed	120
Bottom layer speed	40
Infill speed	40
Top/bottom speed	40
Outer shell speed	40
Inner shell speed	40

Figure 71
New printing settings for Ninjaflex TPU 85A from Morpheesplug (Kim et al., 2021)

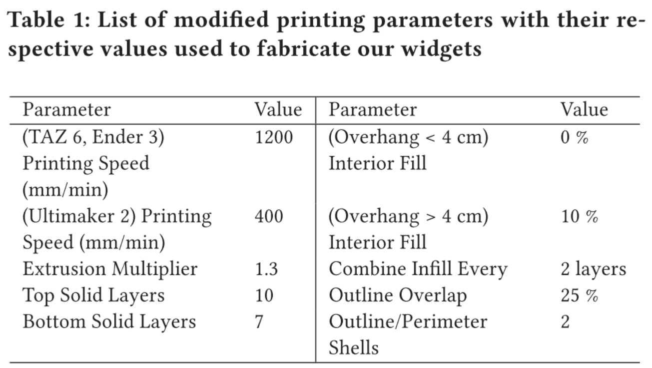


Table 1: List of modified printing parameters with their respective values used to fabricate our widgets

Parameter	Value	Parameter	Value
(TAZ 6, Ender 3) Printing Speed (mm/min)	1200	(Overhang < 4 cm) Interior Fill	0 %
(Ultimaker 2) Printing Speed (mm/min)	400	(Overhang > 4 cm) Interior Fill	10 %
Extrusion Multiplier	1.3	Combine Infill Every	2 layers
Top Solid Layers	10	Outline Overlap	25 %
Bottom Solid Layers	7	Outline/Perimeter Shells	2

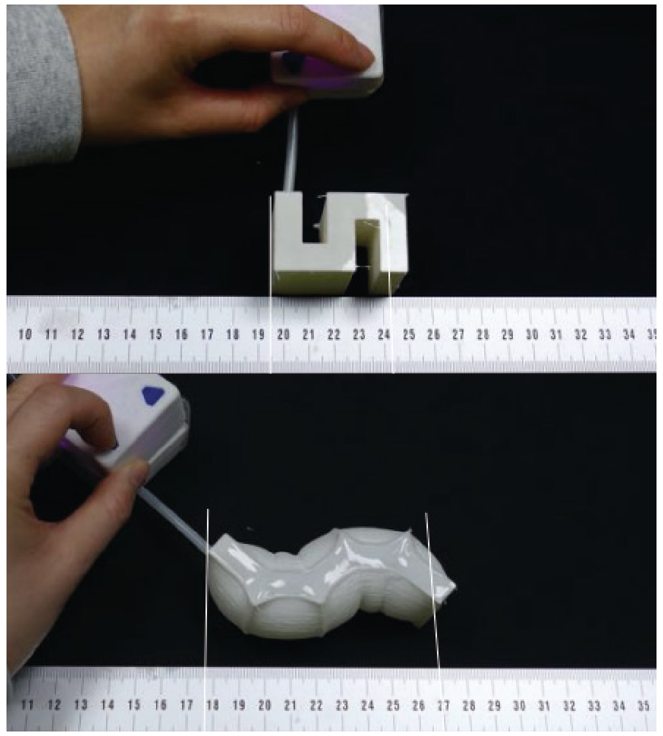
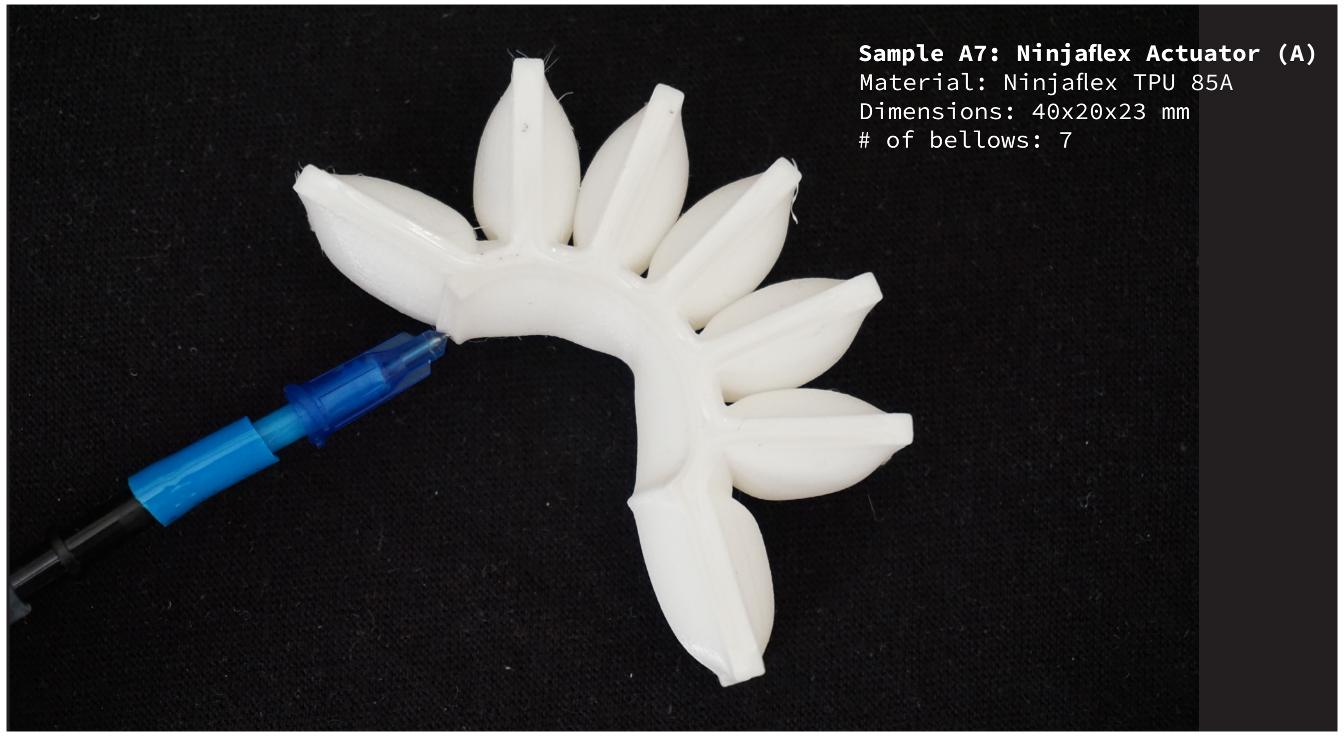


Figure 72
MorpheesPlug Expanding actuator (Kim et al., 2021)

Figure 73
Prototype replicating morpheesPlug settings

Figure 74
3D printed actuator (Ninjaflex TPU 85A)



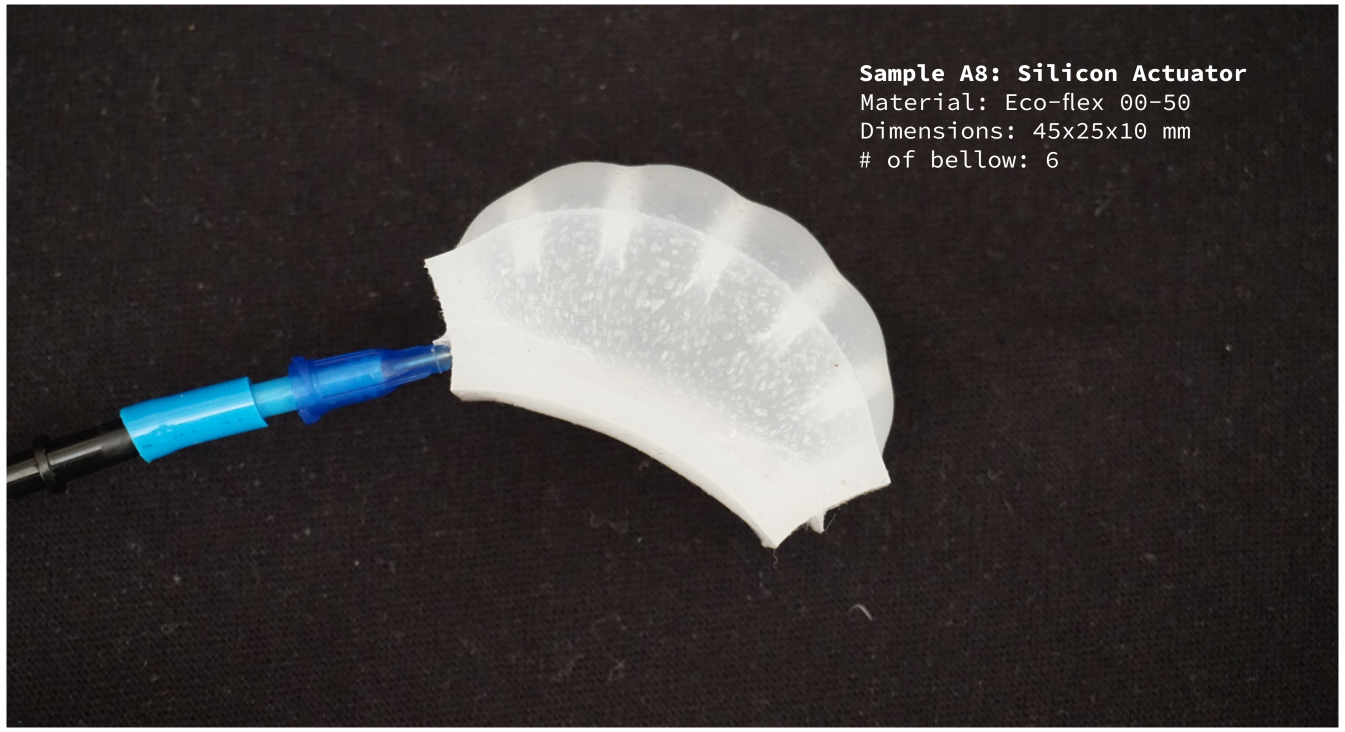


Figure 75
Silicon casted actuator (Eco-flex 00-50)

Insight 6
3D printing actuators provides a quick, accessible method to produce shape changing materials.

Insight 7
3D printed actuators have a higher potential for scalability due to their higher force output.

Alternative Material Process

Material stiffness has an important role in the range of deformation of the actuator and how much force it is able to output. The stiffer the material, the higher the air pressure required to cause it to bend but it is able to produce a higher force output and vice versa. In literature, there are two main methods of creating soft pneumatic actuators: additive manufacturing, which has already been tested, and silicon casting.

Additive manufacturing has the advantage of being able to produce highly complex structures in a short amount of time with little manual effort. Constraints of additive manufacturing include difficulties with creating fully airtight structures and limitations in material stiffness and size of actuator. In traditional FDM printers, the lowest tensile strength achievable is 4 Mpa with the "Ninjaflex" TPU 85A (hardness) filament material.
Silicon casting on the other hand can be used with materials with much lower stiffness and if done properly can successfully create fully airtight structures. That being said, the process is more manually intensive and requires the actuator to be reversed engineered to create the moulds for casting. A common silicon material used for soft robotics is Eco-Flex 00-50 (hardness) with a tensile strength of 2 MPa.

As 3D printed actuators had already been explored during the material exploration phase, a silicon actuator needed to be fabricated to compare the performance of the two. Based on the Soft Robotic Gripper project, an open source mould was modified to a similar size to the current 3D printed actuator. The mould was printed with PLA and the actuator was casted using Eco-Flex 00-50 then left to dry for 24 hours. Figure 74 and 75 shows the silicon actuator side-by-side with the 3D printed actuator.

The main difference can be seen when the actuators are inflated. The 3D printed actuator requires a much larger pressure to show significant deformation (1 bar) while the silicon actuator deforms at much smaller pressure (0,3 bars). The 3D printed actuator also produces much larger force than the silicon actuator as the silicon actuator can easily be bent even when inflated while the 3D printed actuator feels more rigid. The larger force output of the 3D printed actuators and ease of manufacturing has greater potential for scalability as it could actuate larger textiles in future work. Additionally, the silicon actuator extensible layer expands significantly to create a large bubble where the expansion of the walls of the 3D printed actuators is minimal.

5.6 SIZING OF ACTUATOR

As was seen from the larger actuator printed from the MorpheesPlug project, it was found that increasing the actuator size can really enhance the shape changing performance. The straight bellow actuator has multiple parameters that can be fine tuned to maximize the performance. Figures 77 and 78 showcase studies done with varying these parameters and their effect on the bending angle of the actuator (Kim et al., 2021; Zolfagharian et al., 2020). In summary, the main geometrical parameters affecting the performance of actuators include:

Overall Size (Length, Width, Height)

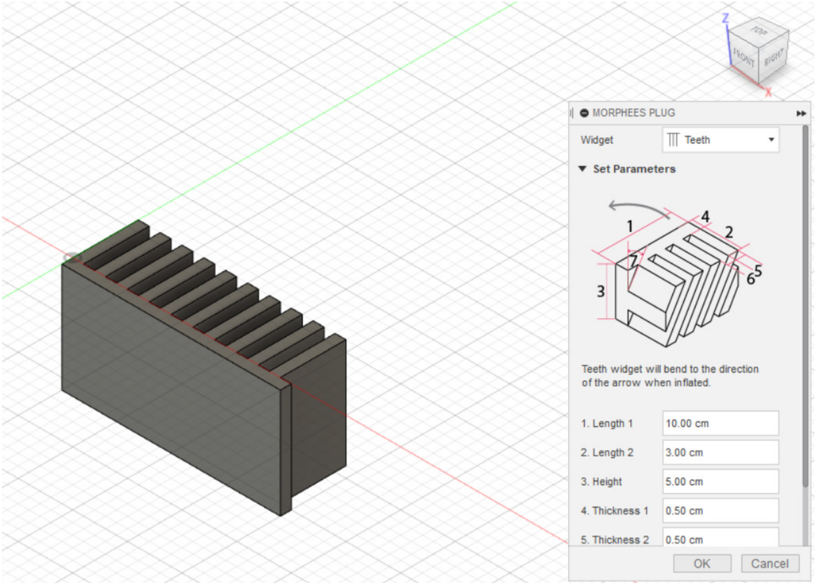
Bellow Size

Bellow Gap

The findings seem to suggest that small mm changes in the geometry of the actuator can make a 5 – 10 degree difference in the curvature angle possible. To maximize the effects of the textile shape change, it is critical to maximize the deformation of the actuators. To test this, multiple straight bellow actuators of varying dimensions were quickly prototyped using the MorpheesPlug plugin for Autodesk Fusion 360. With this plug-in, it is simple to manipulate the parameters of different types of pneumatic actuators in a parametric tool as seen in Figure 76.

Figure 79 summarizes the actuators printed in their deflated and inflated states (1 bar). Overall, it appears that the larger the actuator (in all dimensions), the higher the angle of curvature when inflated. This is as expected as the actuator becomes more flexible with a larger size due to the thin wall thickness and the air inside the actuator is acting on a larger surface area thus causing it to deform more. Additionally, a longer actuator can also accommodate more bellows that increase the curvature of bending as was seen when comparing the straight bellow actuator with other bellows shapes. Finally, it appears that higher bellow gap length increases the angle of curvature in accordance with Kim et al. findings.

Despite the larger size actuators being better in terms of performance, it is critical to remember that when combined with a textile the size of the actuator should not intrude with the experience of interacting with the fabric. In smart textiles, it is often sought upon to minimize the size and integrate smart components seamlessly in the textile. Therefore, there needs to be a balance between actuator size and integration with textile when selecting the best actuator size.



Widget: Teeth

Teeth widget will bend to the direction of the arrow when inflated.

1. Length 1: 10.00 cm
2. Length 2: 3.00 cm
3. Height: 5.00 cm
4. Thickness 1: 0.50 cm
5. Thickness 2: 0.50 cm

Figure 76
MorpheesPlug actuator plugin for Fusion 360 (Kim et al., 2021)

Insight 8

The longer the actuator and bellow gap, the larger the deformation.

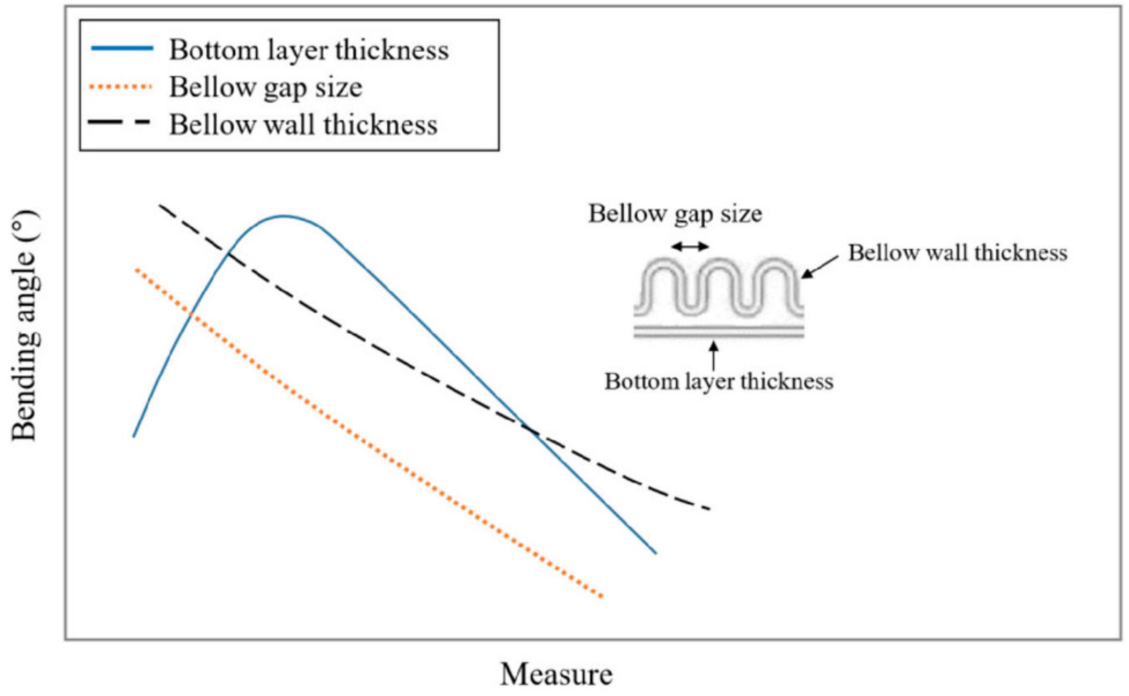


Figure 77
The effects of different geometrical parameters on the bending angle of SPA (Zolfagharian et al., 2020)

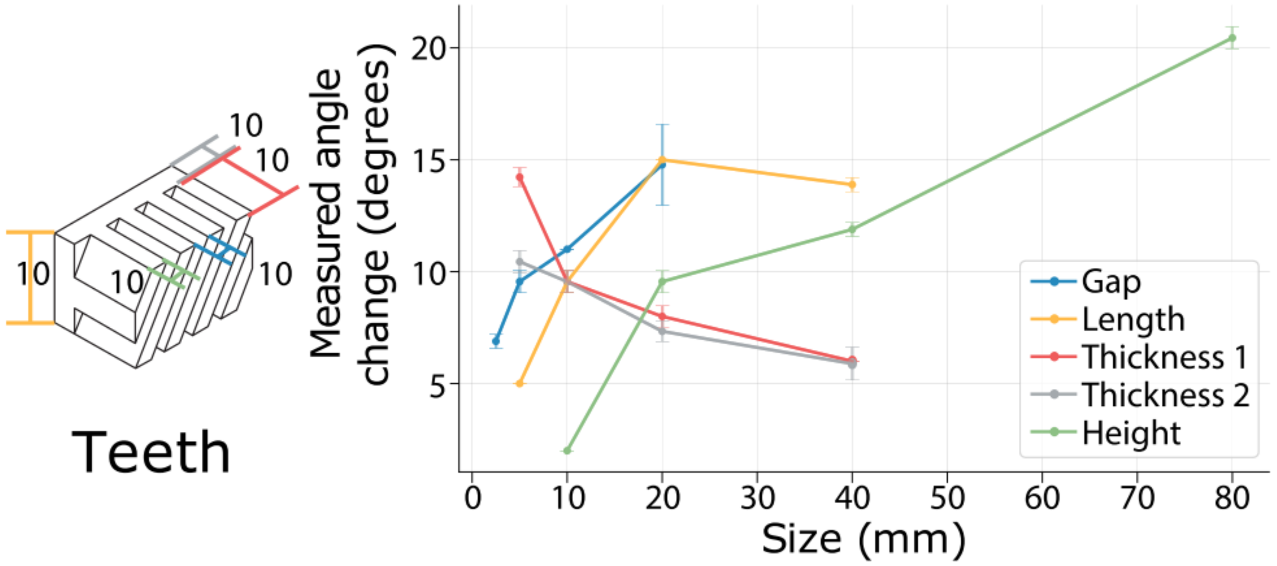
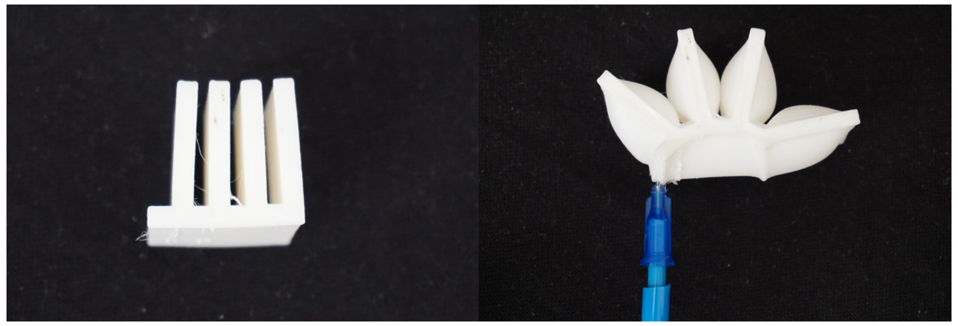
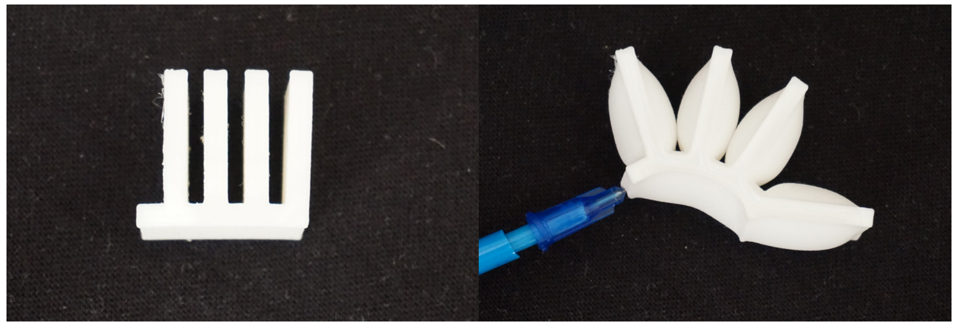


Figure 78
Actuator sizing vs measured angle of deformation (Kim et al., 2021)

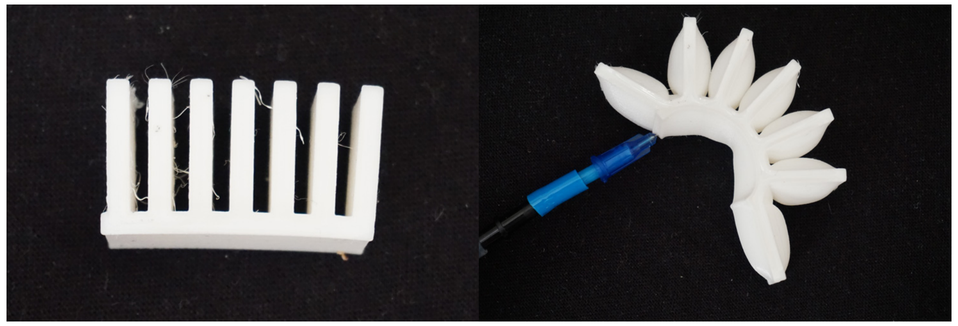
SAMPLE A8: Ninjaflex Actuator (B)
Material: Ninjaflex TPU 85A
Dimensions: 25x30x23 mm
# of bellows: 4



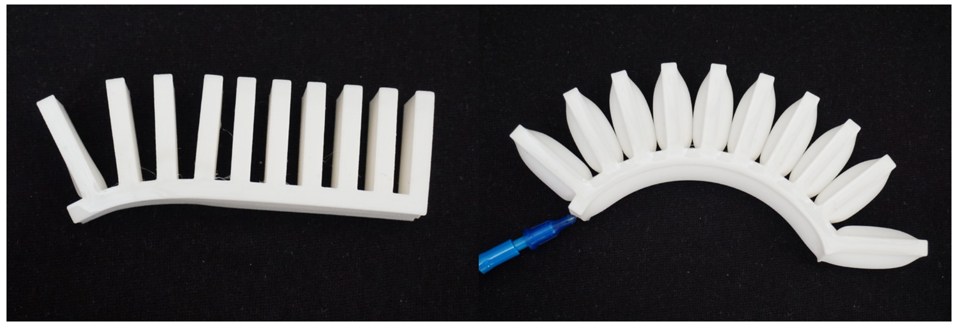
SAMPLE A9: Ninjaflex Actuator (C)
Material: Ninjaflex TPU 85A
Dimensions: 25x20x23 mm
# of bellows: 4



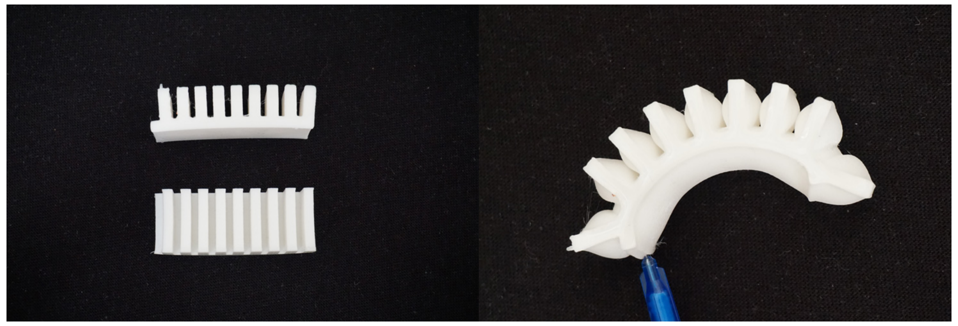
SAMPLE A7: Ninjaflex Actuator (A)
Material: Ninjaflex TPU 85A
Dimensions: 40x20x23 mm
# of bellows: 7



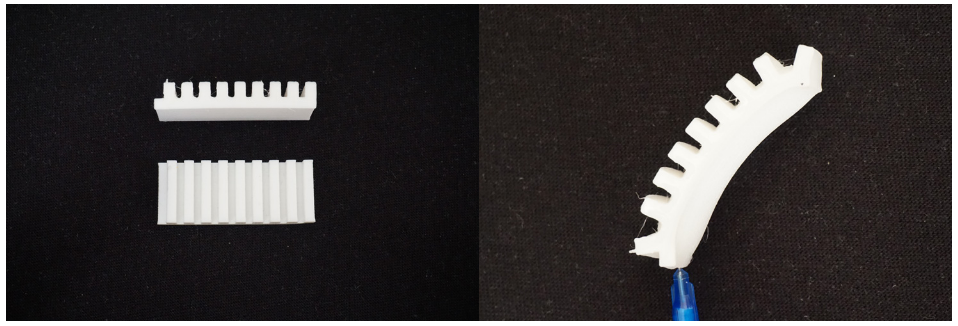
SAMPLE A10: Ninjaflex Actuator (D)
Material: Ninjaflex TPU 85A
Dimensions: 100x20x35 mm
# of bellows: 10



SAMPLE A11: Ninjaflex Actuator (E)
Material: Ninjaflex TPU 85A
Dimensions: 50x20x13 mm
# of bellows: 9



SAMPLE A12: Ninjaflex Actuator (F)
Material: Ninjaflex TPU 85A
Dimensions: 50x20x7 mm
# of bellows: 9



SAMPLE A13: Ninjaflex Actuator (G)
Material: Ninjaflex TPU 85A
Dimensions: 100x20x13 mm
# of bellows: 18

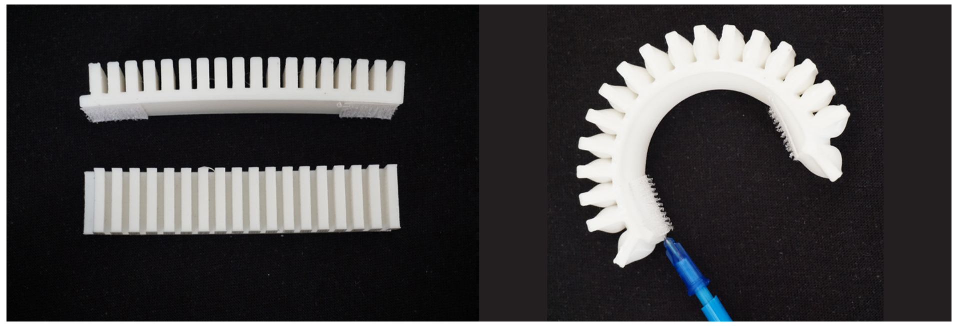


Figure 79
Prototypes of actuators with varied sizing parameters

5.7 3D PRINTED TEXTILES

Figure 80
Moving Textiles by Morasvisa

The 3D printed textile tinkering aims to explore how 3D printing on textile affects the shape change of the textile when the actuator is connected to the textile and inflated. Ideally, it would be interesting to explore how the pneumatic actuators can be directly integrated on the textile as previously mentioned, yet due to the technical complications with printing airtight pneumatic actuators, the 3D printed textiles are explored separately. This section explores the following parameters of 3D printed textiles:

Printing Process

Printing Material

Patterns

Thickness/Width of Material

Materials fabric

Scaling

Although the original inspiration for exploring 3D printed textiles was based on projects that used the stretch qualities of materials such as lycra fabric to create deformations due to the pre-tension of the fabric on the printing bed, this parameter was not studied. This is because the deformations caused by the printing process would add additionally complexity when characterizing the deformations caused by the pneumatic actuators on the textile. Instead the 3D printing is used to add structure and selective stiffness to the textile to guide its deformation when deform by the active element. This parameter can be further explored in the future by adding shape changing elements similar to Naomi Atmopawiro's caterpillar master thesis (Atmopawiro, 2019).

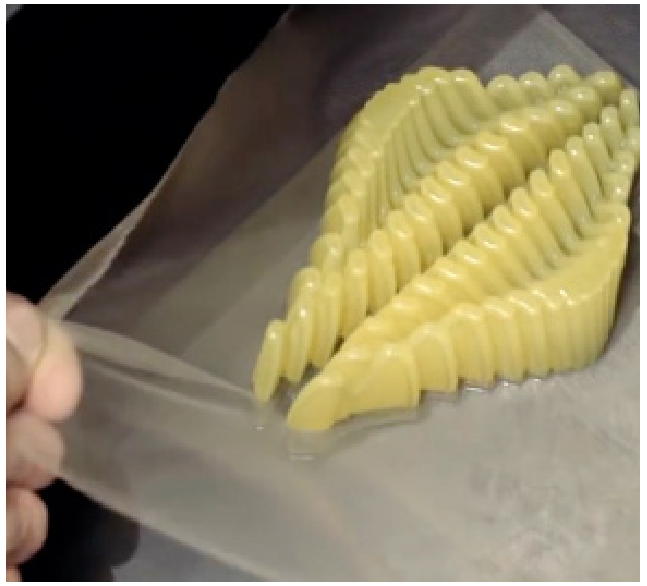


Figure 81
Printing the foliage dress (Doubrovski et al., 2017)

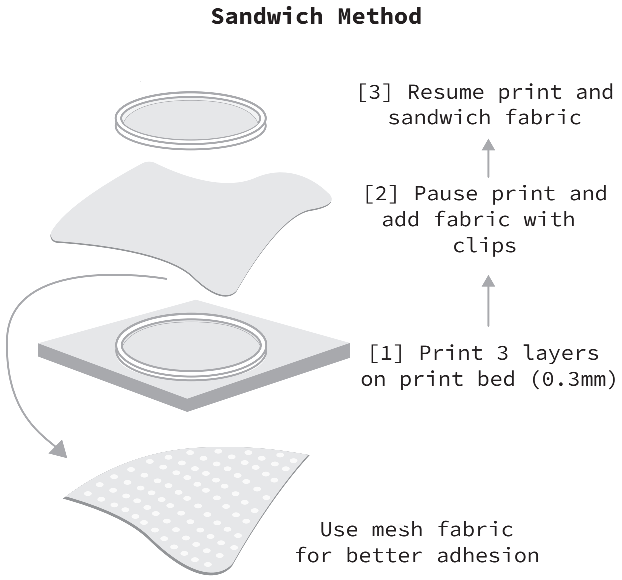


Figure 82
Sandwich printing method guidelines

Printing Process

At the beginning of the tinkering process, solid lycra textile was used for prototyping as it is the most common textile used in 4D textile research. That being said, the initial prototypes of 3D print on textile showed presented complications with adhesion of the 3D print on the textile, which are often not reported well in literature:

1. The 3D print could be fully removed by peeling it off the fabric with sufficient force, which is not an issue for basic prototyping, yet it does reduce the durability of the prototype.

2. The thicker the print, the more warping of the geometry would occur due to poor adhesion with the fabric, which cause imperfections in the design.

To solve this adhesion issue, projects such as the foliage dress recommend using a mesh textile and creating a "sandwich" effect between the 3D print material and the textile. The mesh fabric allows the print to flow through the thread and create a solid bond between the two 3D printing layers. The results of this method can be seen in the foliage dress project (Doubrovski et al., 2017). The basic circle pattern design was tested with a mesh lycra material using the sandwich method as was presented previously in the proof of concept prototype. After a few iterations, the following process was found to be successful:

1. Print three layers of the 3D printing material.

2. Pause the print after layer 3

3. Add the fabric to the printing bed using binder clips

4. Continue the print

The new "sandwich" textile showed improved adhesion and durability of the material making it safer for tactile interactions from users. For the rest of the prints, the "sandwich" method was followed to achieve successful, long-lasting prints. The next few prototypes presented were created using mesh lycra with little tension to reduce the textile deformation and a small Ultimaker 3. When expanding to larger prints using the Ultimaker 5, other complications arise when using the stretchy lycra material. This complications are later addressed in the Large Scale Textile Props section.

Figure 83
4D textiles pattern exploration (Kycia, 2018)

Patterns

In the field of 3D printed textiles, many of the experiments focus on creating intricate computational patterns on the textile that cause local small deformations in 3D space. Research by Agata Kycia and the MIT Self Assembly lab explored how these simple 2D patterns printed on pre-tensed textile result in quite complex deformations when released from the printing bed. These deformations are often unpredictable and surprising resembling complex structures and textures found in nature. Other designers have also explored how 2D patterns can also be printed on stiff textile without pre-tensing it in order to produce stiffer geometries that can bend and sustain themselves to produce 3D geometries and products such as plant vases and lamps with textile material. For this tinkering on 3D printed textile, the aim is to understand how using different 3D printed patterns on the textile can affect the final 3D shape produced when activated with the actuator, thus being able to create interesting 3D geometry from a 2D textile.

To begin understanding how these local deformations can be created in the textile, various basic patterns where printed on the fabric such as triangulations, honeycomb, and voronoi. The first prototypes printed with 1,5mm height. These proved to be too stiff to create local deformations. The next batch of samples were printed with 0,6mm height as seen in Kycia's designs (Kycia, 2018). This pattern height was found to be more flexible to achieve the local deformations wanted. Figure 84 showcases the various prototypes created with their non-actuated/actuated states.

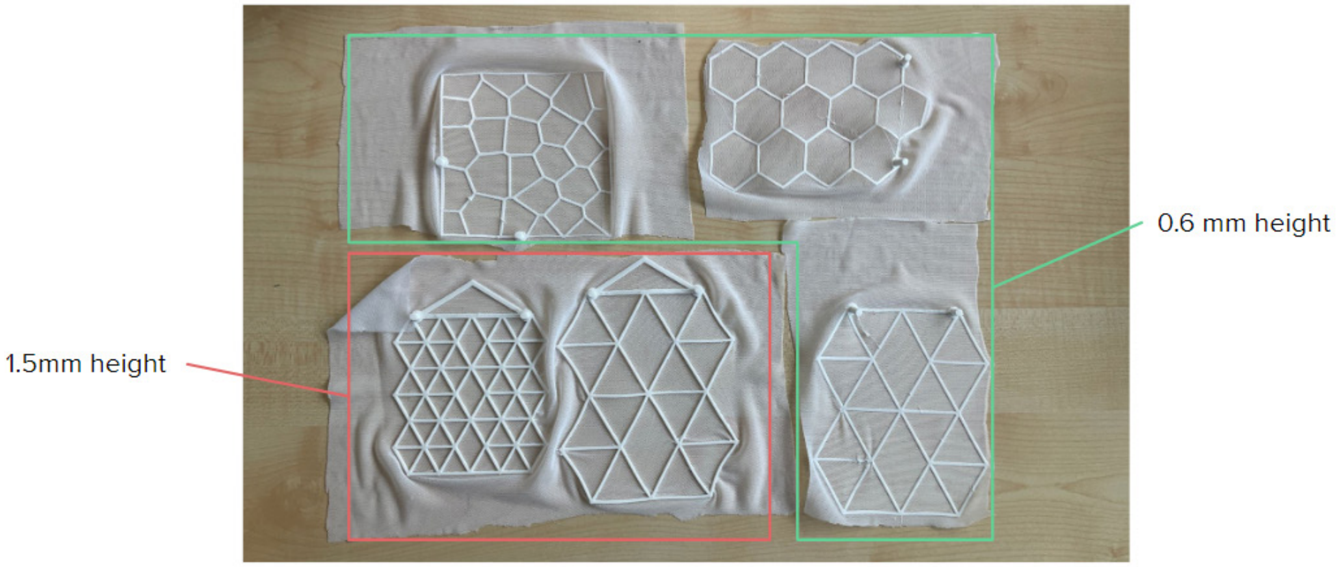
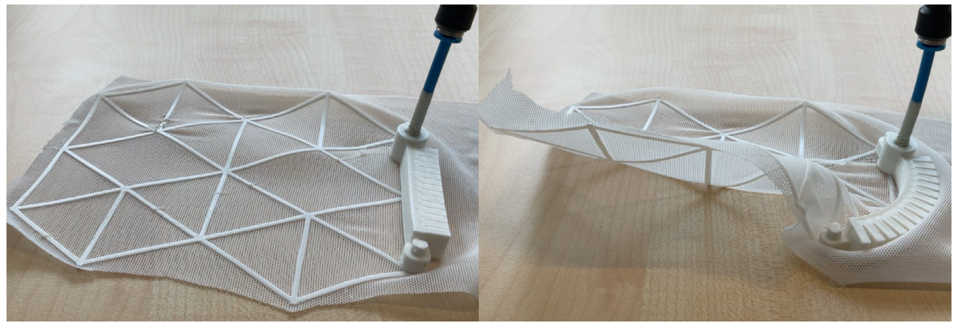
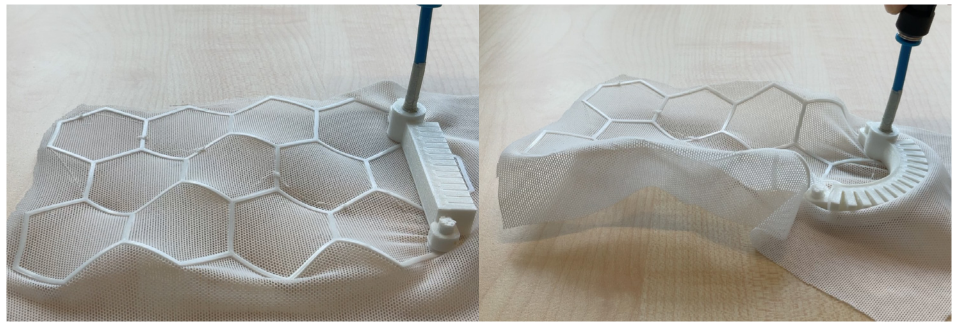


Figure 84
Summary of pattern prototypes printed at two different thicknesses (0,6mm and 1,5mm)

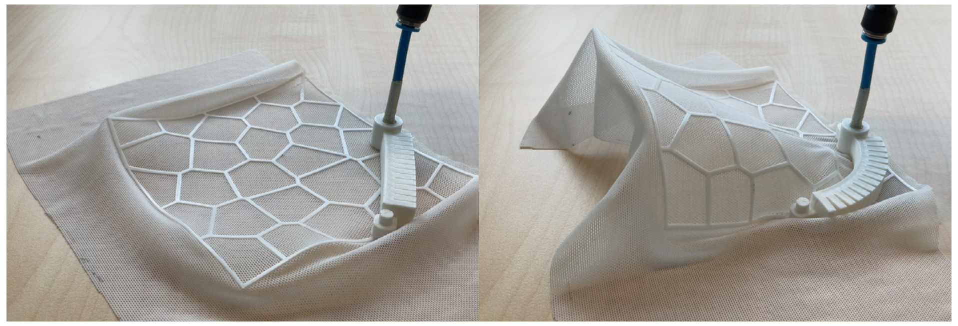
SAMPLE T1: Tri Pattern (A)
Material: UM TPU 95A
Pattern Height: 0,6mm
Pattern Width: 1,5mm
Pattern unit side length: 40mm



SAMPLE T2: Hex Pattern
Material: UM TPU 95A
Pattern Height: 0,6mm
Pattern Width: 1,5mm
Pattern unit side length: 20mm



SAMPLE T3: Voronoi Pattern
Material: UM TPU 95A
Pattern Height: 0,6mm
Pattern Width: 1,5mm
Pattern unit side length: 10-30mm



SAMPLE T4: Tri Pattern (B)
Material: UM TPU 95A
Pattern Height: 1,5mm
Pattern Width: 1,5mm
Pattern unit side length: 40mm

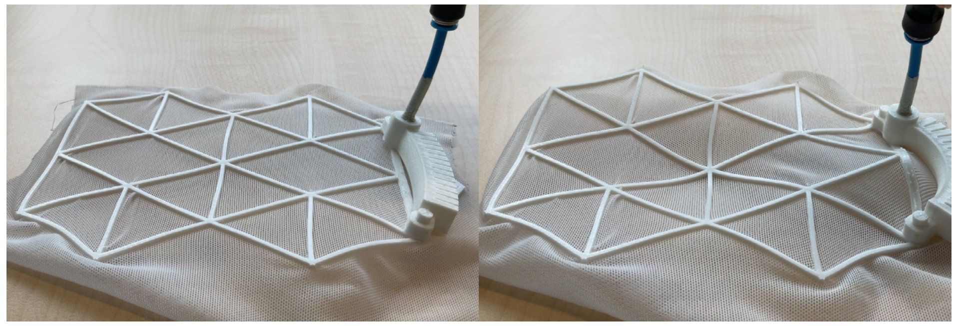
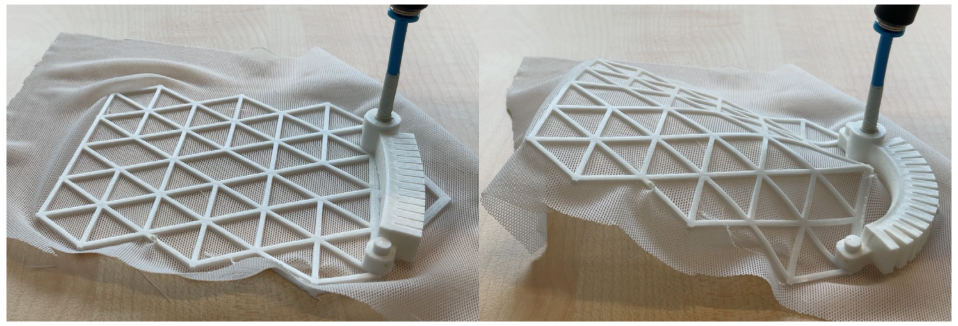


Figure 85 Pattern prototypes (non-actuated/actuated state)

SAMPLE T5: Tri Pattern (C)
Material: UM TPU 95A
Pattern Height: 1,5mm
Pattern Width: 1,5mm
Pattern unit side length: 20mm



Insight 9

Height of the print has a large impact on the flexibility of the textile to create deformations.

Insight 10

Density of the pattern also affects the stiffness of the fabric (e.g. the voronoi mesh was too dense and did not show much local deformation).

These initial prototypes proved that variations in the 3D printed pattern can produce variations in the local deformation of the textile, yet the variability in the deformations were quite minimal. In the end, the actuated form of the textile often ends up being similar to the curved shape from the proof-of-concept prototype instead of the desired local deformations as seen in works using pre-tension textile.

Despite some the minimal variation in deformation, some interesting observations can still be made from these samples:

Height of the print has a large impact on the flexibility of the textile to create deformations

Density of the pattern also affects the stiffness of the textile (e.g. the voronoi mesh was too dense and did not show much local internal deformation)

With the current designs, local deformations are minimal and hard to predict. The next section will explore another method proposed in literature to see if these local deformations can still be activated with the actuator proposed in this project.

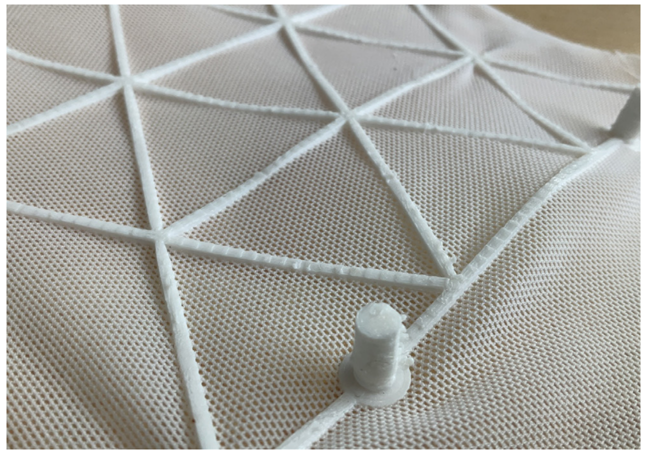


Figure 86
Close up of pattern with local height variation prototype

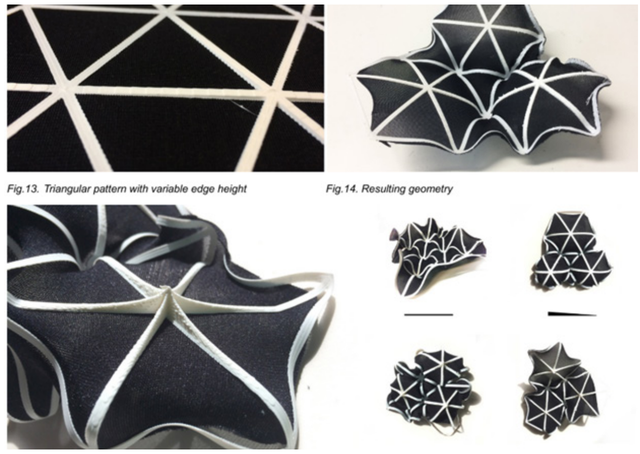


Figure 87
Controlling 4D textile deformation by printing local height variations in the pattern (Kycia, 2018)

Pattern with Local Variations

As shown in Kycia's studies, controlling the local thickness of the pattern, such as the intersection points, can give more direct control of the peaks and valleys of the textile during actuation. Following on Kycia's work, new more advanced patterns were explored in an attempt to create more controlled local deformations within the patterns. The idea of tweaking the local height and width of the pattern, is that when actuated, the fabric would bend on the thinnest parts of the fabric. The thicker parts of the 3D print pattern would then become the peaks/valleys creating a controlled warping of the fabric. For all these prototypes, the highest height or width was placed on the vertices of the pattern cells. A summary of all the prototypes in their non-actuated/actuated state can be found in Figure 88.

By performing this test, it was found that the principle of using local variation to control local deformation of textile works with pre-tension textile, but not with the pneumatically actuated textiles studied in this project. The reason for this is because with the case of the pre-tensed fabric, there is internal compression within each of the cell patterns occurring from the tension on the textile. In the case of the 3D printed pneumatic textiles, the compression only occurs on the outer outline of the fabric when the actuator moves the two attachment points close to each other. Due to the inability to control the local deformation of the textile as initially wanted, the next section of 3D printed pattern will instead explore how to scale up the deformation to produce larger shape change textile as this method appears to be best suited for the 3D printed pneumatic textiles.

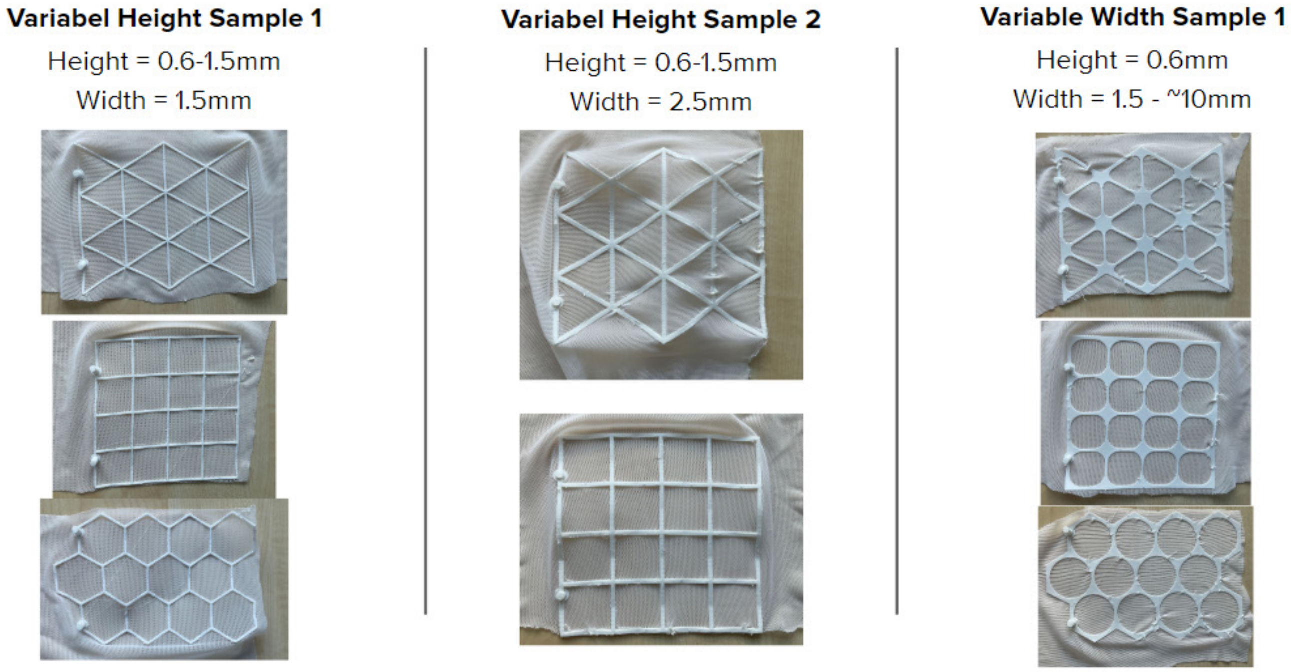
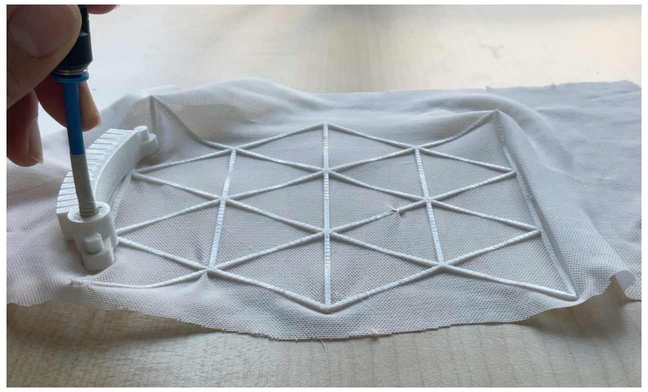
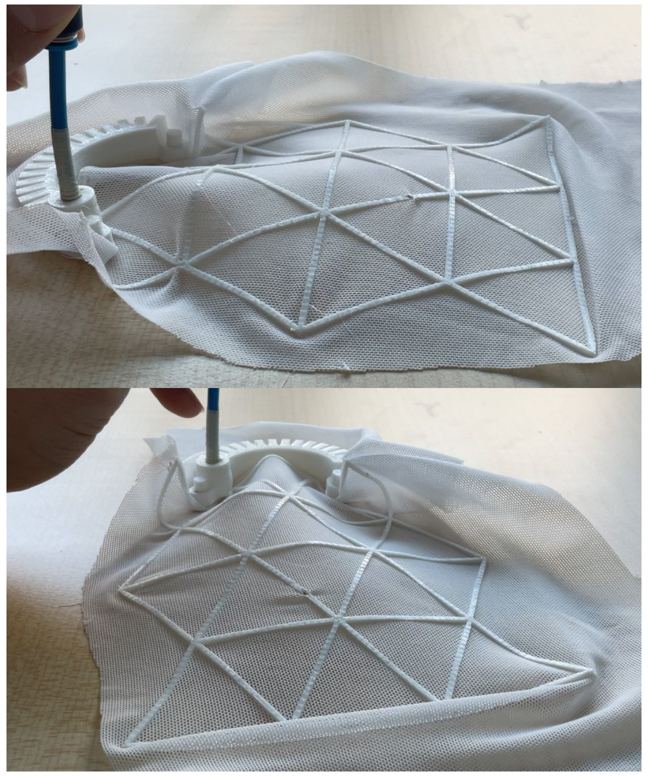
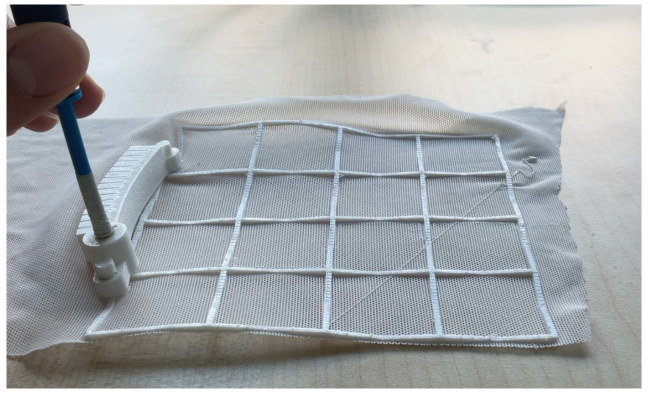


Figure 88
Summary of pattern with local height variation prototypes

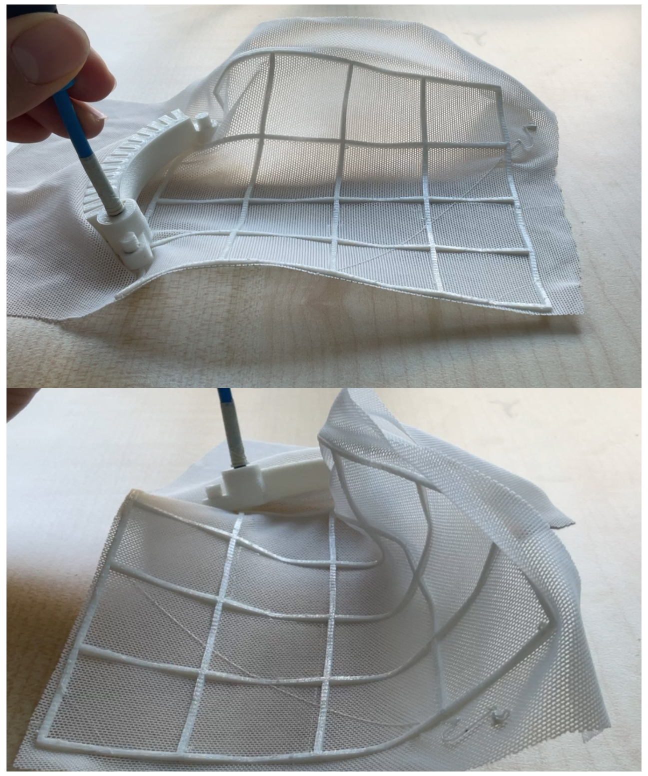


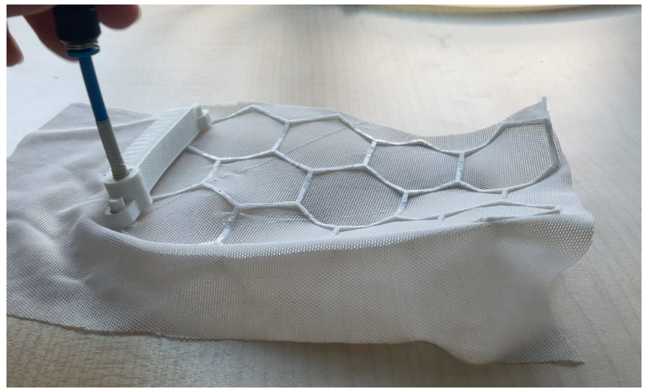
SAMPLE T6: Tri Local Pattern (A)
Material: UM TPU 95A
Pattern Height: 0,6-1,5mm
Pattern Width: 1,5mm
Pattern unit side length: 40mm



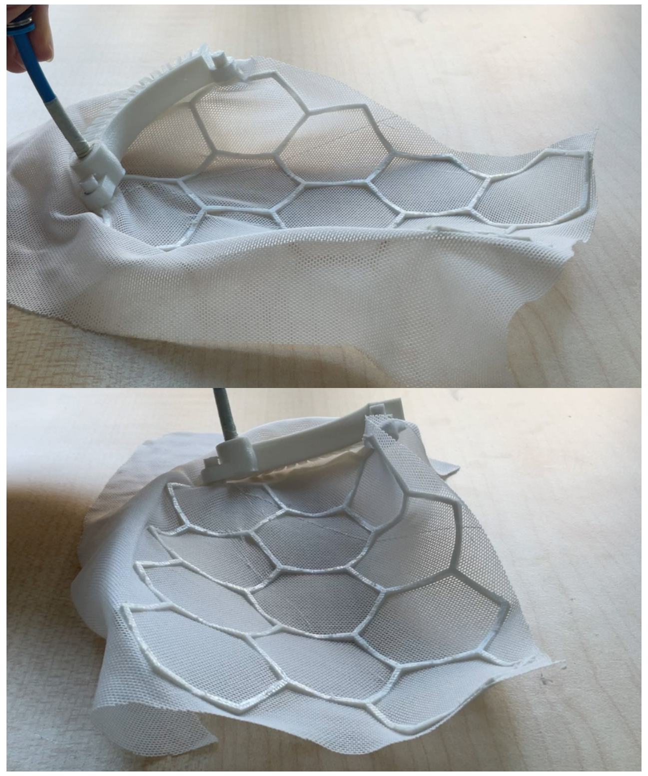


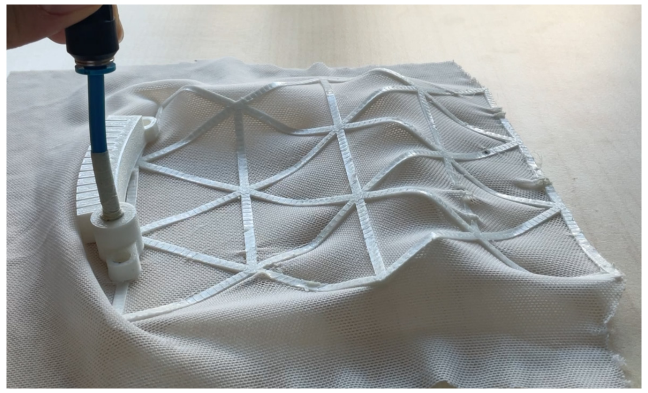
SAMPLE T7: Square Local Pattern (A)
Material: UM TPU 95A
Pattern Height: 0,6-1,5mm
Pattern Width: 1,5mm
Pattern unit side length: 30mm





SAMPLE T8: Hex Local Pattern (A)
Material: UM TPU 95A
Pattern Height: 0,6-1,5mm
Pattern Width: 1,5mm
Pattern unit side length: 20mm





SAMPLE T9: Tri Local Pattern (B)
Material: UM TPU 95A
Pattern Height: 0,6-1,5mm
Pattern Width: 2,5mm
Pattern unit side length: 40mm

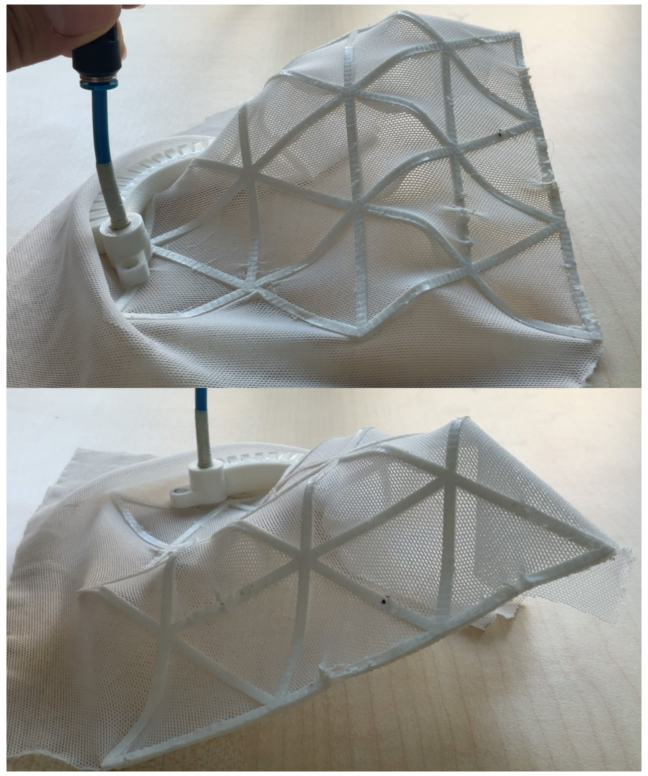
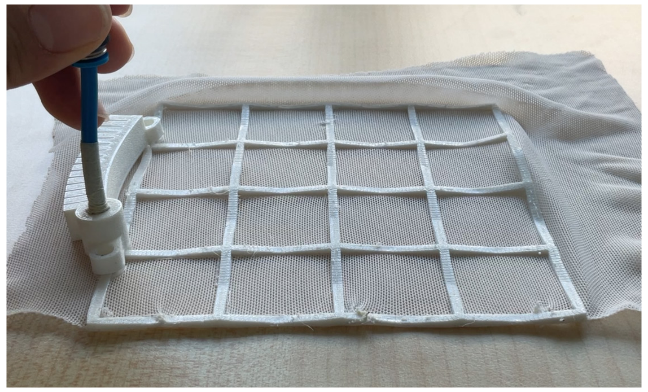
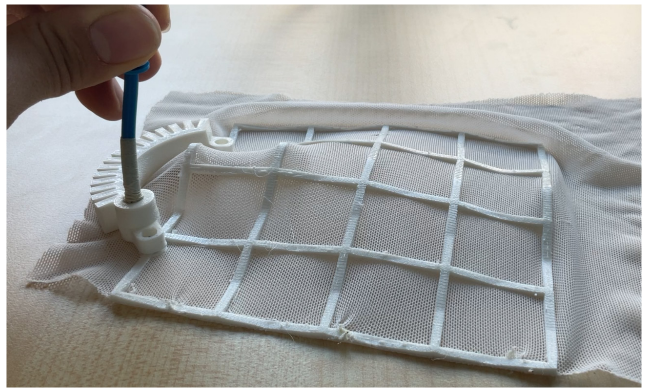
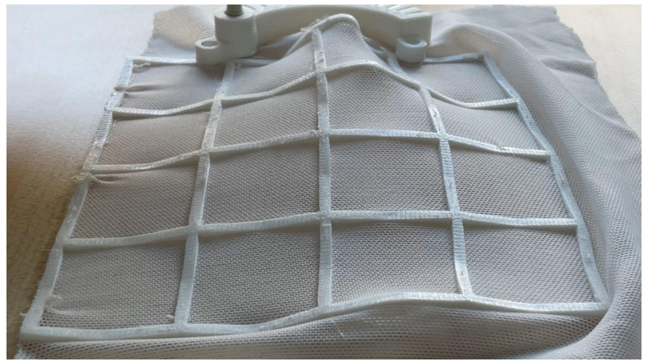


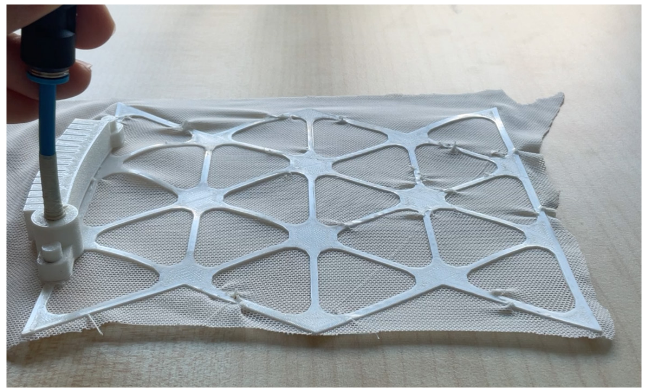
Figure 89
Pattern with local height variation prototypes (non-actuated/actuated state)

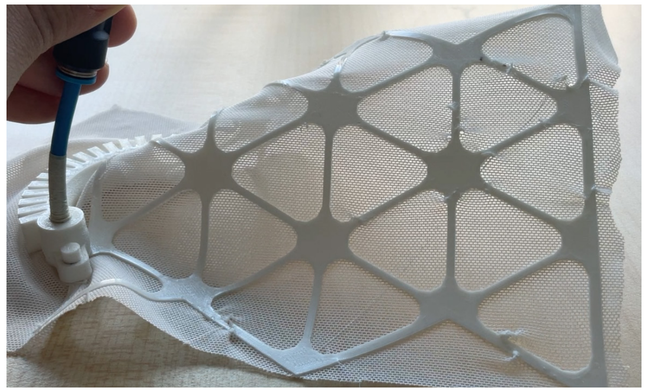


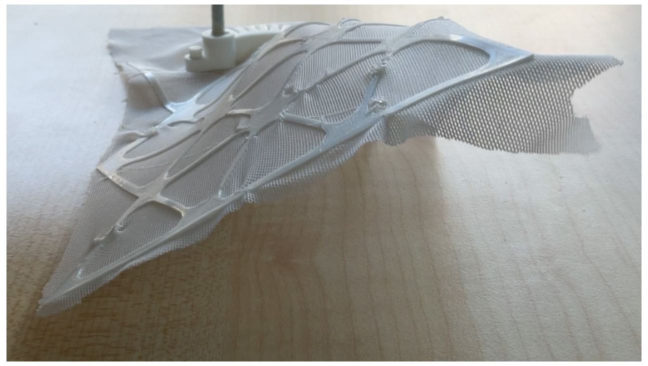




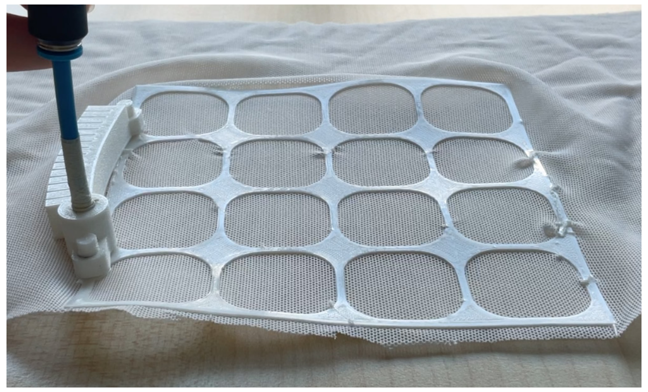
SAMPLE T10: Square Local Pattern (B)
Material: UM TPU 95A
Pattern Height: 0,6-1,5mm
Pattern Width: 2,5mm
Pattern unit side length: 30mm

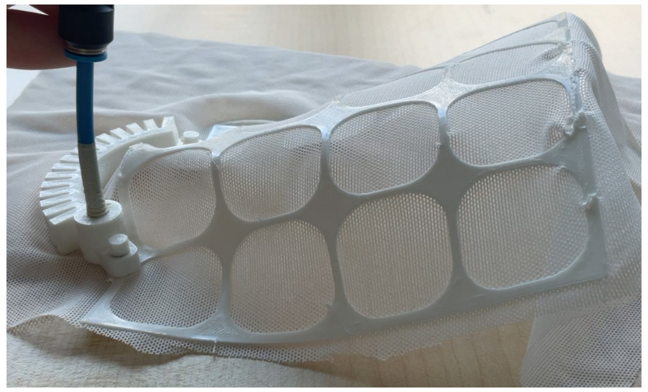




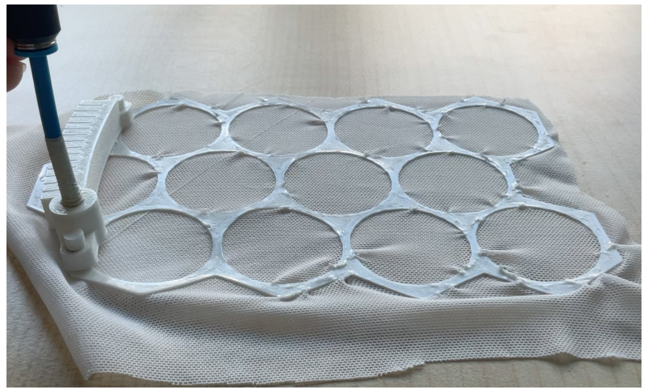


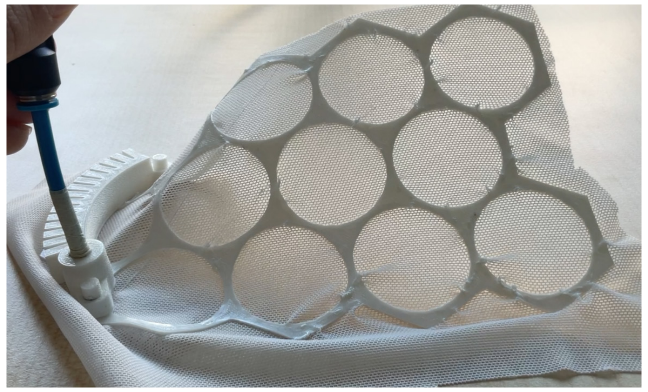
SAMPLE T11: Tri Local Pattern (C)
Material: UM TPU 95A
Pattern Height: 0,6mm
Pattern Width: 1,5-10mm
Pattern unit side length: 40mm

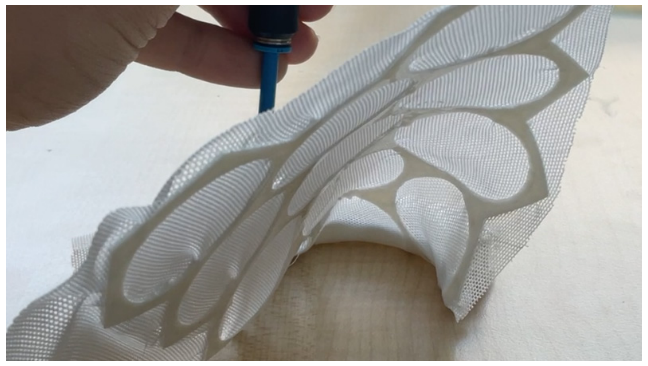




SAMPLE T12: Square Local Pattern (C)
Material: UM TPU 95A
Pattern Height: 0,6mm
Pattern Width: 1,5-10mm
Pattern unit side length: 30mm







SAMPLE T13: Hex Local Pattern (B)
Material: UM TPU 95A
Pattern Height: 0,6mm
Pattern Width: 1,5-10mm
Pattern unit side length: 20mm

Figure 89
Pattern with local height variation prototypes (non-actuated/actuated state)

5.8 LARGER SCALE TEXTILE PROPS

Since the pattern tests showed little potential for local deformation of the textile when actuated with the pneumatic actuators, it was decided to shift to creating large scale props to instead focus on the scalability of the material. During the creation of these large scale props, other parameters were simultaneously tested in order to improve the material.

Creation of the large scale textile props began with an ideation session following the Morphino card method. Morphino is a bioinspired card deck for designers to ideate shape changing interfaces (Qamar et al., 2020).

During the process, other non-biomimetic ideas were also created during the session. Most of the ideas created in this process used only one single actuation point, but some later ideas included multiple actuation points for more complex movements. Figure 90 summarizes the ideation session using the Morphino cards. During prototyping of these larger scale textiles, some fabrication issues arose which meant changes had to be done to the procedure and parameters of the material. The complications and improvements to the fabrication process are presented in the next few sections.

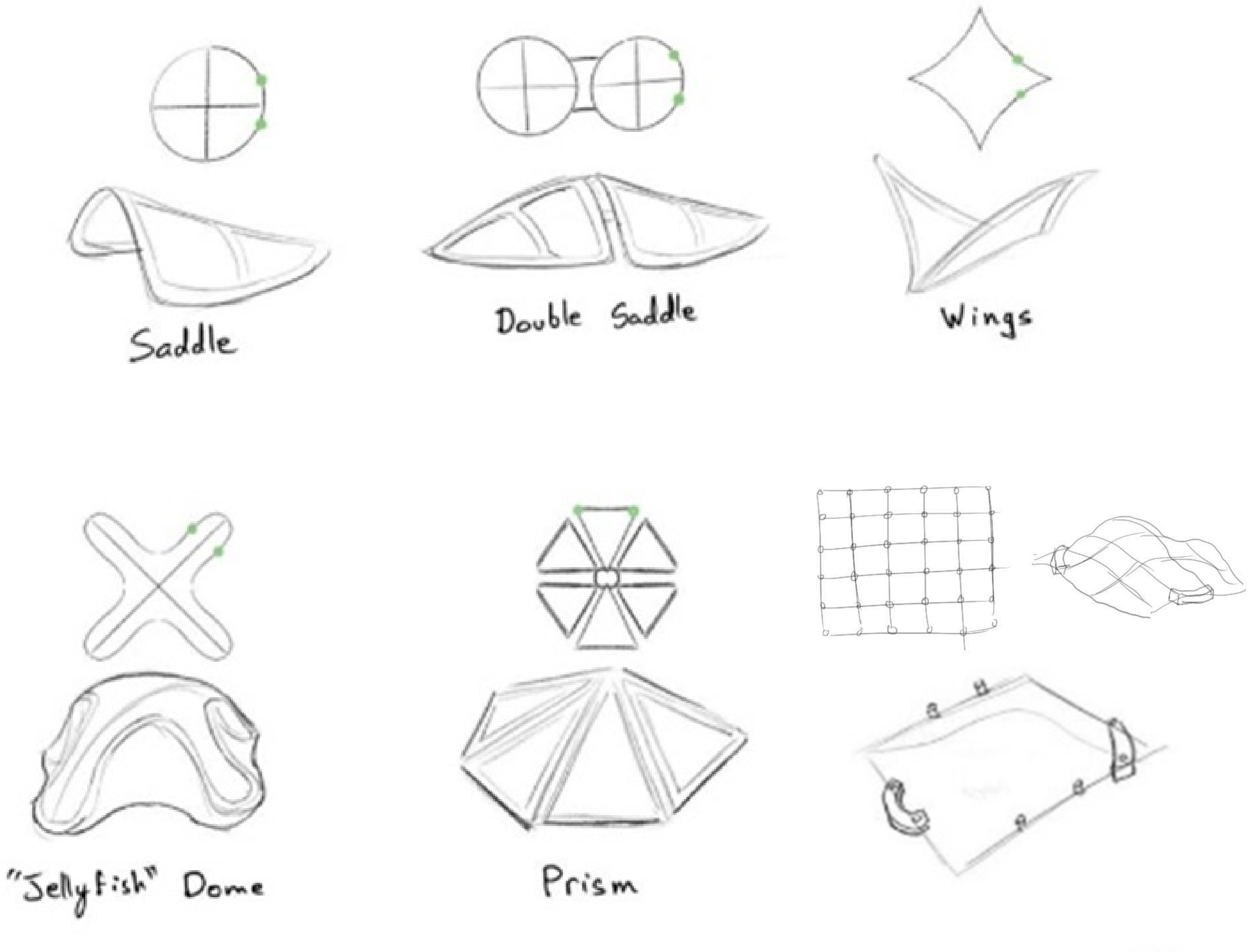
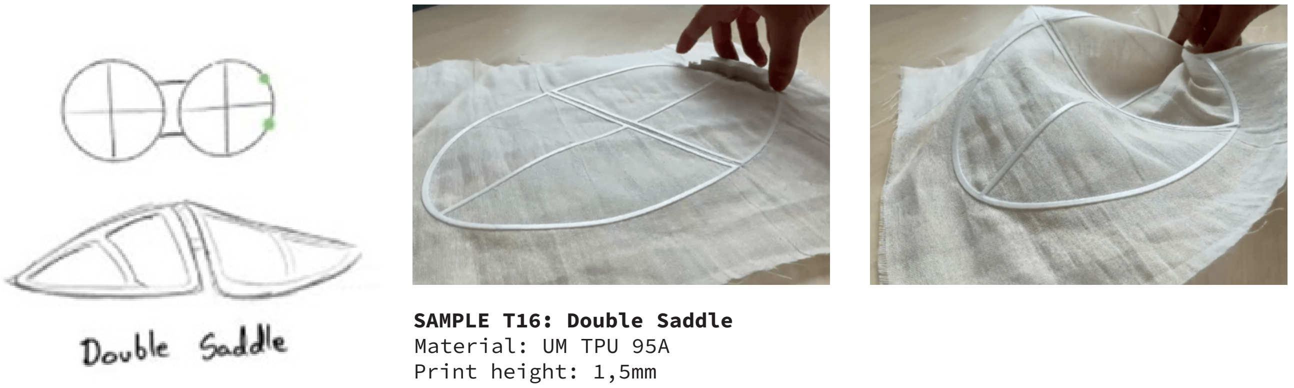


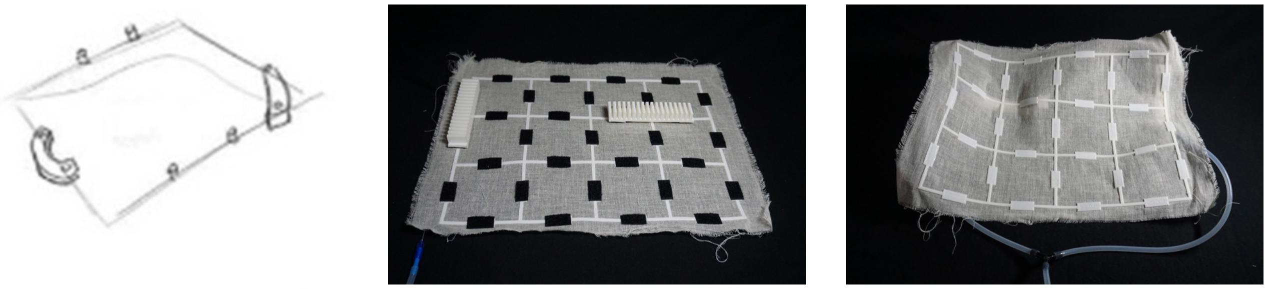
Figure 90
Summary of ideation session using Morphino cards (Qamar et al., 2020)

SAMPLE T14: Wings
Material: UM TPU 95A
Print height: 1,5mm
Print width: 2,5mm

SAMPLE T15: Jellyfish Dome
Material: UM TPU 95A
Print height: 1,5mm
Print width: 2,5mm



SAMPLE T16: Double Saddle
Material: UM TPU 95A
Print height: 1,5mm
Print width: 2,5mm



SAMPLE T17: Modular Grid
Material: UM TPU 95A
Print height: 1,5mm
Print width: 2,5mm

Figure 91
Large scale props (non-actuated/actuated form)

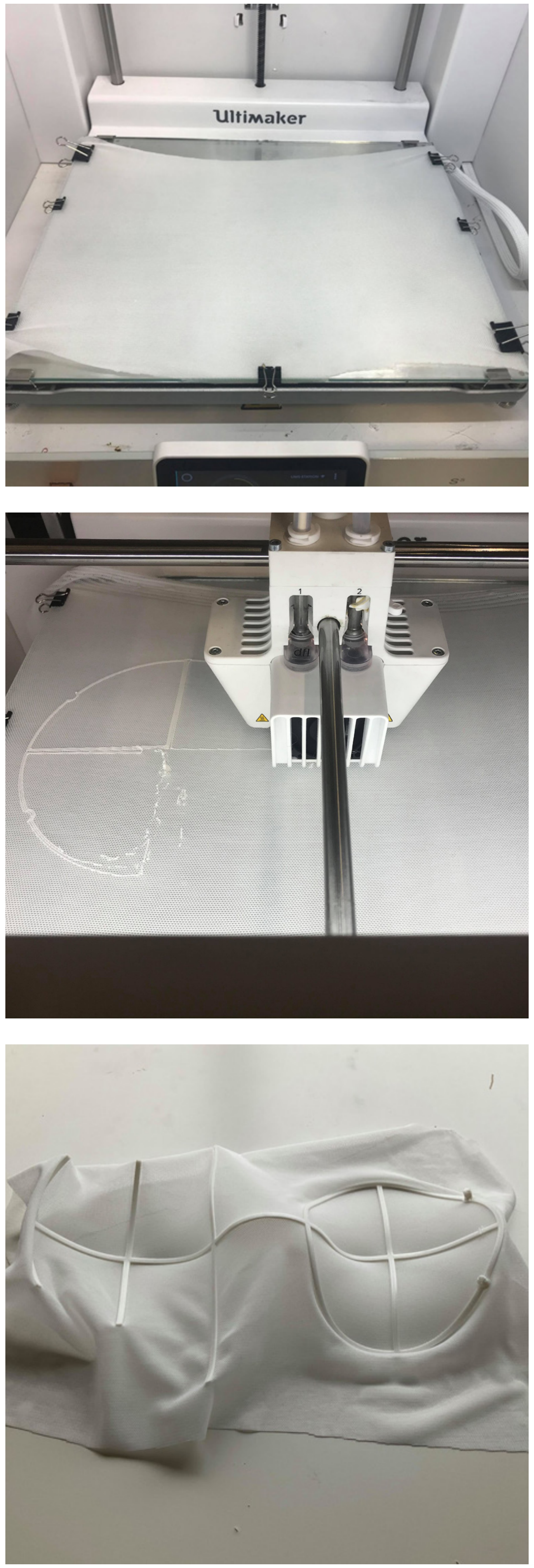


Figure 92
Deformation caused by printing on large scale textile (UM5) using mesh lycra

Materials: Textile

During the process of printing large scale samples on textiles using the Ultimaker 5, multiple prints were failing as they were getting caught on the fabric and stretching/ripping the fabric. To solve this problem, another graduating student specializing on 3D printing on textiles, Dimitra Tsoli, was consulted for help. It was found that issue was because the stretchiness of the mesh lycra was causing the printing nozzle to get caught if no tension is applied (As was done with all prototypes since pre-tension is not a parameter studied during tinkering).

Applying tension on the textile solved the issue, but caused the textile to deform which was not ideal for the purpose of this research. To fix this issue, it was recommended to use a non-stretchy fabric. From Dimitra's research, mesh cotton was found to have high adhesiveness to PLA and TPU and is not stretchy, meaning it is very easy to print on without needing to add additional tension. Additionally, it has an easier printing process. Printing on mesh lycra always required the printer nozzle to have a height offset after applying the fabric, whereas the mesh cotton can be printed on directly without an offset. The next prints were done with mesh cotton successfully and it is recommended to continue with this material as it makes printing on fabric significantly easier.

Lycra has been used since the start of the project as it is referenced in the majority of 4D textiles papers. In these papers, the researchers apply pre-tension to the textiles to create deformations in the textile. For the material tinkering, pre-tension was not selected as a parameter to study. For this reason, the lycra was never pre-tensioned during printing. As mentioned earlier, this causes issues when scaling up on a bigger printer as the fabric on the edges of the printing bed has less tension than in the centre of the bed.

Using mesh cotton solves this problem due to its higher stiffness. Additionally, it produces better bonding between the top and bottom sides of the TPU print as the hot nozzle presses down on the fabric when printing (as it does not require an offset). Additionally, the cotton does provide a more «natural» feeling due to its undyed color and rougher texture. One extra step to consider in the process is that since cotton wrinkles easier than the lycra, it is necessary to iron the fabric before the print for a nicer print.

[1] Iron the cotton fabric to remove wrinkels.

↓

[2] Clip the fabric to the printing bed as tight as possible.

↓

[3] New print on cotton fabric should have less deformation than when using stretchy fabric.

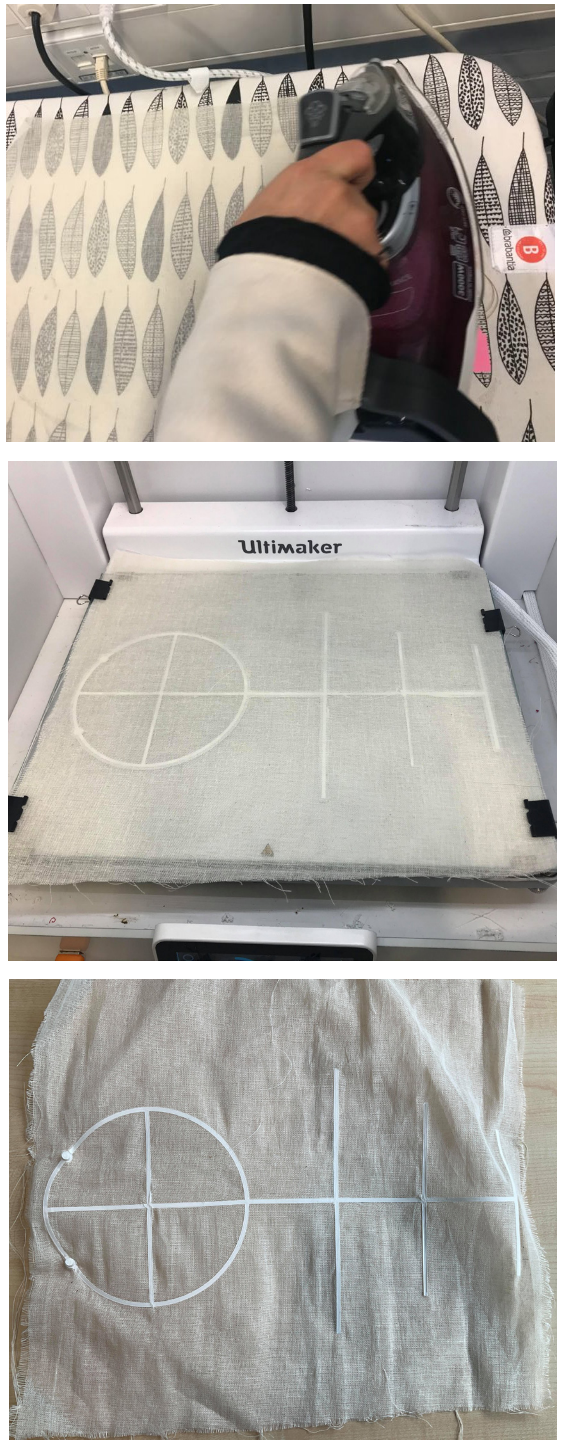


Figure 93
Improved printing method using mesh cotton to reduce textile deformation

Insight 11

Using non-stretchy fabrics (cotton) reduces deformation due to fabric tension on the print bed.

Insight 12

TPU95A adds a good balance between stiffness and flexibility to the fabric.

Figure 94
Close up of UM TPU 95A printed on mesh cotton

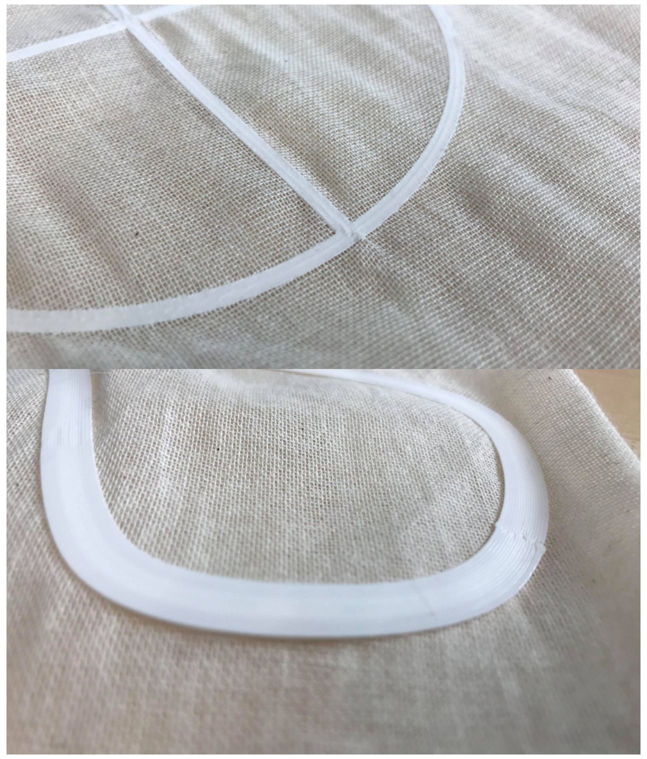


Figure 95
Close up of PLA printed on mesh cotton with brim

Materials: 3D print material (PLA, TPU85, TPU95)

During my collaboration with Dimitra Tsoli, she also recommended to test my prototypes using PLA as it has been found to have better adhesion to the mesh cotton and requires only a thin layer of material to be printed due to its higher stiffness, which can speed up the printing process. The PLA material was tested using the same design from Sample T15 (Jellyfish Dome), but printing only 6 layers (0,6mm thickness) due to the material's higher stiffness. PLA did succeed in providing extra stiffness to the prototypes allowing them to transfer the shape change of the actuator throughout the entire textile. Similar results are possible with TPU, yet a more dense print pattern is required to achieve the same stiffness. PLA also significantly reduced the printing time since it requires less layers to print. Still despite the higher stiffness that can be achieved with PLA by using less layers, TPU 95A is still preferred as the additional flexibility creates more fluid, organic shapes.

Additionally, PLA does give the samples a «brittle» feeling when handling. It prompts the user to be more careful with the sample in fear that they will plastically deform the PLA. TPU provides a nicer tactile feeling due to its flexibility and smoothness inviting the user for more tactile interaction. PLA also requires to print with a Brim, an additional support material, to prevent it from lifting from the bed. This can often be hard to remove without damaging the fabric as it might require a knife to remove and leaves sharp edges on the print. Overall, it is recommended to continue with TPU 95A as its flexibility, adhesion, and improved tactile feel.

Ninjaflex TPU85A was also tested with this design to compare the three materials, yet a successful print was not possible as it had very poor adhesion to the textile.

Insight 13

Varying the actuator orientation/ location creates more modular, interesting deformations.

Figure 96
Sample T16 with actuator oriented out-of-plane

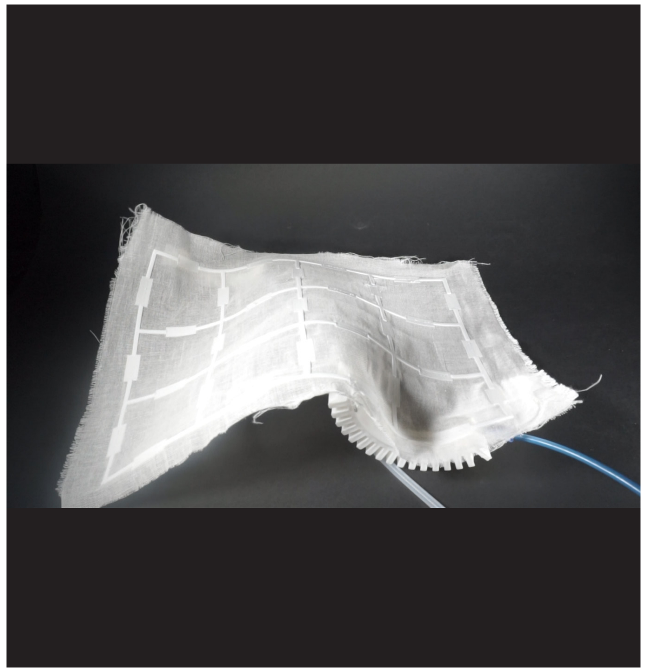


Figure 97
Sample T17 with actuator oriented out-of-plane

Actuator Orientation/Location

So far, the prototypes that had been proposed all used a single actuator oriented to deform in an in-plane deformation when attached to the textile by its two attachment points at both ends. Throughout the material tinkering, this has proven to be quite a limiting factor in exploring the wide range of possibilities that this material has to offer. To expand the range of possibilities of the previous prototypes created, it was decided to test what would happen if the actuator orientation on the textile was shifted, so that they would deform out-of-plane instead and if the actuator location was also changed. Since the actuators could not be connected to the textile in this orientation directly, an adhesive Velcro tape was used instead by placing one small Velcro strip on each actuator end and the other side on the textile. This was tested with both the "Double Saddle" prototype and with the "Modular Grid" prototype. The results were quite surprising as it was found that when the actuators were placed in an out-of-plane orientation it would 1) produce a much larger deformation on the textile and 2) lead to more interesting results that were not found with the initial in-plane orientation.

When the actuator was placed in the centre of the "Double Saddle" prototype, this new orientation transformed the prototype from a simple curved dome into an object that felt more alive and could be associated with a venus flytrap coming to grab your hand or a textile attempting to give you a hug. The "Modular Grid" was originally built with the idea of having the orientation of the actuator in the out-of-plane direction and being able to vary the location of the actuator. The results from using a single actuator appeared to be quite promising as it produced a complex curved shape out of the basic square grid by placing the actuator on the outer side of the grid. These results prove that by simply changing the location and orientation of the active element on the interface element, different forms can be produce using the same interface element. This modularity of the location of the active element is further explored in the next chapter by testing the different shape morphologies that are possible when using the "Modular Grid" prototype and varying the number and location of actuators applied.

5.9 SUMMARY OF INSIGHTS

In this chapter, the parameters for making the pneumatic actuators and the 3D printed textiles were explored from a performance and fabrication perspective. In the end, a proven method for producing both components separately was finalized with the final materials selected: actuators made from Ninjaflex 85A and 3D printed structure made from Ultimaker TPU 95A printed on mesh cotton. These two components can be successfully fabricated using the insights shown in this chapter, which are summarized below. In the end, it was concluded that while having to fabricate the actuator and 3D printed textile separately due to technical difficulties is not necessarily a weakness of the material but can also be use as an opportunity to exploit its modular ability to be able to change the location of the actuator on the same textile interface to produce a wide range of interesting results. Using the insights derived in this section, a Material Making Process chart is presented on the following page as a quick guide to aid the reader in replicating the results found in this chapter.

1) Straight bellow actuators have the highest curvature deformation when inflated.

2) A shell thickness of 0,8mm maximizes the performance of the actuator.

3) 3D printing inflatables require a very slow printing speed (6,5mm/s) to print airtight.

4) Overextrusion, Outline Overlap, and overhang < 4mm when 3D printing helps to seal gaps during printing to increase airtightness.

5) Using a needle syringe tip provides a better airtight connection to actuator.

6) 3D printing actuators provides a quick, accessible method to produce shape changing materials.

7) 3D printed actuators have a higher potential for scalability due to their higher force output.

8) The longer the actuator and bellow gap, the larger the deformation.

9) Height of the print has a large impact on the flexibility of the textile to create deformations.

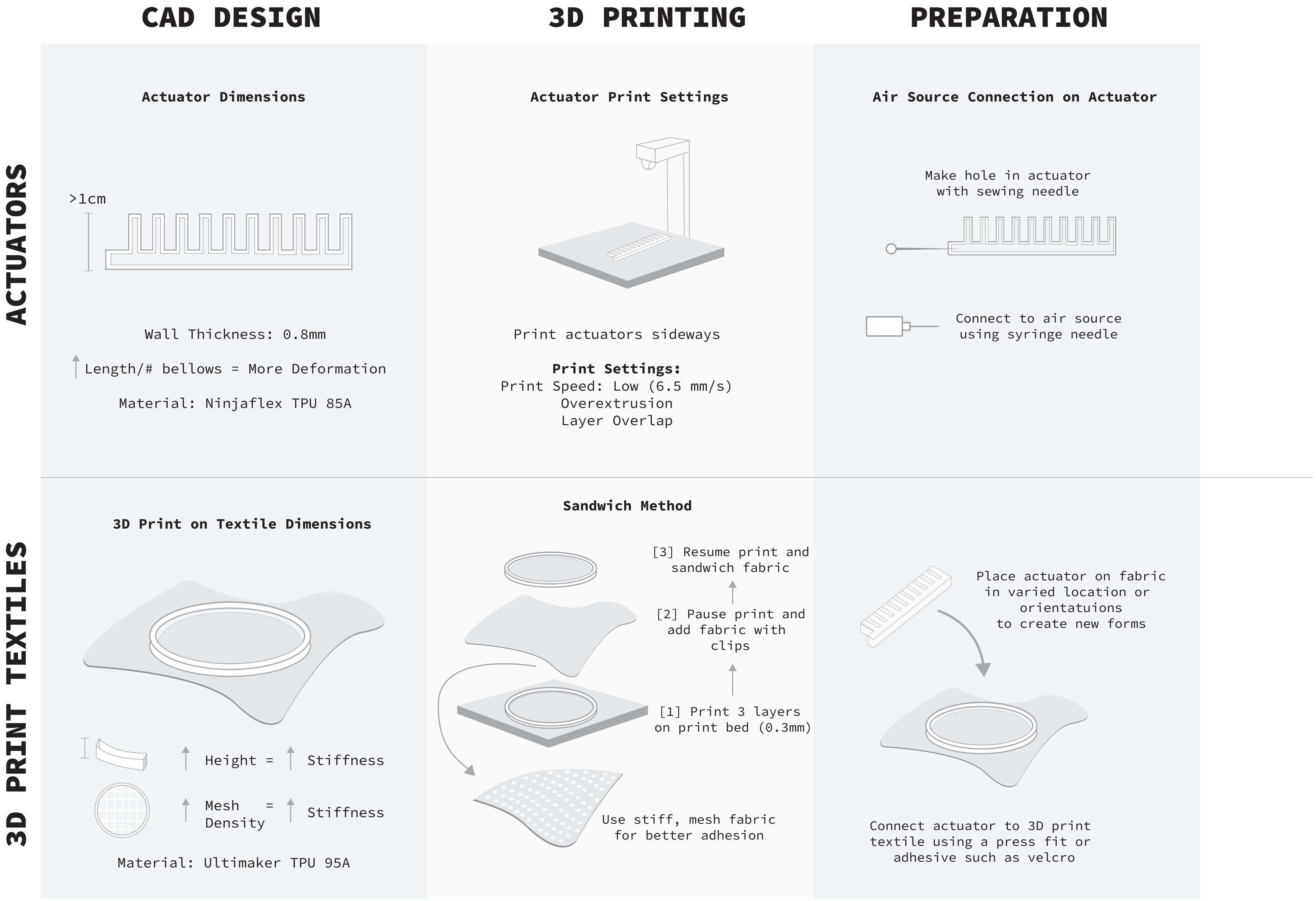
10) Density of the pattern also affects the stiffness of the fabric affecting the local deformations of the textile.

11) Using non-stretchy fabrics (cotton) reduces deformation due to fabric tension on the print bed.

12) TPU95A adds a good balance between stiffness and flexibility to the fabric.

13) Varying the actuator orientation/ location creates more modular, interesting deformations.

Figure 98
Sample A13 actuator in its actuated state



CAD DESIGN

3D PRINTING

PREPARATION

ACTUATORS

Actuator Dimensions

>1cm

Wall Thickness: 0.8mm

↑ Length/# bellows = More Deformation

Material: Ninjaflex TPU 85A

Actuator Print Settings

Print actuators sideways

Print Settings:
Print Speed: Low (6.5 mm/s)
Overextrusion
Layer Overlap

Air Source Connection on Actuator

Make hole in actuator with sewing needle

Connect to air source using syringe needle

3D PRINT TEXTILES

3D Print on Textile Dimensions

↑ Height = ↑ Stiffness

↑ Mesh Density = ↑ Stiffness

Material: Ultimaker TPU 95A

Sandwich Method

[3] Resume print and sandwich fabric

[2] Pause print and add fabric with clips

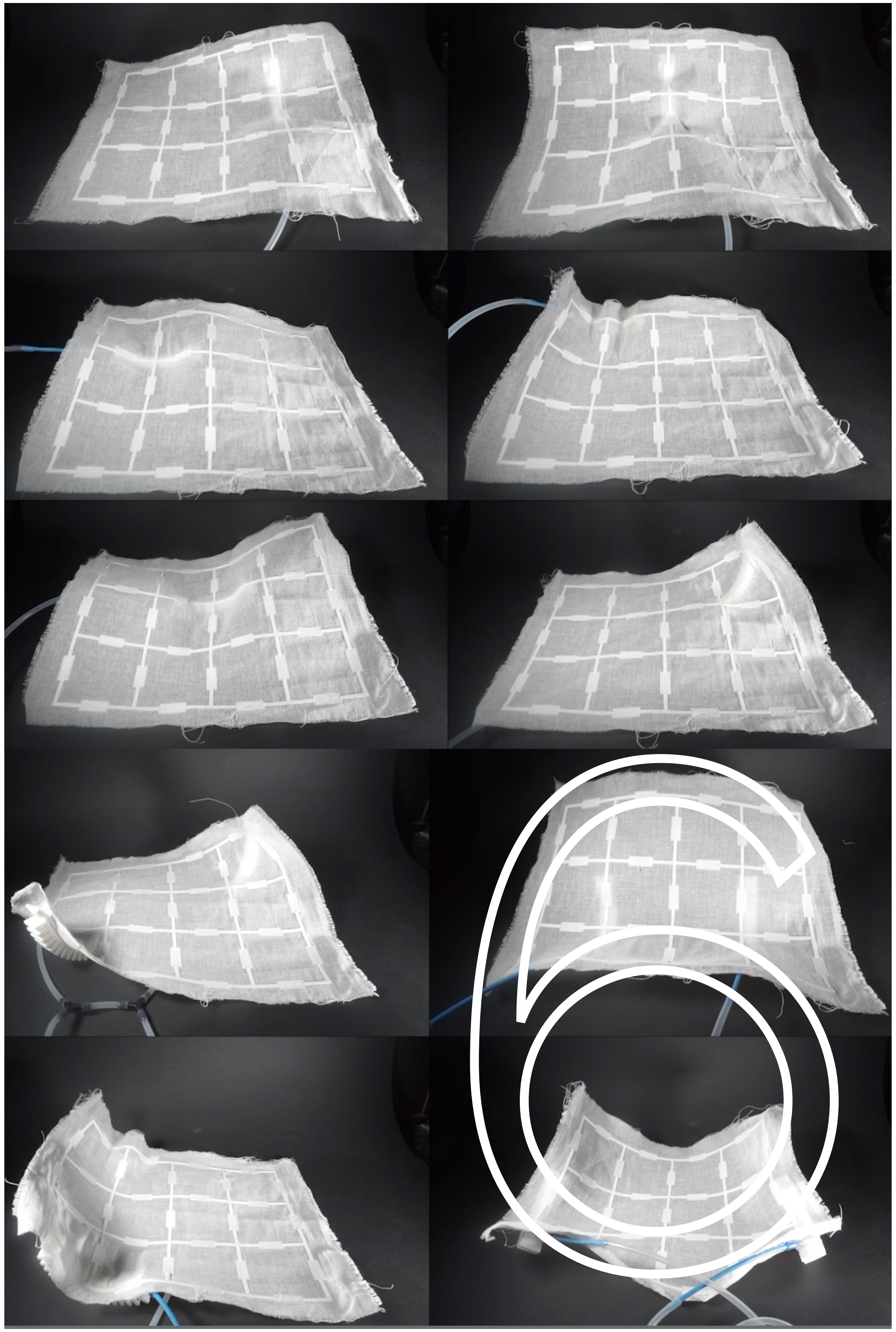
[1] Print 3 layers on print bed (0.3mm)

Use stiff, mesh fabric for better adhesion

Place actuator on fabric in varied location or orientatuions to create new forms

Connect actuator to 3D print textile using a press fit or adhesive such as velcro

Figure 99
3D printed pneumatic textiles fabrication guide



CHAPTER **SIX**

TECHNICAL CHARACTERISATION

This chapter aims to characterize the technical possibilities and limits of the 3D printed pneumatic textiles. It explores the range of deformation of the actuators when inflated at various air pressures, the range of speeds when varying the air flow at constant pressure, and finishes with an exploration on the possible shape morphologies available using the modular grid sample prototype.

6.1 DEFORMATION ANGLE VS. AIR PRESSURE

As shown in Chapter 3 (Section: Sizing of Actuators), multiple actuators of different sizes were created using Ninjaflex TPU 85A. To better understand how the change in size parameters affects the deformation angle of the actuator, a deformation angle vs. air pressure test was conducted. As stated in literature, the deformation angle of a pneumatic actuator is directly related to the air pressure used to inflated it. Therefore, it is expected that as the air pressure is increased, the deformation of the actuator would also increase. The goal of the Deformation Angle vs. Air Pressure test are the following:

[1] Which actuator sizing provides the highest amount of deformation at the highest air pressure?

[2] What is the maximum deformation angle achievable by the actuators?

Method

1. The actuator is connected to an air compressor with an air pressure regulator valve.

2. Using the regulator valve, the air pressure is increased manually by intervals of 0,25 bars and the actuators are allowed to reach a steady state.

3. Once steady state is reached, the deformation angle is recorded for each air pressure value. The deformation angle is measured from the horizontal line on the graph to the line created by the opposite tip of the actuator as shown in Figure 100. To avoid the actuators from breaking due to high air pressure, the air pressure was capped at 1 bar.

4. Steps 1-3 are then repeated for all actuators.

Results

The graph shows that Sample A13 has the highest deformation angle at the highest air pressure of 1 bar. This was as expected since the Sample A13 has a large size and contains the highest number of bellows, which has been shown to increase the deformation angle of pneumatic actuators. The maximum deformation angle of this actuator was 105 degrees. When this actuator is placed in the out-of-plane orientation on a textile interface, it has the potential to create a significant deformation with such a large deformation angle. Even at lower air pressure values, the actuator still showed significant deformation angle meaning it is suitable for use with a portable air pump that can be powered by an Arduino. This is important as the ability to produce large deformation and be controllable by a small air pump opens the possibility of creating a controllable, interactive device for a future prototype.

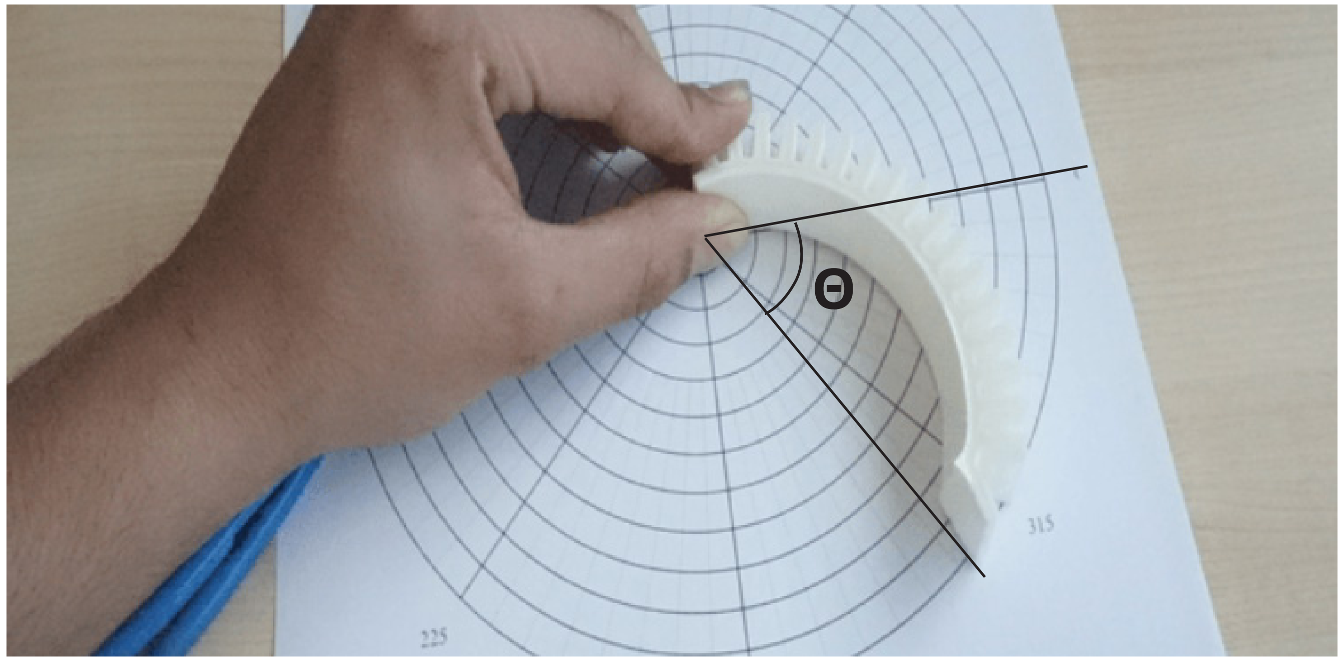


Figure 100
Measuring deformation angle of actuator

SAMPLE A9

SAMPLE A10

SAMPLE A7

SAMPLE A13

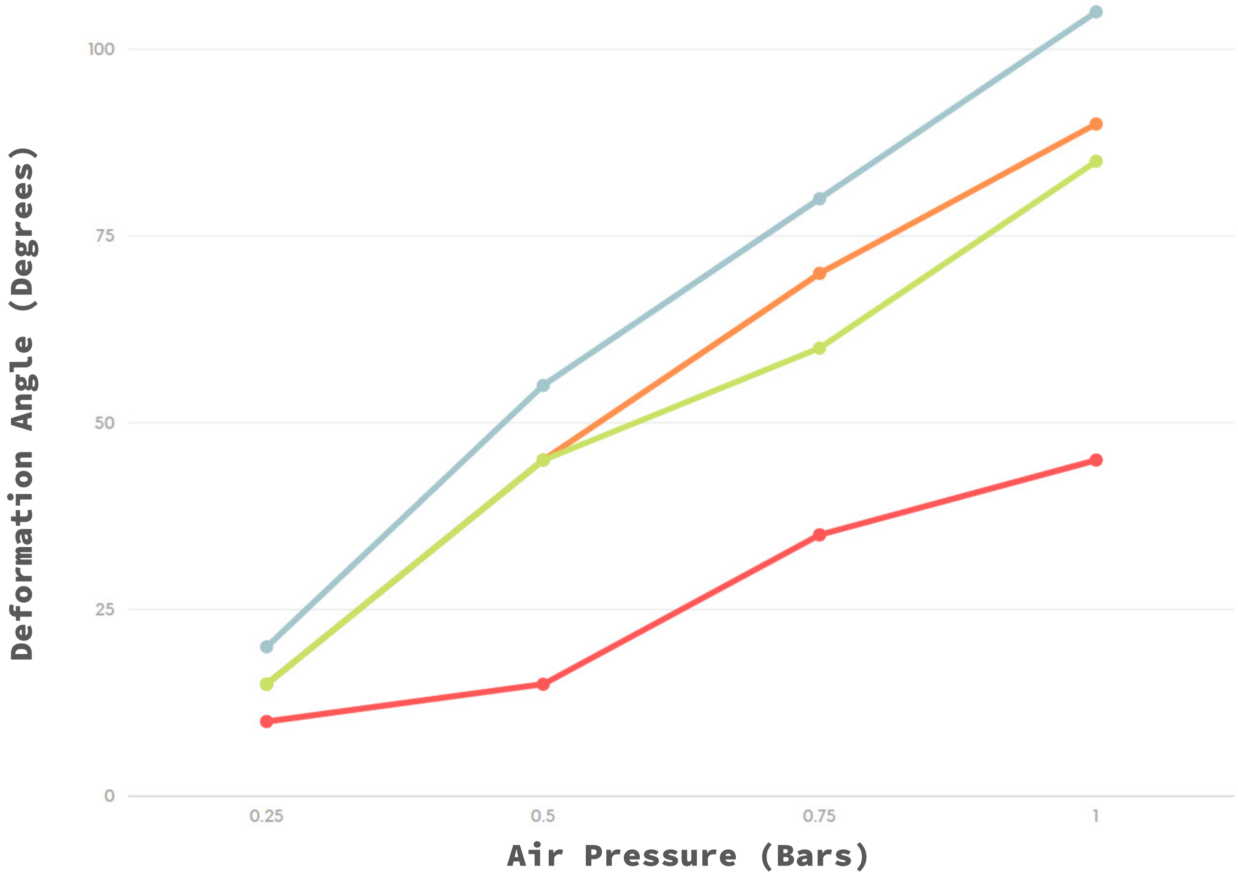


Figure 101
Results from experiment (Deformation angle vs air pressure)

6.2 ACTUATOR SPEED VS. AIRFLOW

Now that the spatial deformation of the pneumatic actuators has been tested, the next step was to test the temporal parameters as well. This means to measure how the speed of the actuator changes when varying the pneumatic parameters. There are various ways to control the speed of a pneumatic actuator. One method is to control the change of air pressure. If there is a large change in the air pressure, also called pressure gradient (0 bars -> 2 bars), the actuator will have a higher speed until it reaches steady state at 2 bars. Instead, if the air pressure is changed in small increments of 0,5 bars over time until it reaches 2 bars, it will have a lower speed due to the lower gradient of pressure. This method for controlling the speed of an actuator technically works, yet it is difficult to include in a control system and does not produce a constant speed.

A more reliable method to control the speed of pneumatic actuators is to simply use a flow control valve at a constant air pressure. Maintaining the air pressure constant ensures that the actuator always reaches the same steady state position despite change in air flow. Before proceeding with measuring the speed of the actuator under different air flows, it is important to first select the components that will be used in the future pneumatic control system for future prototypes. This is because the air source and flow control valve used in the future prototype will have a high influence on the speed of the actuator that can be achieved. A similar test could be done with an air compressor, yet the results will not be as relevant.

Selection of Pneumatic Components

First, it is important to select a low voltage air pump that can be connected to a power relay, so that it is controllable from an Arduino device. Based on the project *Soft Robotic Module for Sensing and Controlling Contact Force*, the same 24V air pump was selected for this test as it allows for easy electronic control and can still provide a relatively high air pressure of 0,8 bars when compared to other low voltage air pumps (Buso et al., 2020). As for the flow control valve, A Festo GRO Series Flow Valve was selected for the valve as it allows for precise manual control of the air flow by turning the needle valve with a very high resolution (around 30 full turns to go from fully closed to fully open) that can allow for variability in the speed of the actuator.

With the pneumatic components for the test selected, the main goal of the test is quite simple:

[1] What is the maximum speed of the actuator using the 24V air pump when the flow control valve is fully open?

[2] What is the minimum speed of the actuator using the 24V air pump when the flow control valve is almost fully closed?

Method

The test was conducted with the Sample A13 actuator as it was the best performing actuator from the Deformation Angle vs. Air Pressure Test.

1. The actuator is connected to the air pump through the flow control valve.

2. The flow control valve is fully opened manually.

3. The air pump is turned on to full power and the timer is started.

4. Once the actuator has reached its final steady state position, the timer is stopped, and the time is recorded.

5. Steps 1-4 are repeated 2 times for repeatability.

6. The flow control valve is then turned until it is almost fully closed. The air pump is turned on, and the flow control valve is slowly open slightly until the actuator begins to move. This is now set as the minimum value possible for the flow control valve.

7. Steps 1-4 are repeated with the new settings on the flow control valve.

Results

The results showed that the pneumatic actuator can achieve a maximum speed of fully inflating in ~1,5 seconds and a minimum speed of fully inflating in ~85 seconds. This proves that the pneumatic actuators have a high variability in its actuation speed as was stated in literature. Additionally, it showcases that the speed can easily be manually controlled with the flow control valve, which can potentially be an added interactive element in future prototypes. One thing to note is that when the actuator was fully closed, the actuator reached a final steady state position that was slightly less than the final steady state position when the valve was fully open. This is reasonable as it is expected that there would be a small air pressure drop on the flow control valve as the orifice is made smaller when the valve is almost at its closed position. The difference in deformation though does not appear to be significant and should not affect the overall performance of the actuator.

Figure 102
Festo flow control valve used to control actuator speed

Figure 103
24V air pump used to inflate actuators

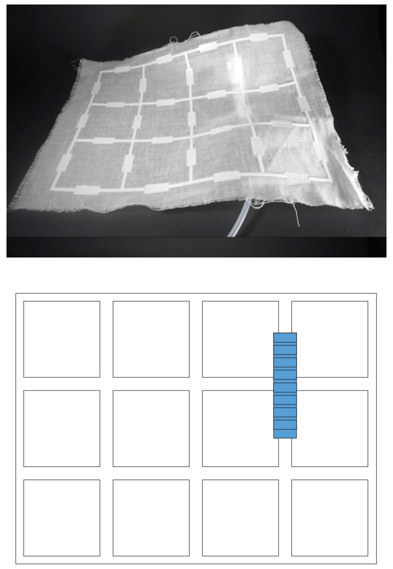
6.3 SHAPE MORPHOLOGIES

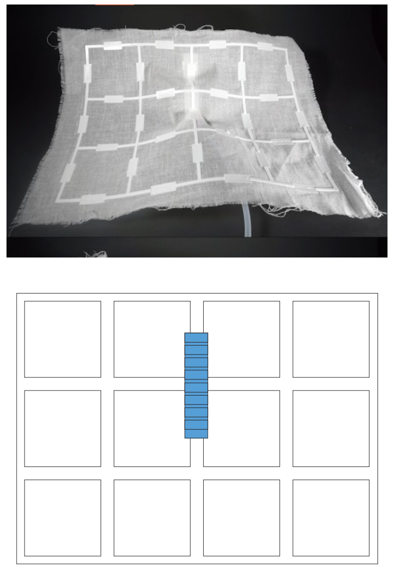
As shown at the end of the previous chapter, by varying the location of the active element (actuator) on the interface element (3D printed textile), new form possibilities can be explored. Using the Modular Grid sample T17 from the material tinkering section, a systematic test was conducted to explore the variety of shape morphologies that are possible with by changing the number and locations of the actuators.

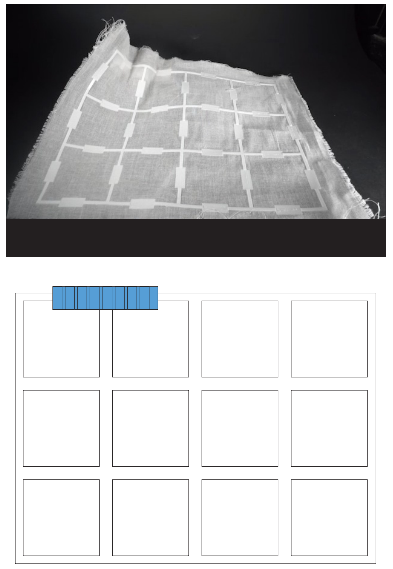
Method

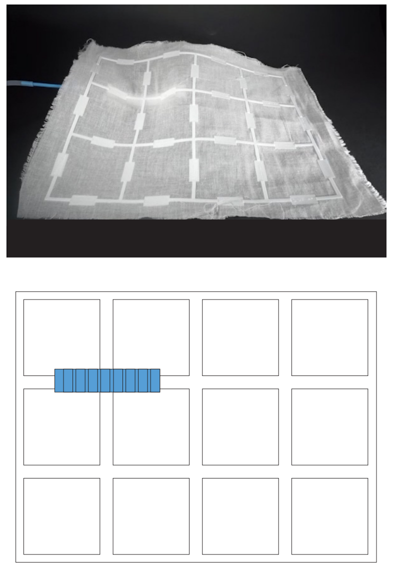
This test was a free exploration of the various forms possible with the prototype. The actuators were placed at various locations in the out-of-plane orientation across the textile sample and the location of the actuators was recorded. The locations of the actuator were varied as much as possible to avoid repetitive shapes. The maximum number of actuators used was 3 due to the size restrictions of the textile sample. The resulting photographs with their corresponding actuator location are shown in the following figures on the next few pages.

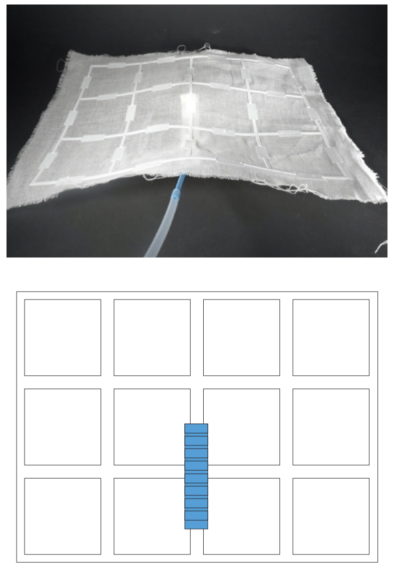
Actuators: 1

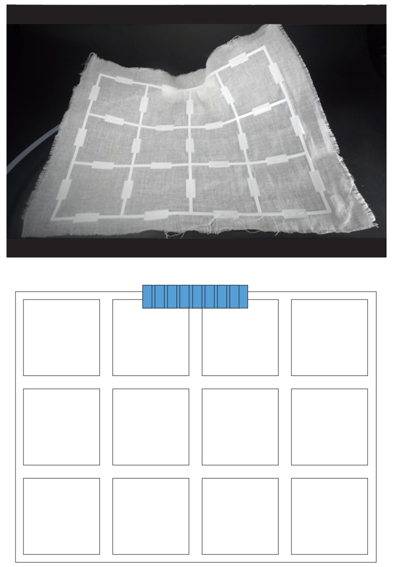


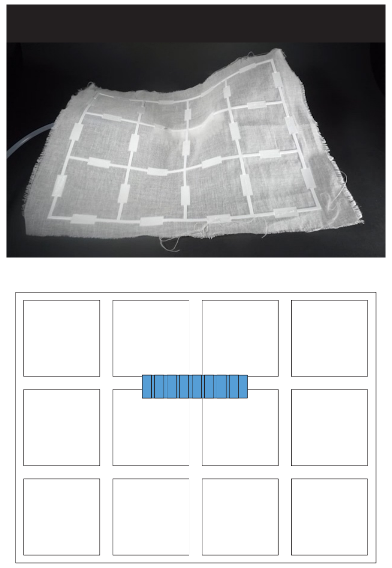


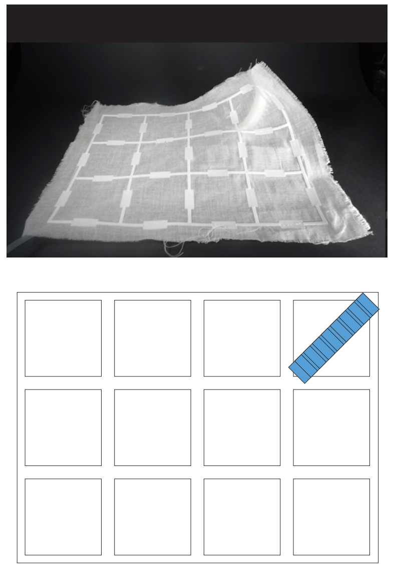


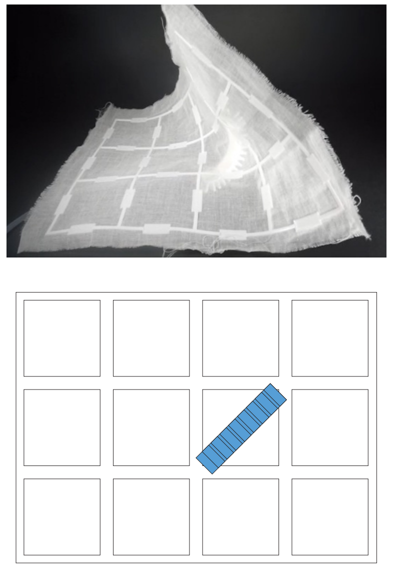




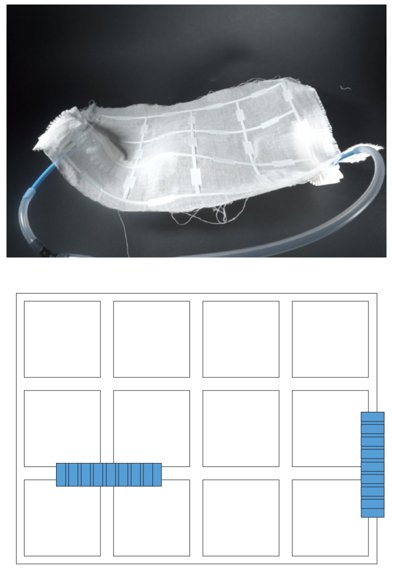


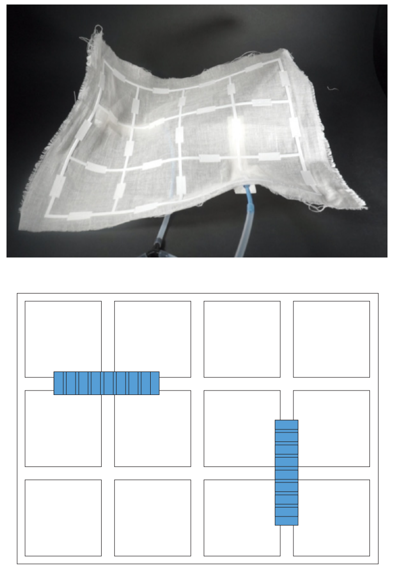


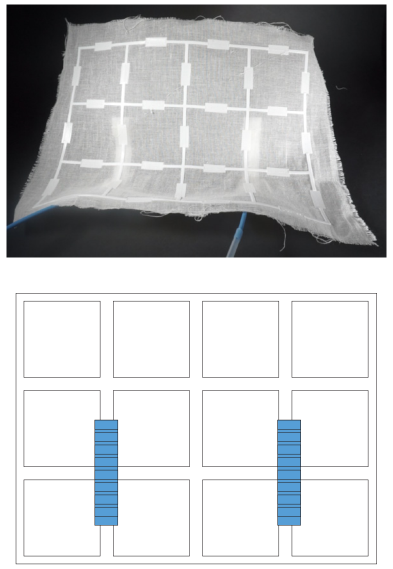


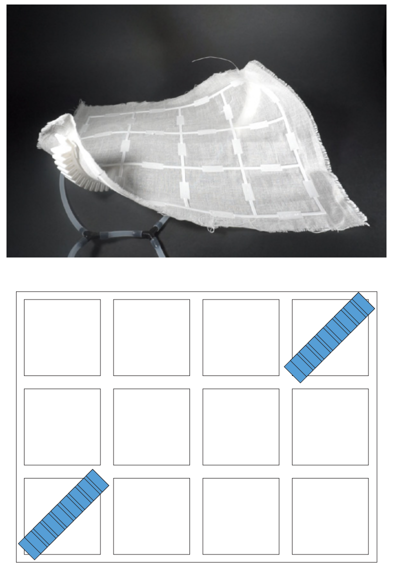


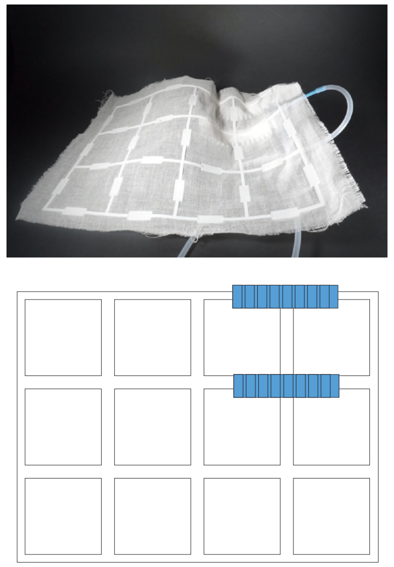
Actuators: 2

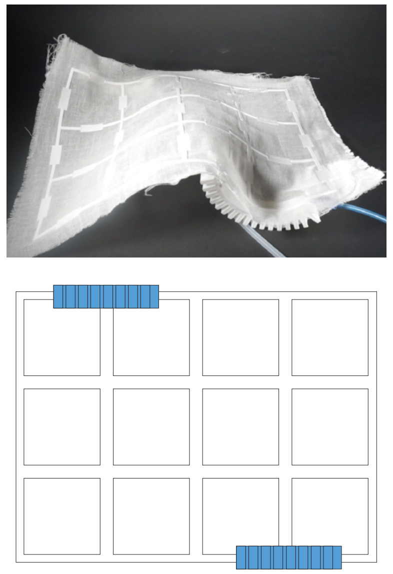


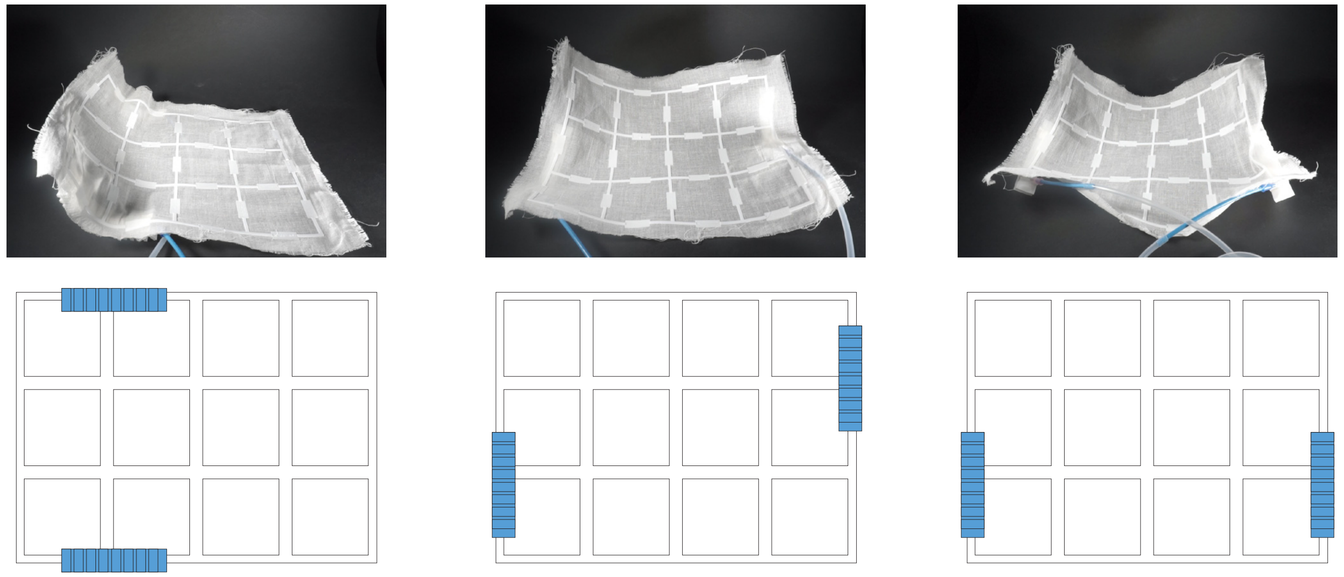












Actuators: 3

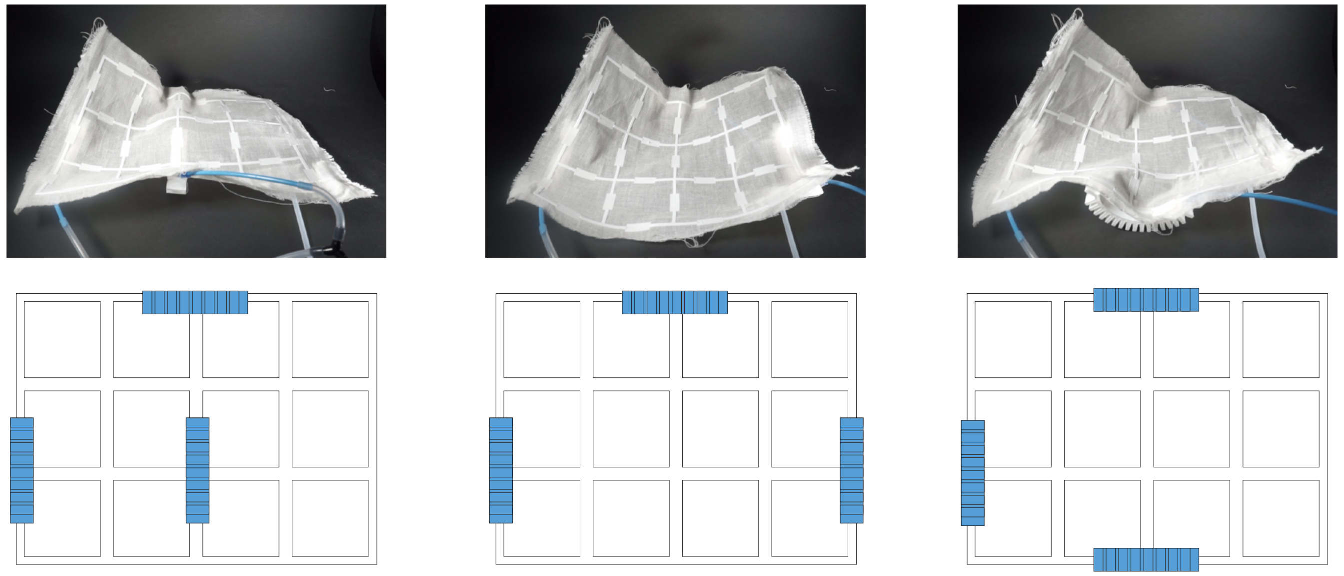


Figure 104
Results of shape morphologies test

Results

The test proved that a wide range of shape morphologies are available with such a modular design. When using a single actuator, the shape change can be rather predictable and simple. When more actuators are added, the fabric movement becomes more alive and complex showing the varied behavior of the system. It was also found that the orientation of the actuator (whether the air input was forward or backwards) had a small effect on the final shape produced, yet this is also a possible result of the pneumatic tubing having an effect on the deformed shape. Unfortunately, as the number of actuators increased, the web of pneumatic tubing became quite large for such a small textile sample, which also distracted from the expression of the textile. That being said, this exploratory test still proves that a large variety of forms and deformations are possible even with a small sample of textile. With a larger piece of textile, the complexity of the deformations can be increased to enhance the expression of the textile.

CHAPTER **SEVEN**

MATERIAL CONCEPT

This chapter brings together the findings from the literature review, material tinkering, and technical characterisation to create a material vision and product concept that best suits the material studied. Additionally, this section presents an overview of the material qualities and material benchmark showcasing other applications of shape changing materials.

7.1 MATERIAL QUALITIES

Due to the technical difficulty in fabricating these pneumatic textiles and the time constraints of the project, it was decided to focus on the technical characteristics of the material and develop a concept that could be used to test the material experience of livingness for future work. Therefore, an experiential characterisation of the material was not performed to determine the experiential qualities of the material. Instead, the future product concept will be tested with users to obtain a better understanding of the material qualities in the future chapters. In reality, it is best to perform the experiential characterisation of the material prior to the development of the material concept, therefore, the concept should be reassessed in the later chapters with the findings from the user test of the product concept. The technical qualities that were studied during this research project show great promise in the future of the 3D printed pneumatic textile materials. The controllability and range of speed are highly important qualities as this sets the material studied apart from the literature results. Most papers on shape changing interface focus solely on the spatial form of the material and fail to recognize the importance of speed and movement. Showcasing this quality in the material vision will allow the concept to differentiate itself from previous literature. The modularity of the material also proved to be an unexpected opportunity of the material caused by separation of the actuator from the 3D printed textile. Also the ability for seamless integration into the textile was lost because of this decision, the ability to easily change the form of the textile interface by varying the location of the actuator adds an additional unique element to the material. Finally, interactivity and scalability possibilities of the material allow the ability to create large scale interactive exhibits, which is often difficult with other shape changing materials.

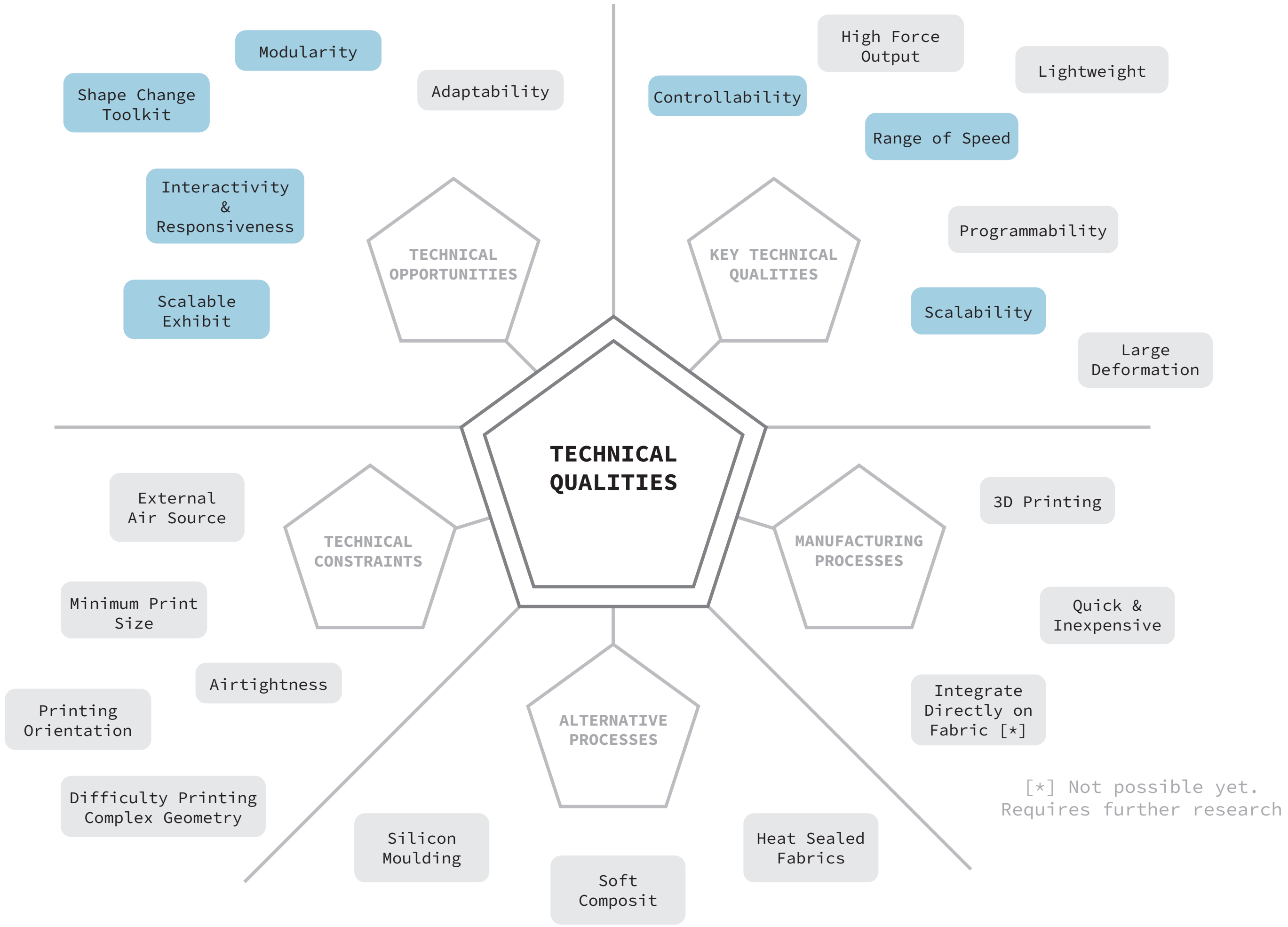
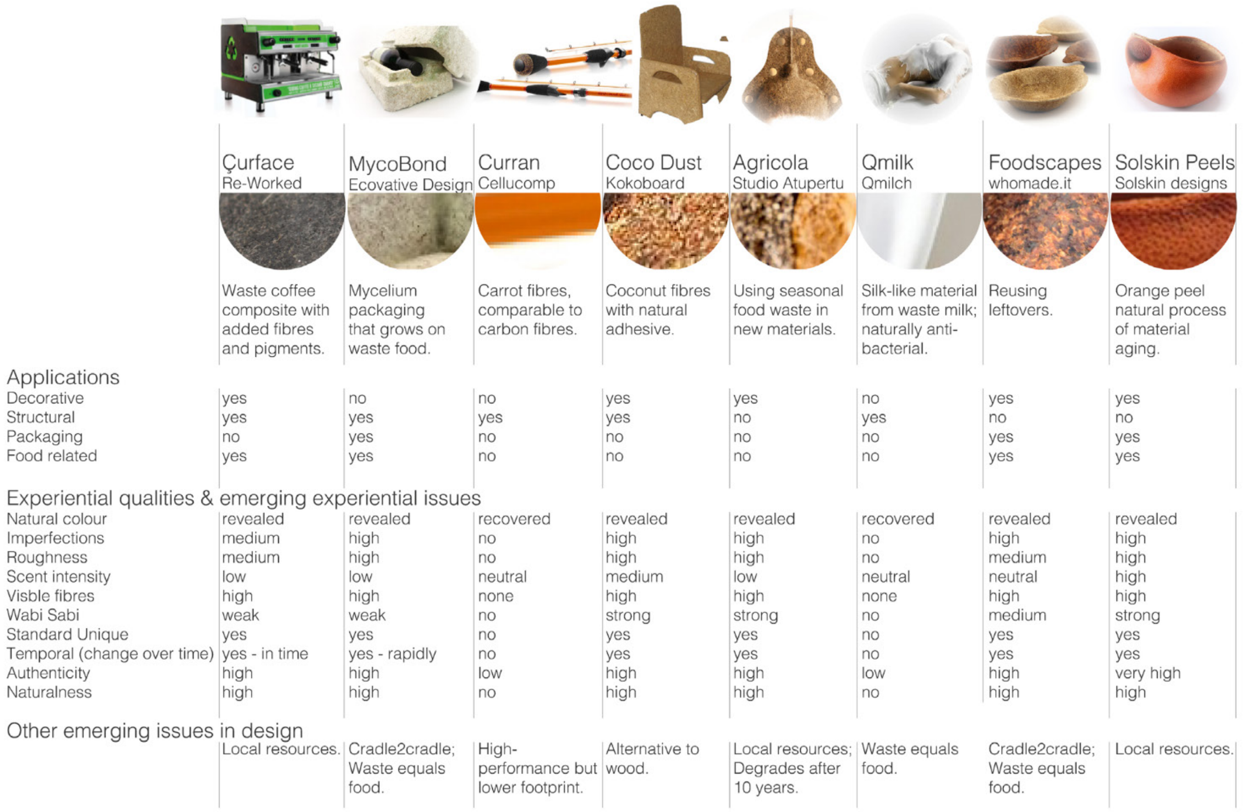


Figure 105
Technical qualities of 3D printed pneumatic textiles

7.2 MATERIAL BENCHMARK

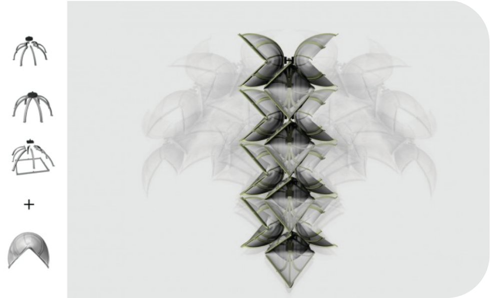


	Çurface Re-Worked	MycoBond Ecovative Design	Curran Cellucomp	Coco Dust Kokoboard	Agricola Studio Atupertu	Qmilk Qmilch	Foodscapes whomade.it	Solskin Peels Solskin designs
	Waste coffee composite with added fibres and pigments.	Mycelium packaging that grows on waste food.	Carrot fibres, comparable to carbon fibres.	Coconut fibres with natural adhesive.	Using seasonal food waste in new materials.	Silk-like material from waste milk; naturally anti-bacterial.	Reusing leftovers.	Orange peel natural process of material aging.
Applications								
Decorative	yes	no	no	yes	yes	no	yes	yes
Structural	yes	yes	yes	yes	no	yes	no	no
Packaging	no	yes	no	no	no	no	yes	yes
Food related	yes	yes	no	no	no	no	yes	yes
Experiential qualities & emerging experiential issues								
Natural colour	revealed	revealed	recovered	revealed	revealed	recovered	revealed	revealed
Imperfections	medium	high	no	high	high	no	high	high
Roughness	medium	high	no	high	high	no	medium	high
Scent intensity	low	low	neutral	medium	low	neutral	neutral	high
Visble fibres	high	high	none	high	high	none	high	high
Wabi Sabi	weak	weak	no	strong	strong	no	medium	strong
Standard Unique	yes	yes	no	yes	yes	no	yes	yes
Temporal (change over time)	yes - in time	yes - rapidly	no	yes	yes	no	yes	yes
Authenticity	high	high	low	high	high	low	high	very high
Naturalness	high	high	no	high	high	no	high	high
Other emerging issues in design								
	Local resources.	Cradle2cradle; Waste equals food.	High-performance but lower footprint.	Alternative to wood.	Local resources; Degrades after 10 years.	Waste equals food.	Cradle2cradle; Waste equals food.	Local resources.

Figure 106
Example of Material Benchmarking for food-based composites (Karana et al., 2015)

The material benchmarking is used to showcase what other research projects and products are doing within the same design space. Material Benchmarks help to inspire the designer in creating their material vision, but also to validate the uniqueness of their material concept when compared to what has already been done. The material benchmark created showcases the main applications found in the shape changing interface space that are related and have similar qualities to the 3D printed pneumatic textiles studied. The material benchmark showcases many projects that are also using pneumatics as their active element, yet also explores projects from other active elements such as SMAs, mechanical actuation, and magnets. All the projects showcased in the Material Benchmark are either research projects or art exhibitions as it is often rare to see commercial products using shape changing interfaces as they are still in their early development and exploration. These projects share similar qualities to the technical qualities showcased in the previous section. The modular toolkit application explores how modularity of a shape changing material can be used to give designers the freedom to easily prototype their own shape changing interfaces. This is quite important as many shape changing materials require a certain level of engineering, which might prevent many designers from having easy access to such materials. The adaptable spaces and interactive application showcase how interaction between material and user can be embedded into the product by making the material respond to user behavior in both a small and large scale. Combining the insights from the material qualities and material benchmark, a material vision could now be created that can incorporate the most qualities of the material to achieve its most suitable application.

Adaptable Spaces


Fabricflation (Papakonstantinou, 2015)


Urban Impact by Studio Ini

Modular Toolkit

MorphIO (Nakayama et al., 2019)


Magnetform (Yehoshua Wald & Zuckerman, 2021)

Dynamic Affordances


PneUI (Yao et al., 2013)


Transform (Ishii, 2015)

Self Assembly


Knitflatable Architecture (Šinke, 2015)

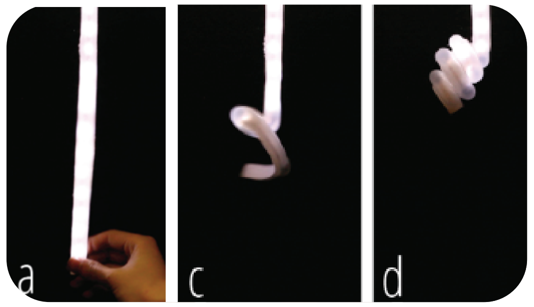

Pneumatic Objects by Christopher Guberan

Alive-like Expressions

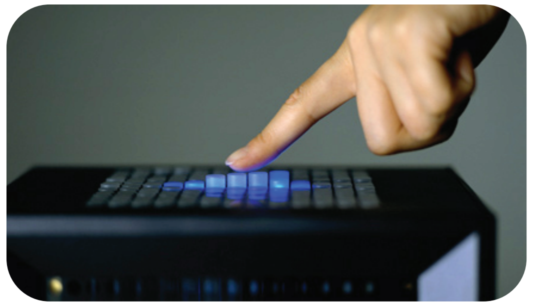

Shylight by Studio Drift


Thrifty Faucet (Togler et al., 2009)

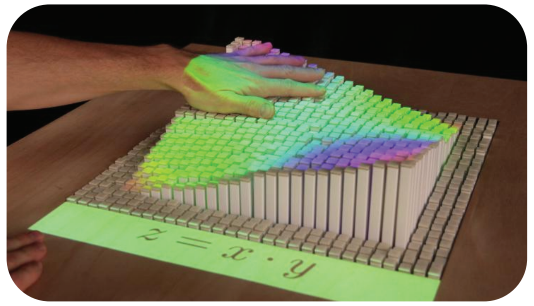
Interactivity

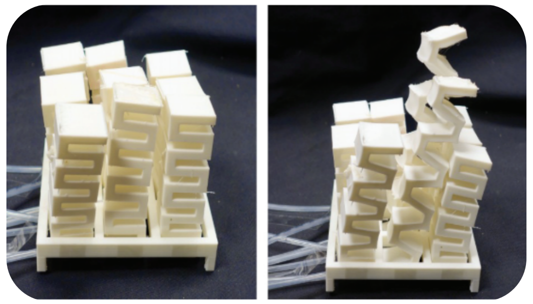


PneUI (Yao et al., 2013)


Lumen Display (Poupyrev, Nashida, Maruyama, Rekimoto, & Yamaji, 2004)

Communicate Information


Transform (Ishii, 2015)

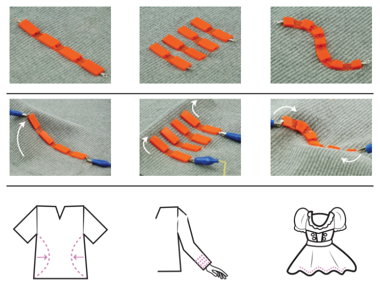

MorpheesPlug (Kim et al., 2021)

Haptic Interface


Aeromorph (Ou et al., 2016)

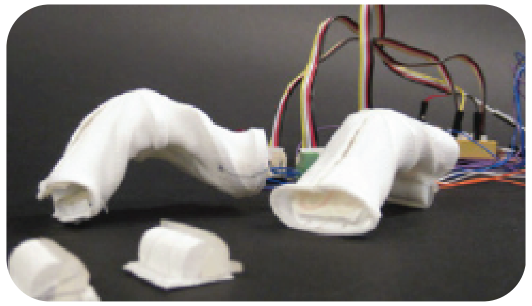

Tactile Vision by Jiabao Li

Adaptable Wearables


ClothTiles (Messerschmidt & Matthies, 2021)


BioLogic (Yao et al., 2015)

Mimicking Locomotion


Caterpillar Locomotive Device (Atmopawiro, 2019)

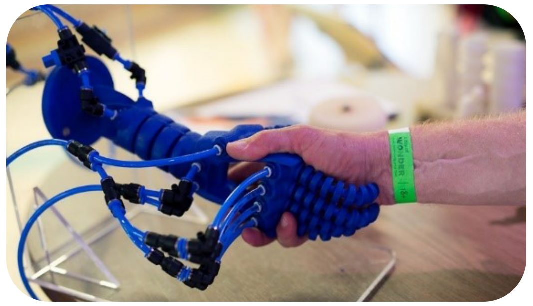

Soft Robotic Hand (Scharff et al., 2017)

Figure 107
Material benchmark for shape changing interfaces

7.3 MATERIAL VISION IDEATION

In collaboration with my supervisors, an collaborative ideation session was done to explore the future direction and visions of the designs based on the material props created during the previous phases. From this ideation phase, two main directions were selected inspired by two of the material samples: A Modular Toolkit and Interactive Exhibit. These two directions are further discussed below:

Modulart Toolkit

This concept aims to showcase the modular ability of the actuator to be able to be placed at different positions in the textile to achieve a variety of shape changing morphologies. Multiple actuators can then be manipulated by the designer to quickly iterate between alive-like expressions or other applications. Currently, modularity is not common among other popular shape changing materials such as SMA's, yet has been displayed using pneumatic actuators in other ways (Nakayama et al., 2019; Niiyama et al., 2015). These other modular toolkits mainly focus on providing the user with an actuator that they can place on any object.

Our concept instead provides the user not only with the actuators (active element), but also with a textile interface (interface element) where the designer can prototype curved surfaces. Additionally, it is important to showcase the controllability and speed range of the actuators by giving designers the digital tools to control the movement qualities of the material. This control of both the spatial and temporal qualities of the shape change interface will provide an open experience to explore shape changing interfaces and the livingness of their newly created expressions.

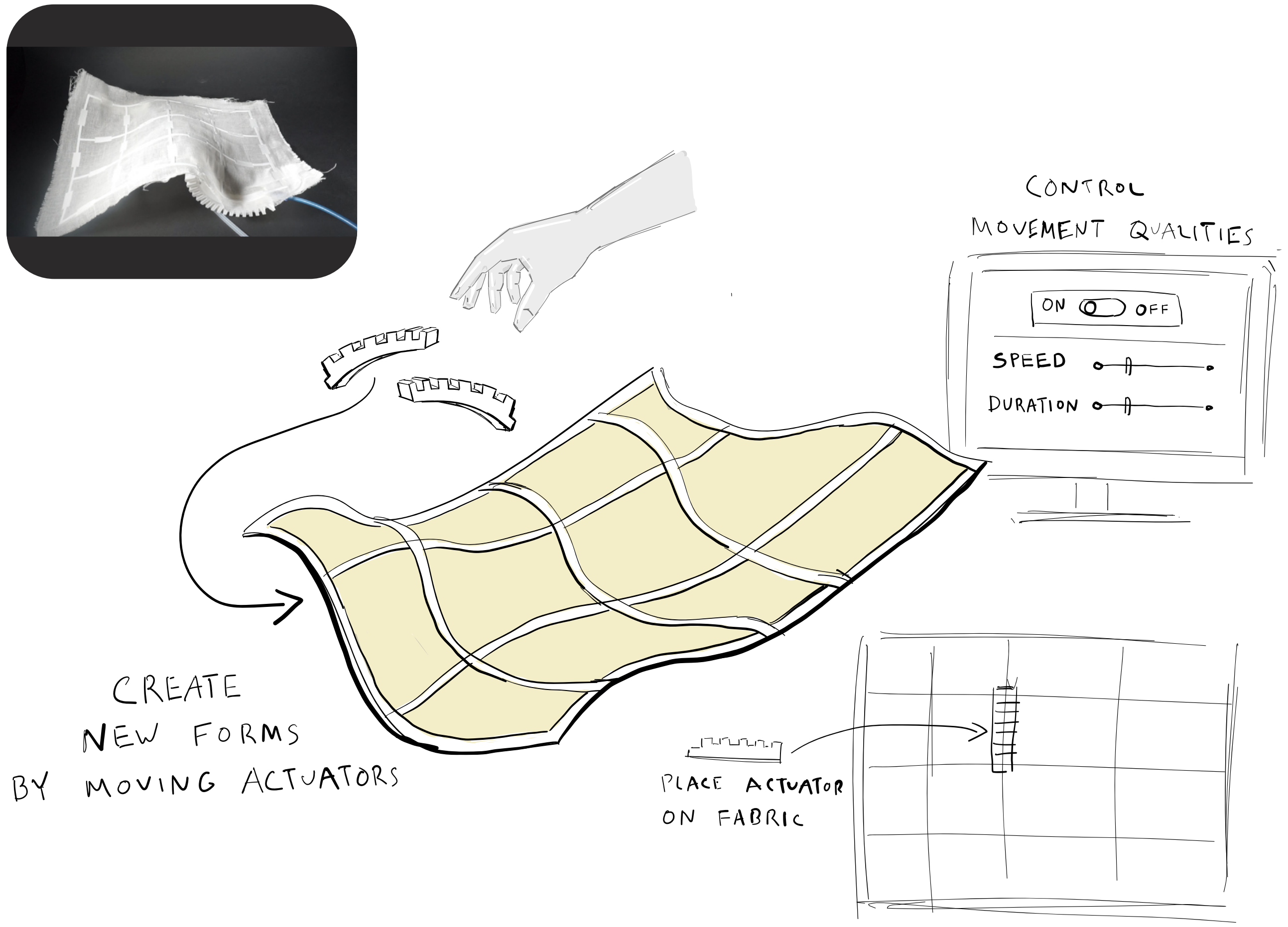


Figure 108
Modular toolkit vision idea

Interactive Exhibit

This concept showcases the scalability and interactivity of the material by creating a large (human size) material prop that can interact and respond with its users. This vision was inspired by the shape change created from the "Double Domed" prototype and how it moved itself as in attempt to grab its user. This interactivity can come in the shape of a "living hugging curtain" as shown in the sketch, which wraps around the user in a comforting manner when the user approaches it. The scale and responsiveness of the interactive exhibit adds to the experience of livingness of the material and can be used to study how users would interact with a "living" interface. This is similar to the large scale interactivity seen in projects such as Urban Imprint where a large urban space was transformed to respond to the users movement patterns. Despite its mechanical construction, the scale, responsiveness, and fluid movement of such structure still gave an expression of livingness. These same principles can be used to create an interactive exhibit with the 3D printed pneumatic textiles that feel alive.

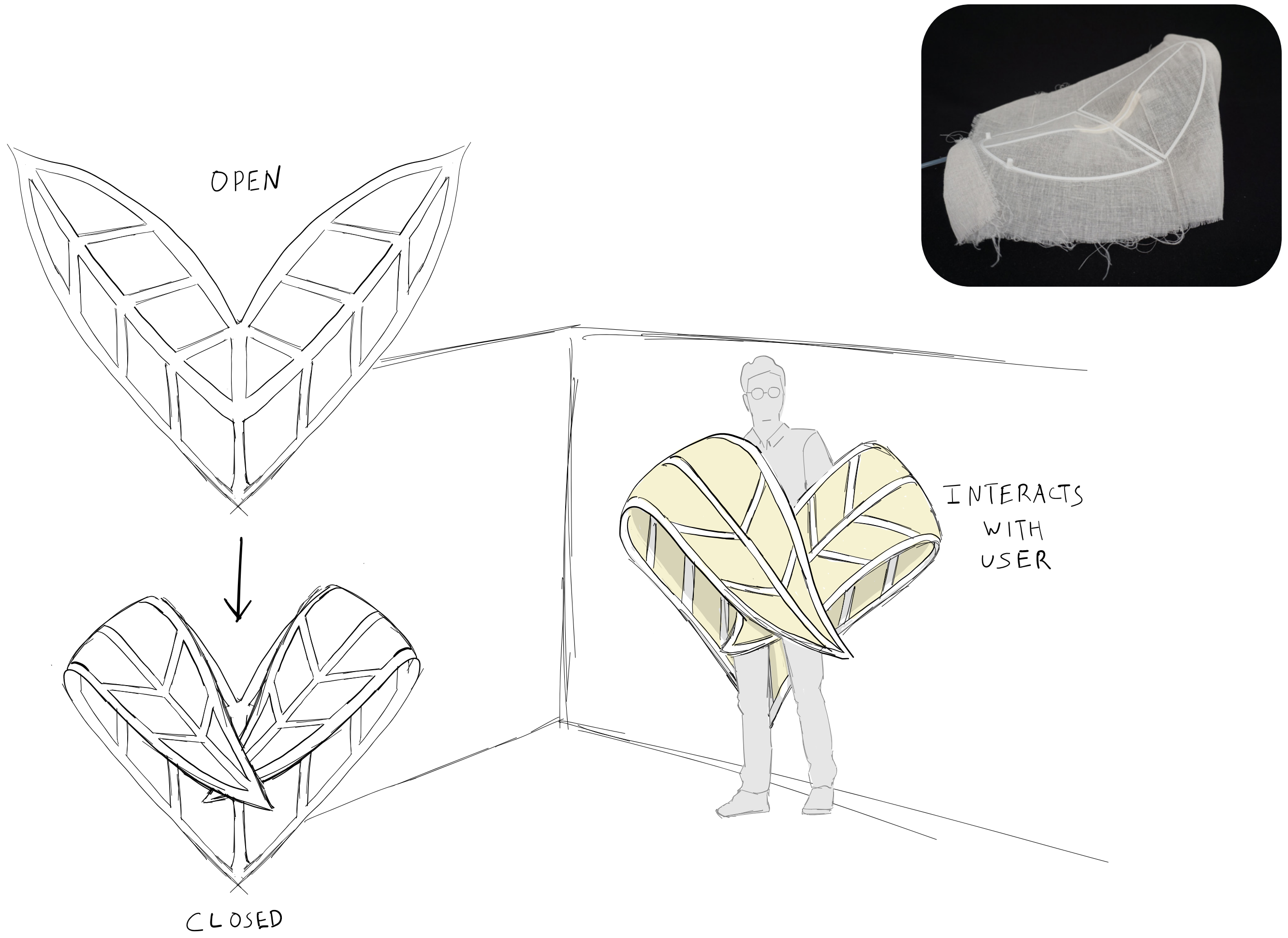
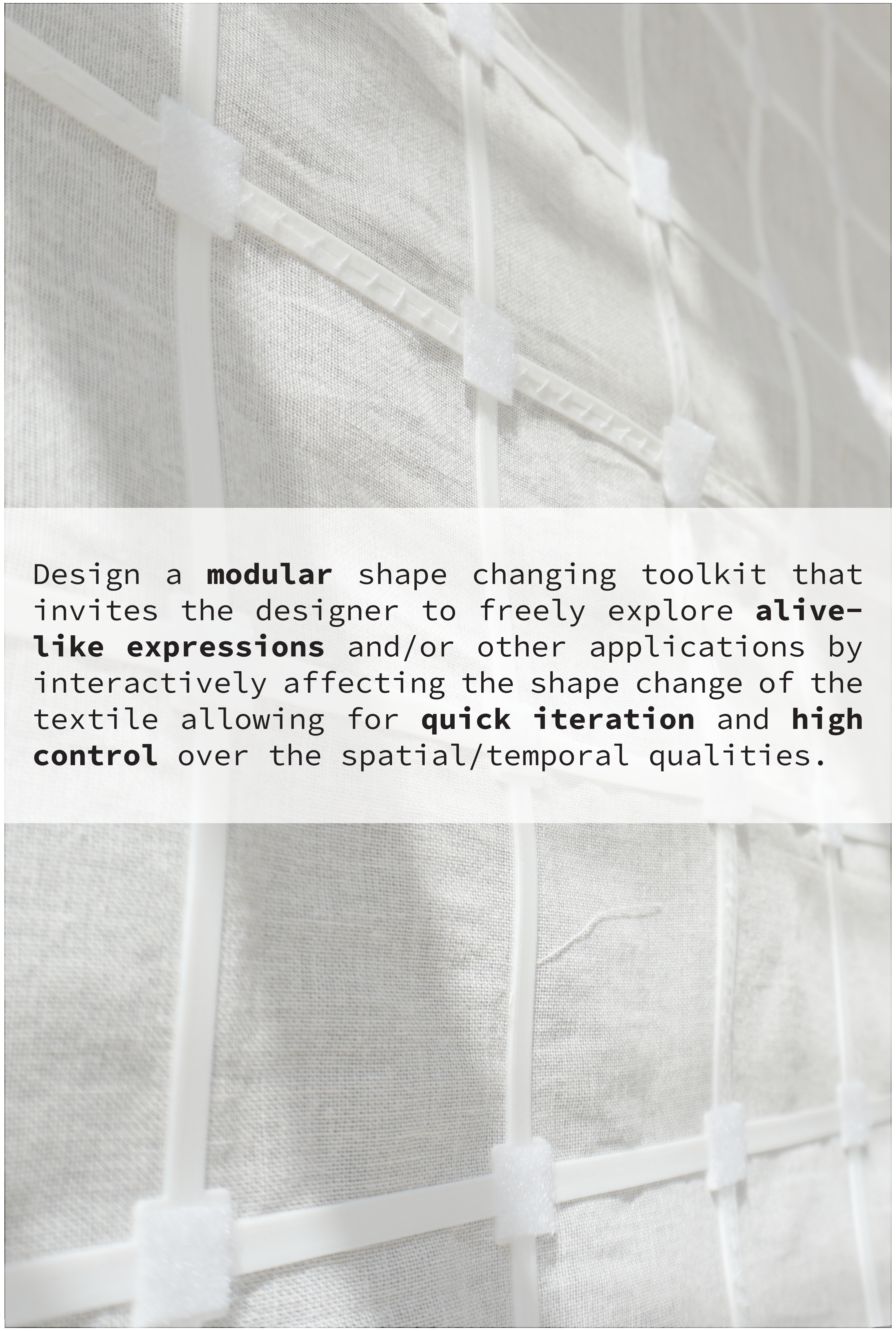


Figure 109
Interactive exhibit vision idea

7.4 MATERIAL VISION SELECTION

Both visions proposed showcase the most important qualities of the material: its modularity, controllability, scale, and instructiveness. Each vision is a valid showcase of the material qualities. When comparing the two, the modular toolkit attempts to display the modularity and controllability of movement of the actuators, which is as of now not well explored in literature. The ability to give designers control over the speed of the textile interface adds a novel concept that is essential to understanding the material experience of shape changing interfaces. Additionally, creating a modular toolkit opens up the possibility for conducting a wide range of material experience studies in the future by changing the parameters of the toolkit, which can be conducted personally or by other researchers in the future.

The interactive exhibit, on the other hand, does not provide the same flexibility for material experience studies due to the lack of modularity in the proposed vision. As it is still critical to study the material experience of the material and its alive-like expressions in future works, it is recommended to pursue the modular toolkit vision as it provides the higher flexibility for answering future research questions on the material experience of livingness that were not covered during this research project. With the material vision selected, the final written vision is presented showcasing the main material qualities included in the vision to guide the creation of the modular toolkit in the next chapter.



Design a **modular** shape changing toolkit that invites the designer to freely explore **alive-like expressions** and/or other applications by interactively affecting the shape change of the textile allowing for **quick iteration** and **high control** over the spatial/temporal qualities.

7.5 MOTIVATION FOR DESIGNING A TOOLKIT

Up to this point, the focus of the project had been heavily on the technical material research of 3D printed pneumatic actuators and 3D printing on textiles to explore its possibilities as a shape changing material. This was due to the realization of the difficulties of fabricating these new active materials, which is a common trend in other shape changing materials such as SMAs. In addition to the difficulties in fabrication, the majority of shape changing materials only have a singular state of shape change making it difficult to quickly iterate between different shape changing form and movement qualities. The technical difficulties behind creating and studying some of these materials is a main factor that holds designers back from exploring the experiential characteristics of shape changing materials and its alive-like expressions in a systematic fashion.

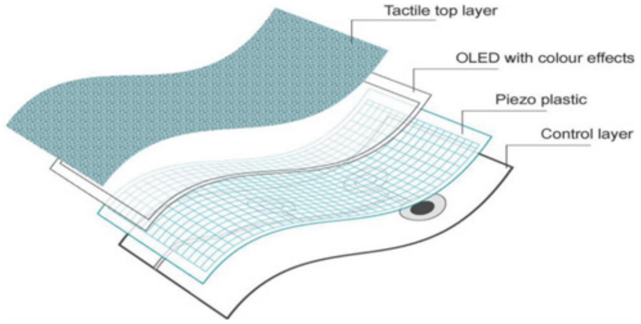


Figure 110
Diagram of Light-Touch-Matters material (Barati, Karana, & Hakkert, 2020).

By exploiting the main qualities of the material studied such as its modularity to create a toolkit for designers, these technical limitations can be removed to pave the way for more free, creative exploration. Researchers in the past have also attempted to fabricate many different types of shape changing toolkits to also reduce the technical barriers. As can be expected from the grand variety of shape changing materials out there, these toolkits have vast differences in their material qualities and the features they offer. This section explores some recent toolkits published in literature to understand the most important qualities to be included in a toolkit for shape changing interfaces.

Light-Touch-Matters

Light-Touch-Matters explores the creation of a future toolkit to help designers in exploring and developing promising, yet under-developed smart materials (Barati, Karana, & Hakkert, 2020). In this study, Barati et al. aims to understand the strategies designers employ when working with these new kind of materials by conducting a 20 week design project with master level designers. Throughtout the study, they came across the following interesting findings, which relates to the development of the toolkit in this project:

1. Majority of students (designers) are unfamiliar with abstract material driven design briefs without an initial context already established.

2. Using "physical probes/tangible represenations" can help to temporarily remove the technical barriers of smart materials to explore their experiential qualities.

3. Through the process of prototyping and creation, students began to inherently explore the materials sensorial and performative qualities. Through the process of brainstorming, students began to explore the materials affective and interpretive qualities.

4. The use of the materials unique dynamic qualities is important to include in a toolkit for exploration of its emotional and performative qualities.

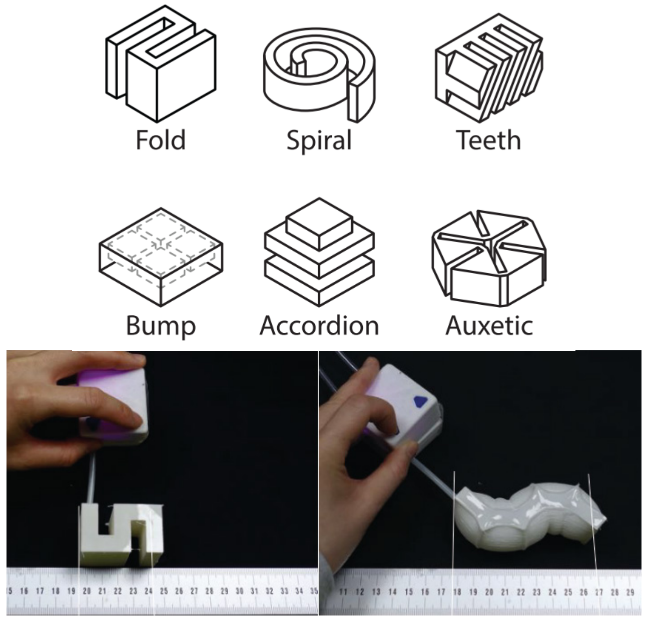


Figure 111
MorpheesPlug project (Kim et al., 2021)

Nurbsform

Nurbsform is an interactive modular toolkit that combines SMA actuator modules with a surface fabric to create programmable shapes (Tahouni, Qamar, & Mueller, 2020). Each module can be controlled individually allowing for precise control over different forms. Additionally, it includes a sensor that can react to your hand to create a responsive design that reacts to user proximity. With the digital tool included, the forms and curvature of the fabric can also be prototyped digitally before creating it with the physical toolkit. The main focus of this toolkit is on scalability and form, and exploration of kinetic qualities is not included.

MorpheesPlug

MorpheesPlug is a continuation of multiple research projects exploring the properties of shape changing interfaces, specially in form development (Kim et al., 2021). From the insight of their previous project, they developed 6 base unit designs (3D printed inflatables/actuators) that cover a wider range of form possibilities including a parametric design tool to help with prototype creation. With this tool, designers can digitally create a variety of shape changing products and quickly test them by simply 3D printing with their custom printing method (this method is also used in this project). This study focuses only on the form of shape changing interfaces and does not include exploration on the kinetic qualities of their prototypes.

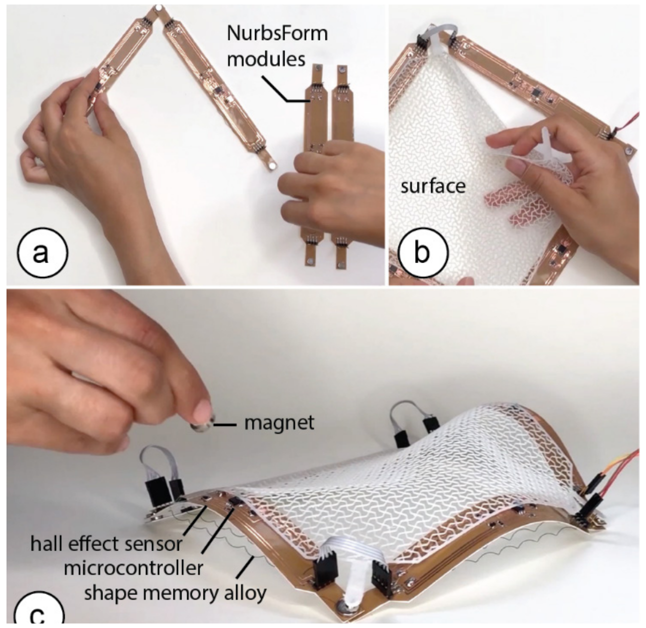
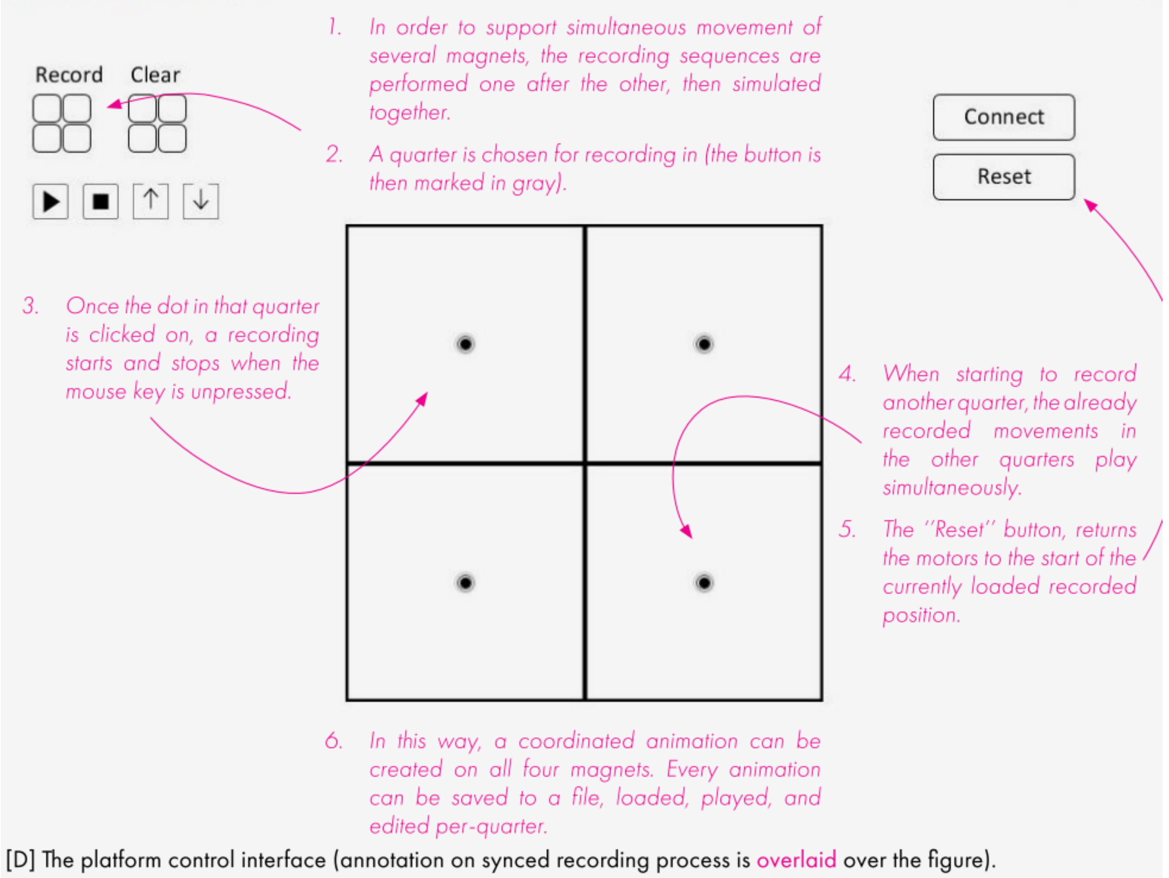


Figure 112
Nurbsform (Tahouni, Qamar, & Mueller, 2020)

Figure 113
Magnetform (Yehoshua Wald & Zuckerman, 2021)

MagnetForm

Different from previous projects described so far, Magnetform's focus is on motion with form being the result of the motion patterns created (Yehoshua Wald & Zuckerman, 2021). This project presents a tabletop hardware tool containing 4 robotic arms with magnets underneath the surface. By placing a soft material on top of the table surface with magnets to constrain the soft material, a shape changing interface is created. The designer can then easily program the movement of each of the magnet points as described in Figure 114. This approach to exploring form and movement simultaneously is a quite innovative way to explore shape changing interfaces and shows the importance of giving control over the kinetic qualities of the material to designers.



1. *In order to support simultaneous movement of several magnets, the recording sequences are performed one after the other, then simulated together.*
2. *A quarter is chosen for recording in (the button is then marked in gray).*
3. *Once the dot in that quarter is clicked on, a recording starts and stops when the mouse key is unpressed.*
4. *When starting to record another quarter, the already recorded movements in the other quarters play simultaneously.*
5. *The "Reset" button, returns the motors to the start of the currently loaded recorded position.*
6. *In this way, a coordinated animation can be created on all four magnets. Every animation can be saved to a file, loaded, played, and edited per-quarter.*

[D] The platform control interface (annotation on synced recording process is overlaid over the figure).

Figure 114
Magnetform digital user interface (Yehoshua Wald & Zuckerman, 2021).

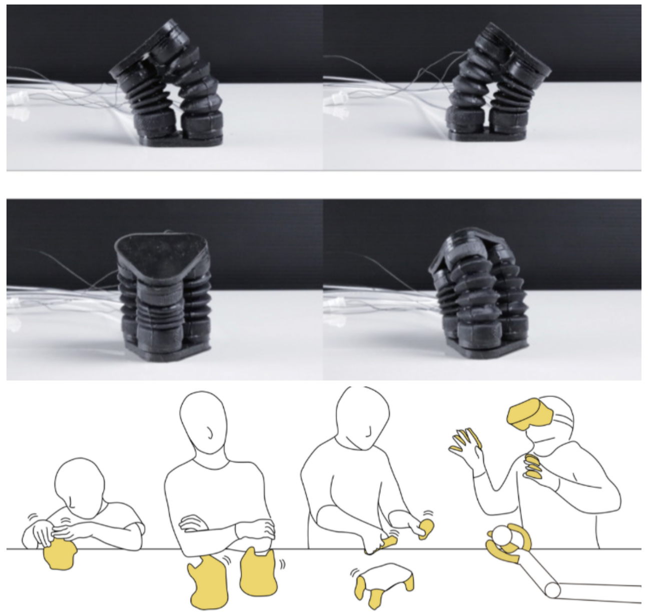


Figure 115
MorphIO (Nakayama et al., 2019)

MorphIO

MorphIO presents a modular, pneumatic actuator that can be used to create shape changing interfaces out of any objects or surfaces as described in their sketch on Figure 115 (Nakayama et al., 2019). Their modular actuator consists of three air chambers that can be actuated separately to create diverse movement of the actuator. By being able to attach multiple of these modules anywhere, designers have the freedom to create a shape changing interface out of anything. Additionally, the project takes advantage of the sensing qualities of pneumatic devices as the module can sense when a user presses down on it by sensing changes in pressure inside the actuator through a sensor. While the module itself is very well developed, the lack of an interface element, such as a textile to attach it to, seems to limit the applications imagined by designers as their user study only showcased already common uses such as a soft robotic gripper and a locomotive device.

Conclusion

From the toolkit examples showcased, the following insights are taken into consideration in the development of the toolkit:

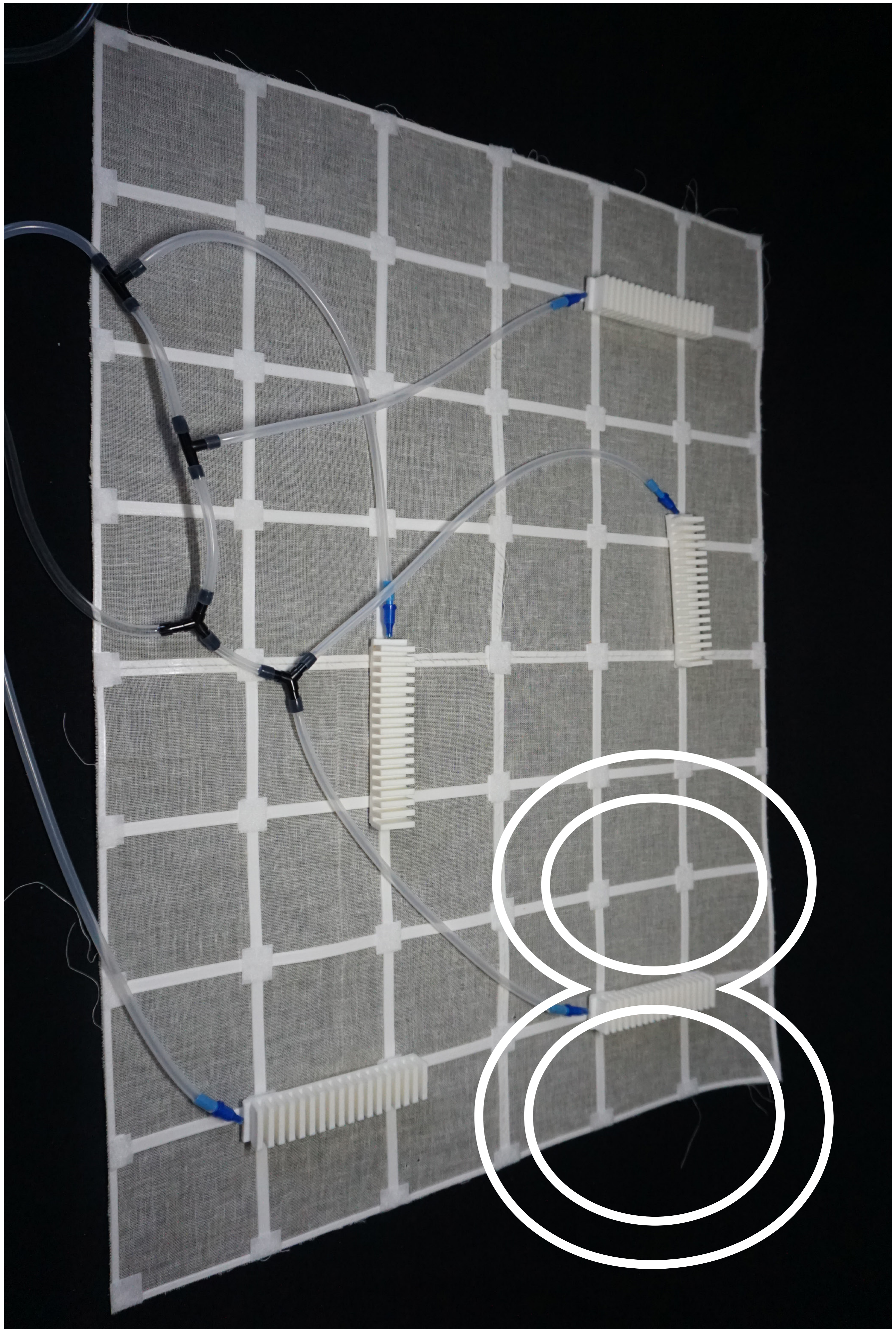
1. Allow for easier creation of physical probes to remove technical barriers and help designers explore the experiential qualities of shape changing materials.

2. Use modular elements to give designers direct control over the curvature of the shape change.

3. Add control over the kinetic qualities of the shape changing material to aid in exploring emotional and performative qualities.

4. Using readily available materials (3D printing, textiles, open-sourced electronics) makes the toolkit accessible to other designers.

5. Create a digital tool to quickly test form ideas and expressions.



CHAPTER EIGHT

CREATING THE TOOLKIT

Based on the material vision of creating a modular toolkit for designers, this chapter documents the journey of the creation and fabrication of the toolkit by showing some of the critical design decisions made, the scaling up the textile samples, and the final pneumatic control system with a digital user interface.

8.1 MODULAR TOOLKIT FOR DESIGNERS CONCEPT

The Modular Toolkit for Designers concept is an expansion of the already created Modular Grid prototype from the material tinkering. While the Modular Grid prototype already showcased the potential of using a modular pneumatic textile to explore shape change, it still requires some design changes and features to improve its performance as full feature toolkit. Therefore, the following additional requirements need to be met to create the Modular Toolkit Concept:

[1] Select the best suited actuator for the toolkit

[2] Increase the number of actuators that can be used on the textile interface

[3] Select the best suited pattern for the textile interface

[4] Scale up the textile interface

[5] Design an electronic control system to control the actuators

[6] Design a digital interface for the user to control the actuators

The following sections shows the journey in the creation and fabrication of the toolkit as each of these parameters are explored individually.

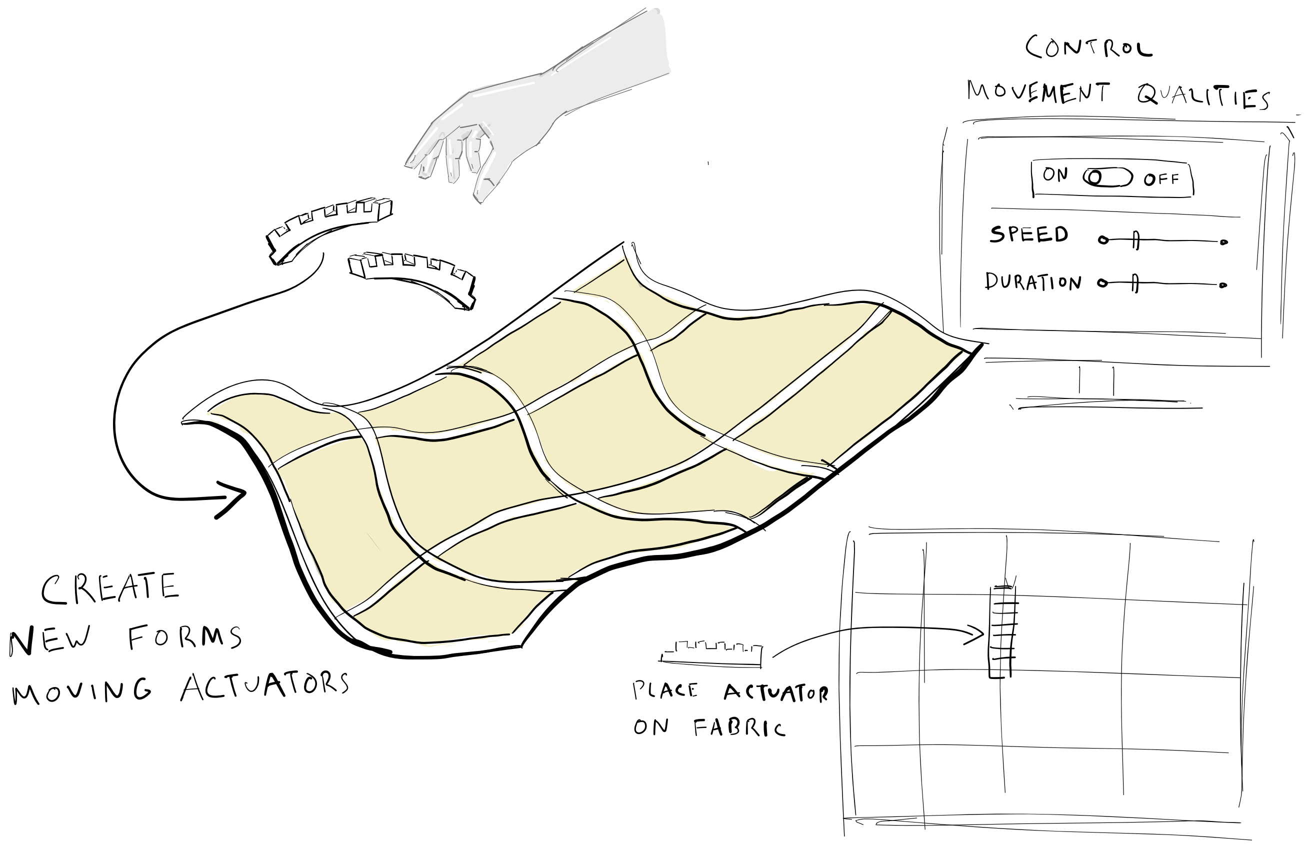


Figure 116
Modular toolkit vision

8.2 ACTUATOR SELECTION

Figure 117
Sample A13 in actuated state (selected actuator)

Based on the technical testing, it was found that Sample A13 was the best performing actuator during the deformation angle vs. air pressure test due to its longer geometry and higher number of bellows allowing for a greater deformation angle. Due to its high deformation angle, this actuator was selected for the toolkit. Additionally, its 1cm height provides a balance between integrating in the textile and still providing sufficient deformation. Minimizing the height of the actuator would be ideal to allow the textile interface to lie flat on a plane, yet the actuator samples with a height less than 1cm showed significantly lower deformation, specially when attached to the textile interface.

Five of these actuators were printed to be used simultaneously on the textile interface. Despite the additional pneumatic tubing and volume that is added to the system, the inflation of the actuators still appears to perform similarly to when using only one actuator. The most important thing when adding additional actuators is to still maintain the pneumatic tubing connections as short as possible. While longer connections do allow for more flexibility in moving the actuators around the textile interface, an excess of length of the pneumatic tube does cause significant drops in the air pressure of the actuator, thus reducing the final deformation.

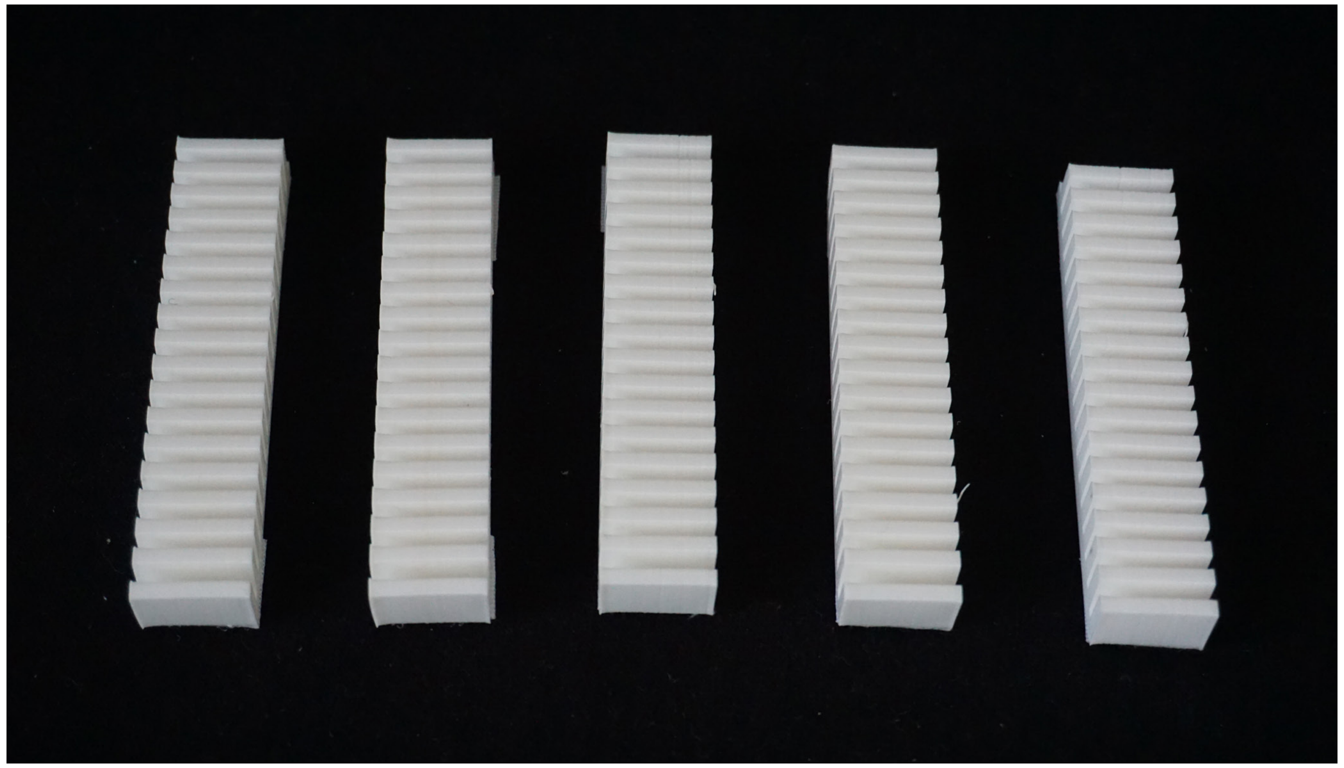


Figure 118
5 printed versions of Sample A13 prototype to be used with the modular toolkit

8.3 PATTERN SELECTION

The Modular Grid prototype showed that a simple square grid design can still create complex curvatures on the textile simply by changing the actuator location. A similar square grid design is used for the modular toolkit as the simple grid design provide obvious use cues for where to place the actuator and allows the form and associations of the shape change to define by the creativity of the designer and not by the pattern printed on the textile. For this reason, a simple pattern design is preferred to allow the designer using the toolkit to place their own associations to the shape changing material according to their goal and application. The square grid pattern from the modular textile sample was still used with the following changes:

The connection points were moved to the intersections of the grid and reduced in size for a more minimal look.

The edges were made thinner to allow space to connect with other modules and maintain even grid thickness throughout.

The connection points between the actuators and the textile interface were moved to the intersection of the grid pattern as it allowed the deformation of the actuator to be displaced over a wider area of the textile interface. When scaling up the prototype in the next section, it was important to make the square grid a repeated pattern that could be connected together, so that multiple “modules” could be printed and connected to each other.

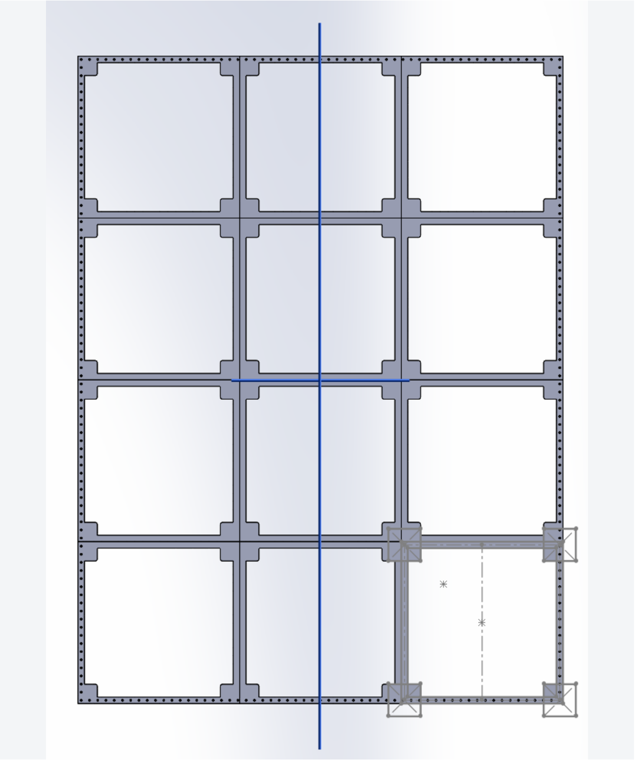


Figure 119
Modular toolkit grid pattern design (1 module)

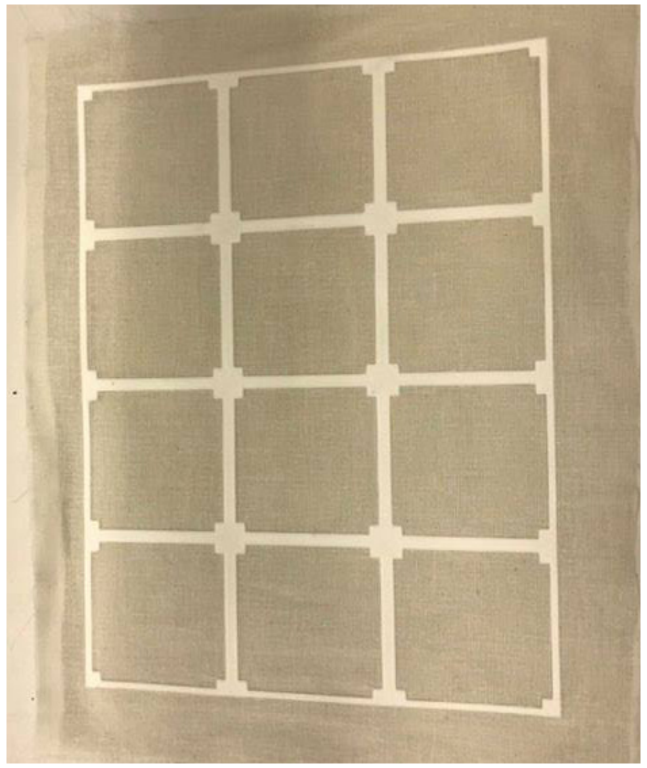


Figure 120
Printed module for modular toolkit

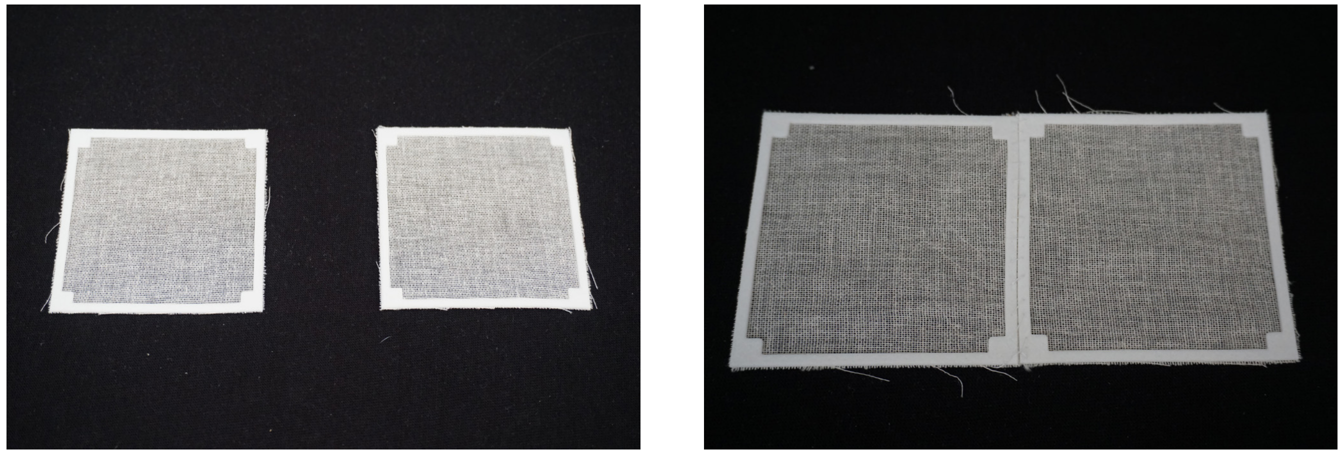


Figure 121
Sewing 3D printed textile modules test

Scaling Up

Besides making the square grid design a repeating pattern, the 3D design was also reconfigured by adding 0,8 mm holes along the outer edges of the grid to allow multiple modules to be sewn together. Since it is common practice to join multiple textile pieces using various sewing methods, it was natural to attempt to connect multiple modules together for scaling by sewing them together. After attempting to print the new model with sewing holes, two things became apparent:

If the holes are too small <0.8mm, the holes shrink and do not show up on the print.

If the holes are too big >0.8mm, the print does not have sufficient surface area to stick to the print plate and the print fails.

Due to this, it was decided that it was best to test the model without any sewing hole first (make the holes manually) and to test the method on a smaller size module to see if the connection would remain stiff enough to be worth exploring on a larger scale. Therefore, 4 small modules were printed and sewn together by forcefully pushing the needle through the 3D printed material. This method does work, but is manually intensive due to having to punch each one of the holes manually through the print and is not recommended for larger samples unless holes are made on the 3D print. The results show that if it is sewn properly, the connection remains very stiff and has the potential to be expanded to the larger textile samples.

The next samples were printed using the full-scale 3D printed grid pattern on the Ultimaker 5 with sewing holes of 1,2mm. To ensure proper printing despite the reduced surface on the outline of the pattern due to the larger holes, a “brim” was added on the 3D printing settings and removed after printing. The final result was successful, and a 2 x 2 module was created to finalize the textile interface of the modular toolkit shown in Figure 123.

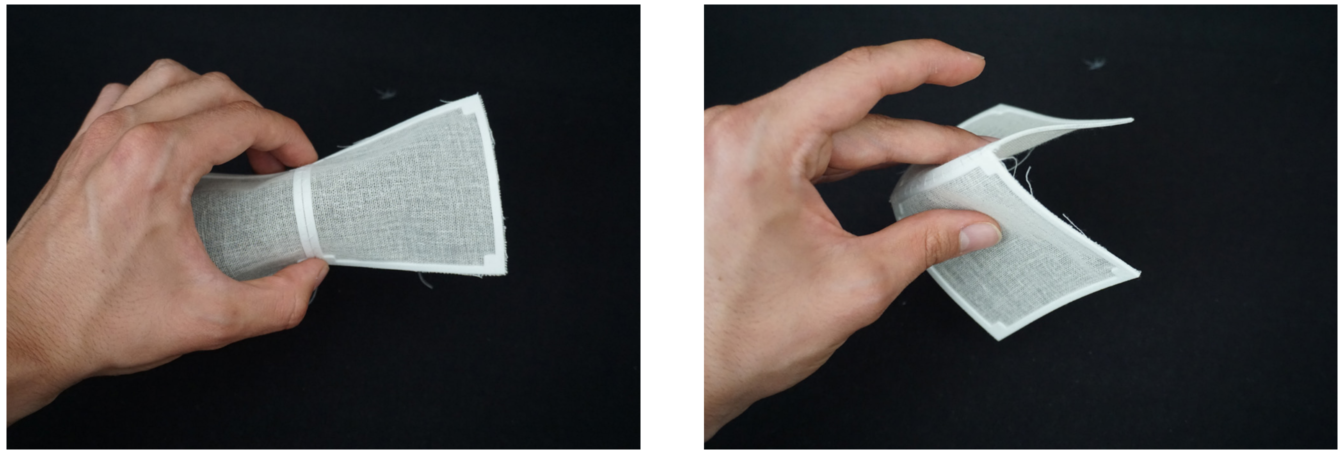


Figure 122
Testing rigidity of sewing connection with manual handling

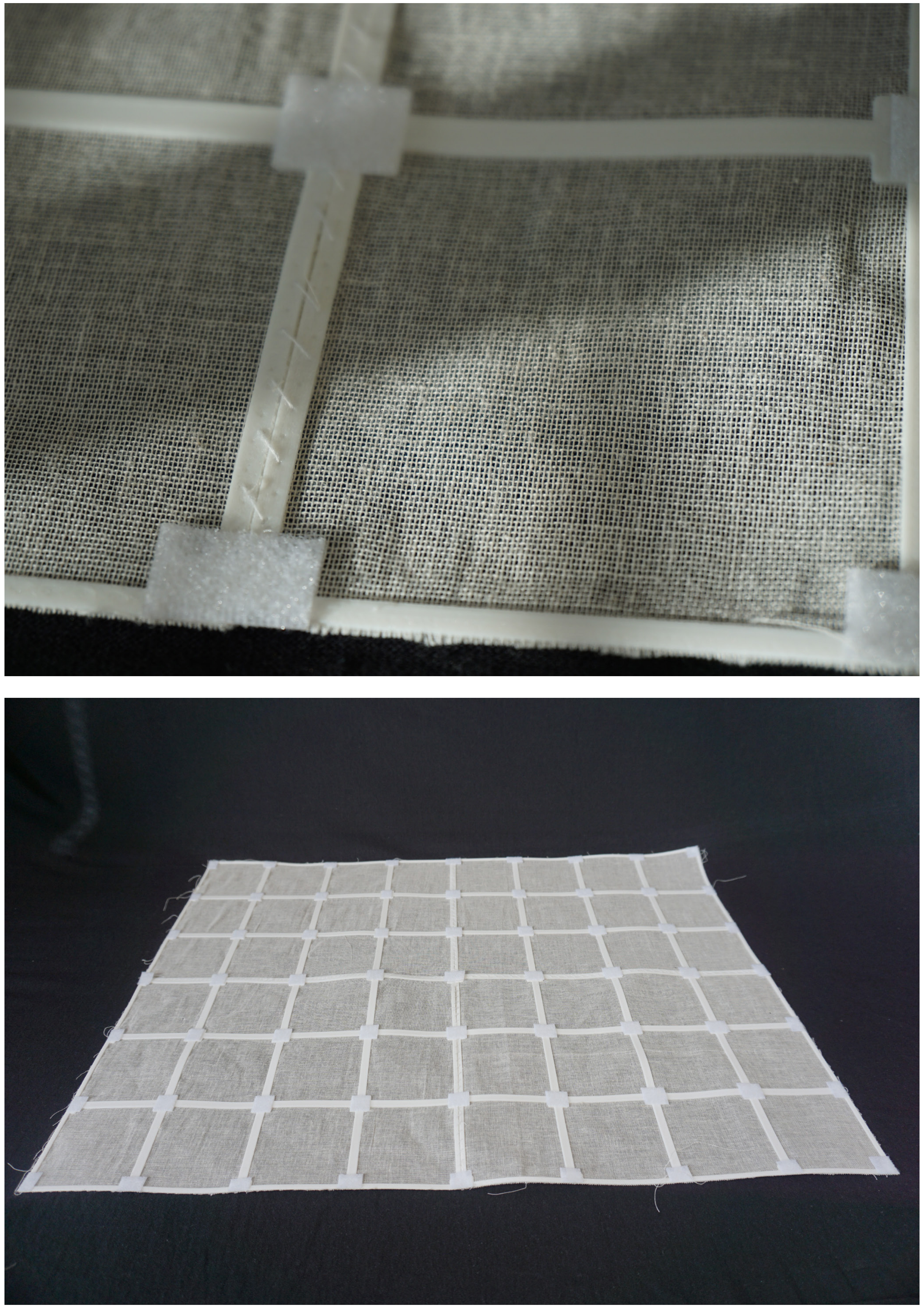


Figure 123
Connecting modular toolkit modules together with sewing method

8.4 ELECTRONICS AND CONTROL SYSTEM

Kinetic Requirements

To properly showcase the pneumatic qualities of the material and differentiate this toolkit from ones found in literature, it is important to show how the kinetic parameters of the material can easily be manipulated by the user. Based on the unique qualities of pneumatic interface and their benefits for use in shape changing interfaces, the pneumatic control system must have the following qualities:

Controllability

Speed control

Forward/Reverse Movement Control

From the Material Benchmark, it was found that pneumatic toolkits proposed in literature focused solely on the spatial parameters and do not provide any tools or insights to control the kinetic parameters of the material. MorpheesPlug, for example, simply connects the pneumatic shape change samples to an air compressor with an on/off switch at a constant pressure (Kim et al., 2021). This approach to shape changing interfaces misses a major opportunity of exploring the temporal qualities of the material as well, which is very often overlooked. The electronics selected for this project must, therefore, allow for a wider range of control over the kinetic parameters to differentiate itself from other toolkits in literature.

Pneumatic Electronics

To allow for easier control of the kinetic parameters from users and provide a more open-source solution, it was decide to shift away from using an air compressor. Instead, two 24V open-source air pumps (~0,8 bars maximum) are used that can easily be controlled with an Arduino Uno using a power relay and are significantly more portable than an air compressor. The final electronics set up was built by Alice Buso during her research with soft robotic modules at TU Delft (Buso et al, 2020). The electronics components in the system allowed for all the necessary control over the kinetic parameters that are required for the toolkit. Figure 124 and 125 show an overview of the electronics components in the system.

1. Pump: used to inflate actuators

2. Vacuum: used to deflate actuators

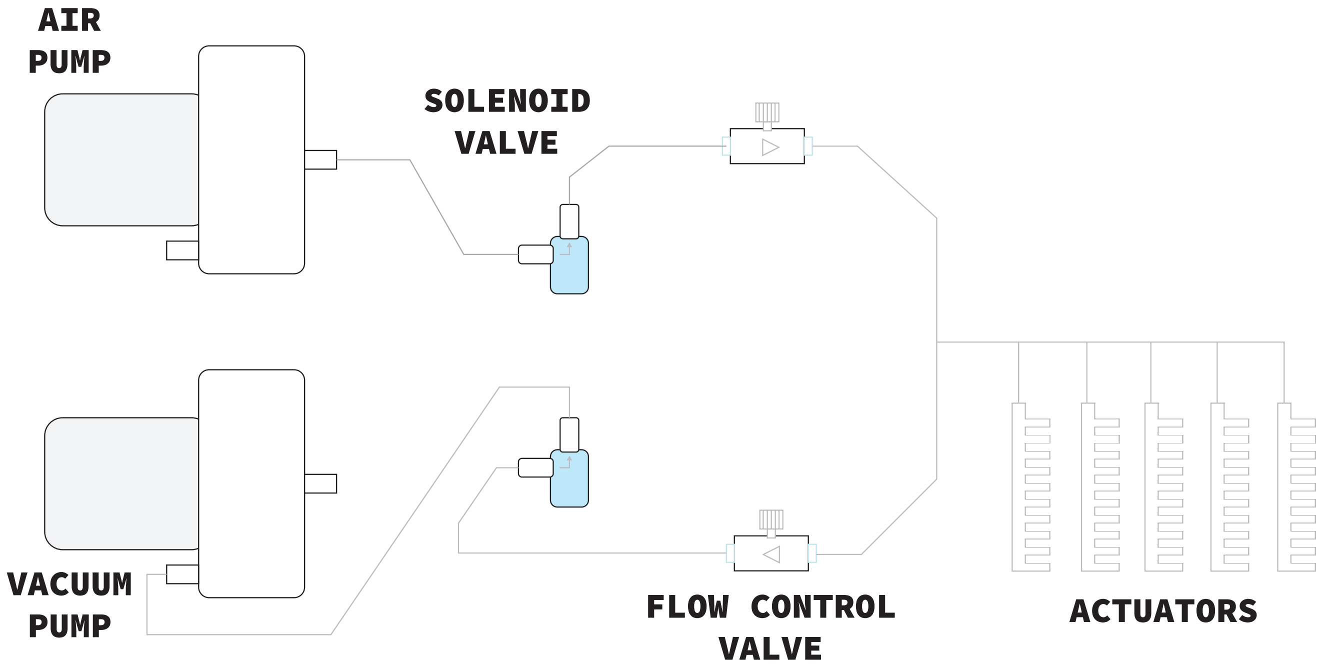
3. Relay: Turns the pump/vacuum on/off

4. Solenoid Valve: opens/closes the airway for the pump/ vacuum

5. Control Relay: Turns the solenoid valve on/off

The system works with an alternating pump and vacuum system used to create forward and reverse movement of the actuators. The power relays are used to communicate between the Arduino and the pumps to turn them on and off. Since the pneumatic system is an open loop, the solenoid valves are required to prevent air leaking from the system when one of the air pumps is not in use. For example, when the pump is on and the vacuum is off, air can escape directly through the vacuum airways. The solenoid valve ensures this airway is closed off to prevent air flow in that direction. With this electronic set-up, multiple actuators can be connected to the system by splitting the airways using pneumatic connectors. If wanted, additional pairs of solenoid valves can be added to the system to allow for independent control of multiple actuators at once.

Figure 124
Pneumatic electronic set up diagram



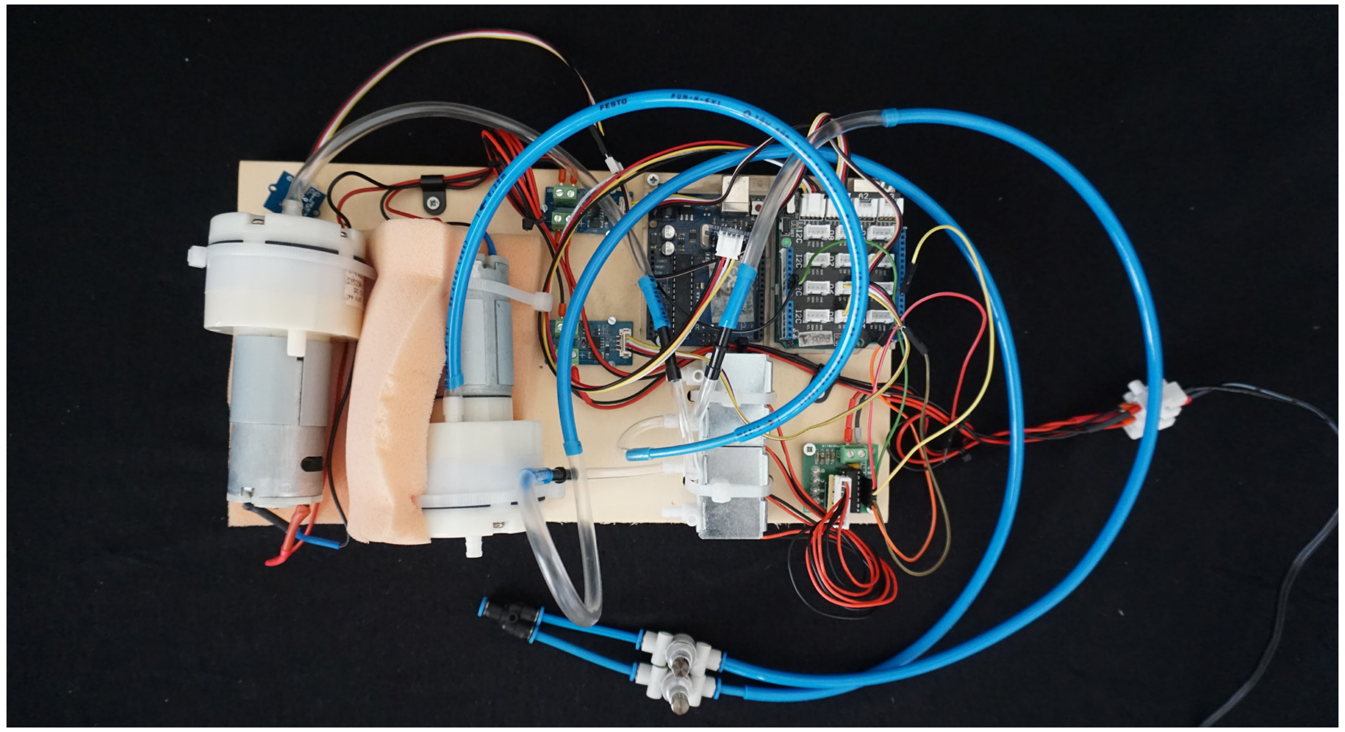


Figure 125
Pneumatic electronic set up with flow control valve

Digital Interface

Currently, the electronics require direct editing of the Arduino code to change kinetic parameters of the system. To enhance the user friendliness of the system, a user interface was created that allows real time manipulation of the kinetic parameters of the system. Using the DeviceDruid online software, a deployable, easy-to-use user interface was made to include on/off controls and control over the duration of the inflation and deflation cycles of the system (Fig. 127). Additionally, some pre-sets were created for the inflation/deflation cycle times to allow for designers to quickly test some common settings. At the current state, the speed of the forward/reverse movement of the actuators is controlled manually using a flow control valve since the flow control valve cannot be currently controlled by the Arduino. Thus, changing the speed of the actuators requires a coordination of changing the duration cycle of the inflation/deflation and to change the flow rate of the actuator with the flow control valve. The current pre-sets available in the system include:

[1] Fast Movement: sets inflation time to 2 seconds and deflation time to 2 seconds.

[2] Slow Movement: sets inflation time to 10 seconds and deflation time to 10 seconds.

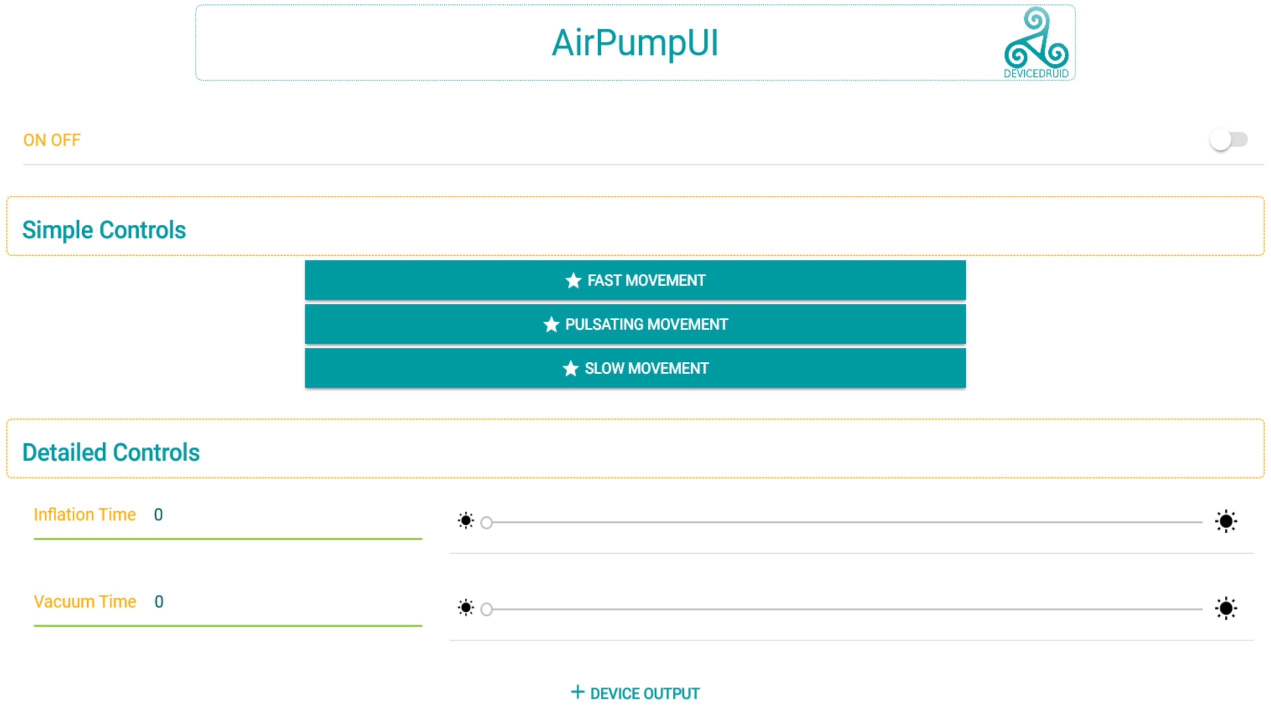
[3] Pulsating Movement: sets inflation time to 1 seconds and deflation time to 1 seconds.

Since the actuator speed is not fast enough to fully inflate in 1 second, it is only partially inflated when using the Pulsating Movement setting. If more complex movements are desired, the Detailed Controls allows the user to individually set the inflation and deflation time. Thus, if for example, a designer wants to prototype a textile interface that quickly inflates when a user interacts with it and slowly deflates over time to its initial position, the designer could set the inflation time to 2 seconds and the deflation time to 10 seconds to achieve this result.

Physical Interface

To achieve precise control of the speed of the actuators, it is best to control the air flow and keep the pressure constant. Varying the pressure applied to the actuators will cause the actuators to reach a different level of deformation based on the pressure applied which is difficult to control. Instead, if the pressure is kept constant but the air flow is changed, the actuator will achieve the same final state at different levels of speed. The proposed method to control speed is to use a manual needle flow control valve. The Festo Flow Control Valve (Fig. 126) has a high resolution of control allowing for a large range of speeds. When using both the digital and physical interface together, the duration of the pump/vacuum cycle time and the flow control valve need to be synchronized in the digital and physical space to control the speed of movement. For example, if a fast movement speed is desired, the valve should be fully open and the duration of the pump/vacuum cycle should be low and vice versa. While this can have an initial learning curve, once the process is understood it allows for quick, precise, and interactive manipulation of the speed by turning the valve physically and immediately visualizing the results. In future iterations of this toolkit, it is possible to connect a motor to the needle valve that can allow for automatic turning of the needle valve through the digital interface, thus digitally controlling the speed. This, of course, adds an additional layer of complexity to the system and is added a future recommendation for future projects.

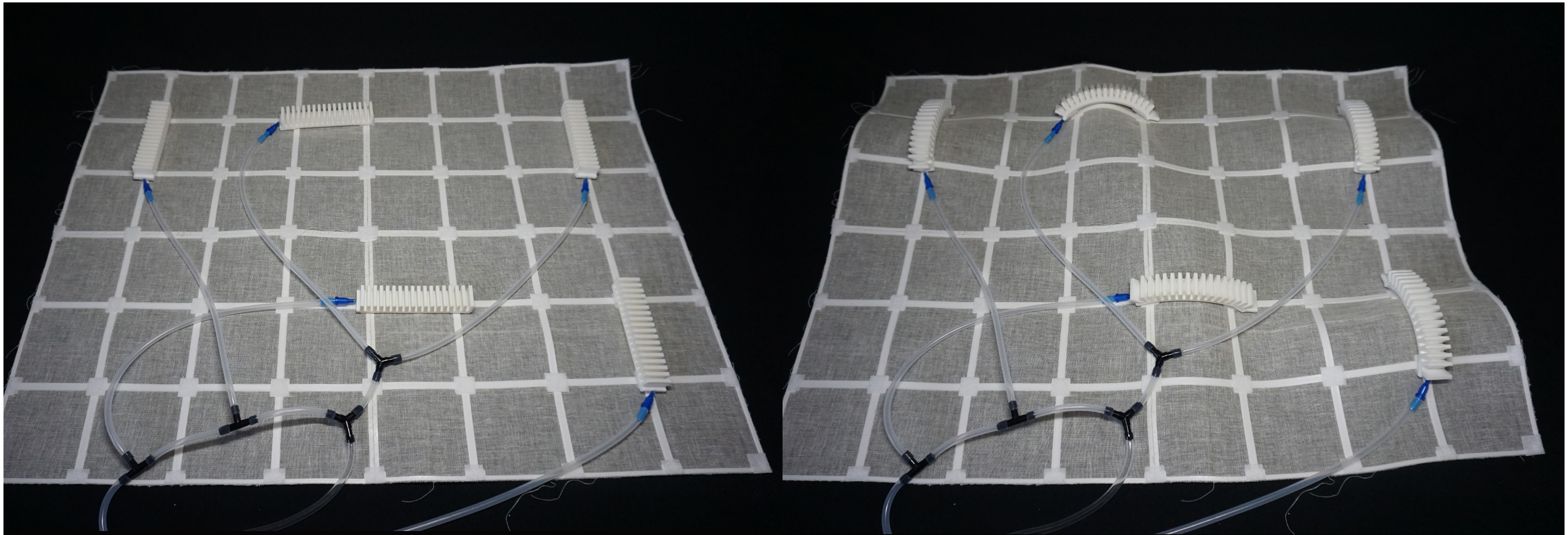
Figure 126
Flow control valve as the physical interface to control actuator speed



Inflation Time 0

Vacuum Time 0

Figure 127
Digital User Interface for controlling electronics



INTRODUCING TEXTALIVE

THE ANIMATED TEXTILE TOOLKIT

With all the components of the modular toolkit completed, they can now be integrated together into the final material concept. The modular toolkit allows for 5 actuators to be connected to the textile interface at the same time using the Velcro tape. The following figures on the next few pages show some examples of the modular toolkit in used and the shape deformations it produces. Appendix A shows more examples of the Shape Morphologies that can be created with the expanded version of the Animated Textile Toolkit allowing for more possibilities from the previously shown shape morphologies during the technical characterisation. The new Animated Textile Toolkit now creates the possibility of performing user studies to gain a better understanding of the user experience of using the toolkit and the types of expressions and application that other users can create as areshown in the next chapter.

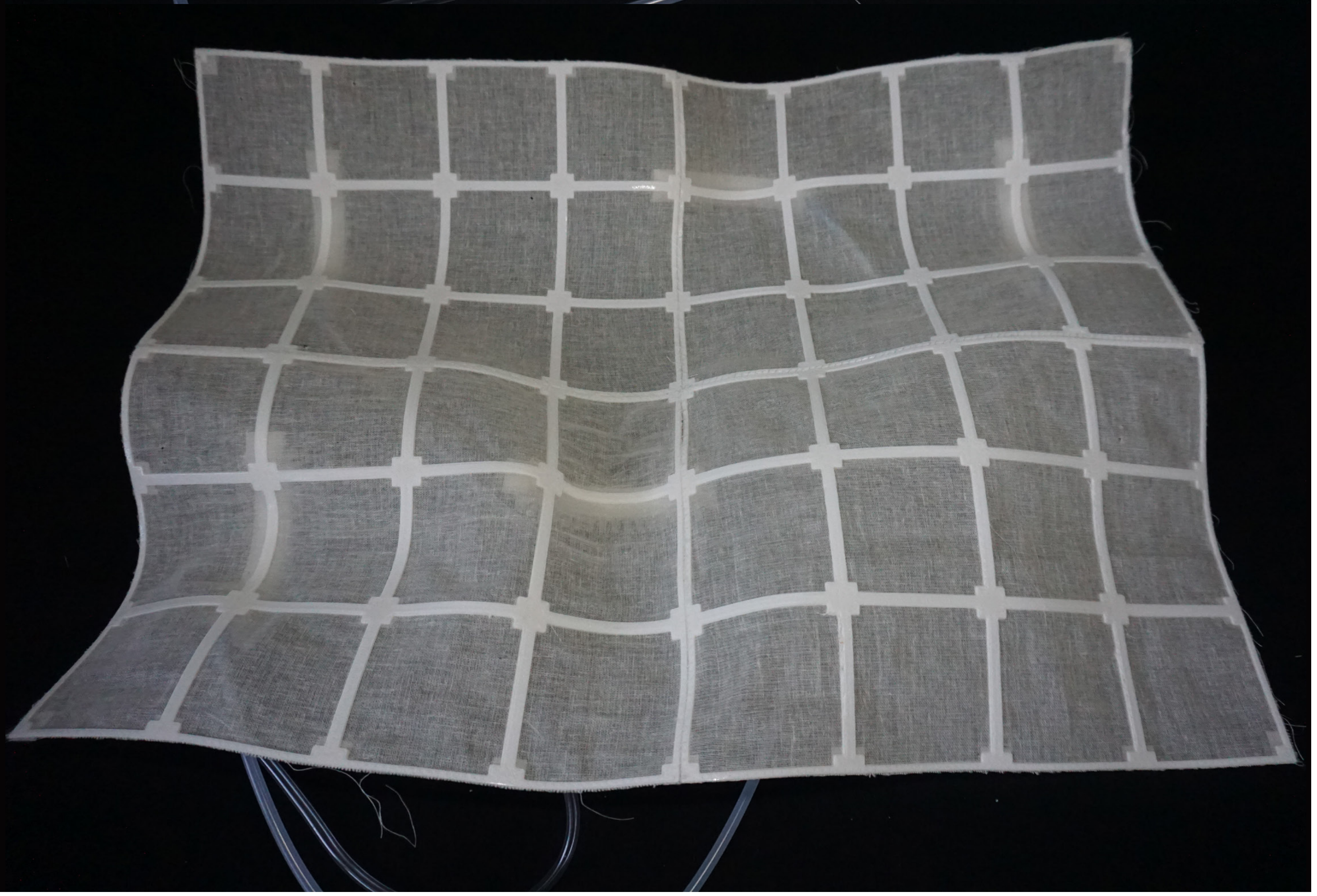


Figure 128
Introducing Textalive

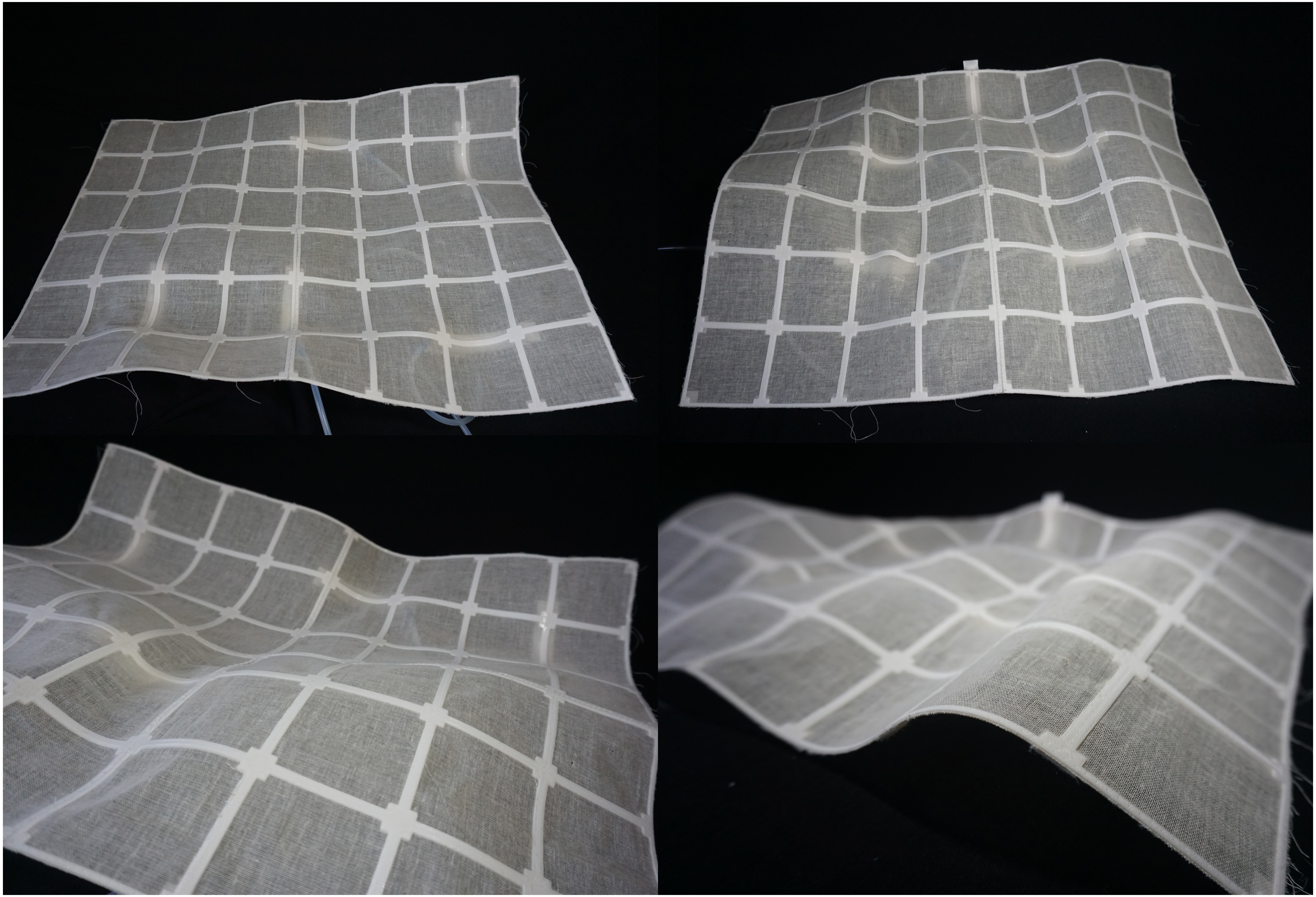
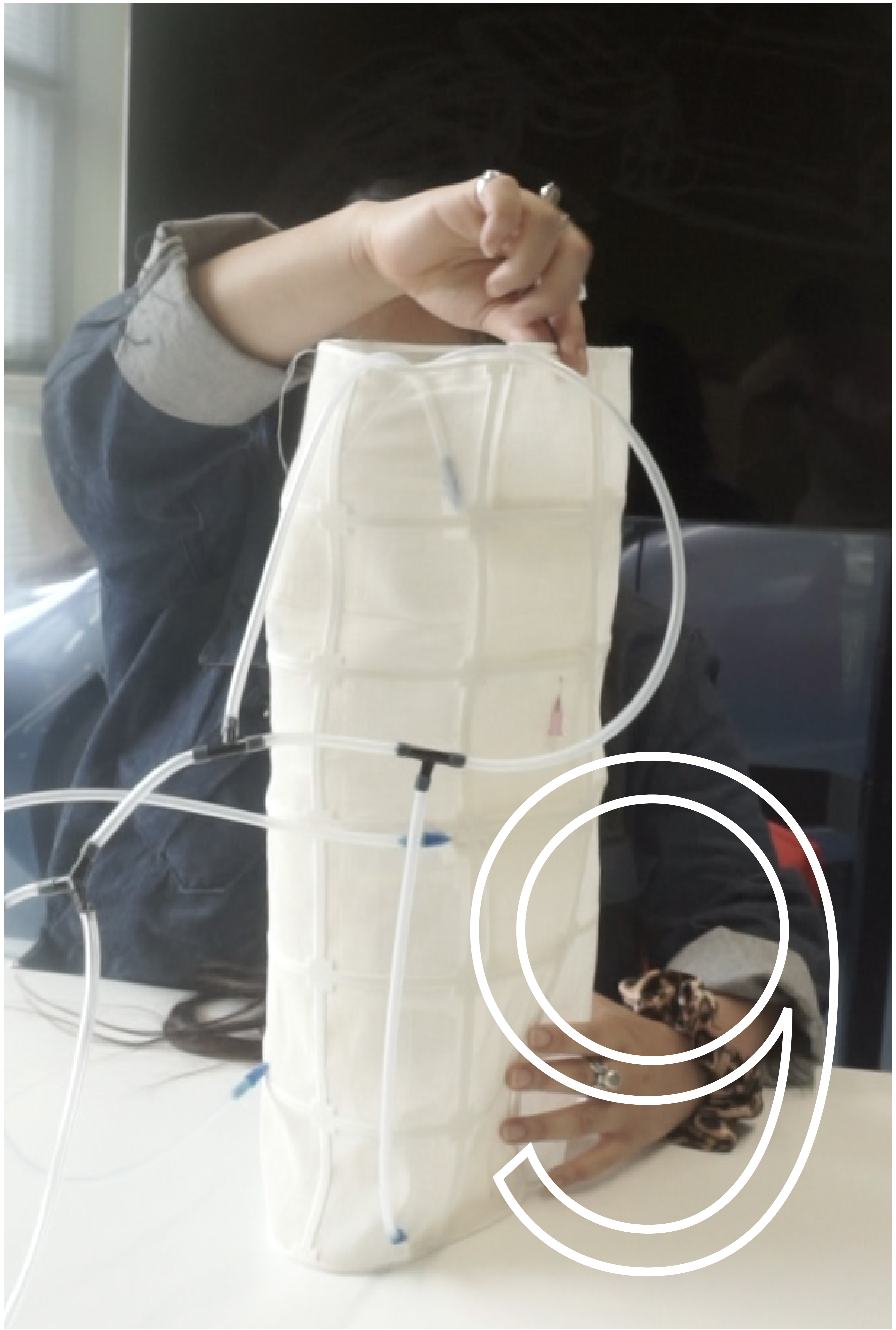


Figure 129
Additional images of Textalive



CHAPTER NINE

USER STUDY EVALUATION

In order to validate the toolkit as an aid for designers to explore shape changing interfaces, a user study was conducted to understand how users explore shape change with the toolkit, the types of applications that they create, and the material experience of interacting with shape changing interfaces.

9.1 USER STUDY INTRODUCTION

The goal of this user study is to explore how designers from different areas of expertise might utilize the Textalive Animated Textile Toolkit to prototype and experiment with shape changing interfaces. The toolkit allows the designer to create a variety of forms by adjusting the location of the actuators on the textile and manipulate kinetic parameters such as speed of forward/reverse movement and duration of movement using the electronic interface. The study participants will consist of experts, semi-experts, and non-experts in working with smart textiles. The participants will have the opportunity to freely experiment with the toolkit after a short introduction, which will be followed by a small, personal design challenge where the participant attempts to create their desired shape changing interface based on a set goal and a discussion of the process.

Purpose

To evaluate the toolkit, a user study was done with the following goals:

1. To evaluate the usability of the toolkit in aiding designer with creating shape changing interfaces by controlling its spatial-temporal qualities

2. As a secondary goal, to explore the material experience of the material based on user interaction and discussion with the material. This was not the main goal of the study, therefore, the MDD Ae24 was not used for the study as to not extend the duration of the study. Instead, it was simply gathered from observations and discussions with users

Participant Selection

For this study, it was highly important to select specific type of designers that might actually use such toolkits in their works. The field of industrial design is highly varied, and not all designers take a hands off approach with the materials they work with. For this study it was critical to select designers who were both aware and confident with the MDD process as they are comfortable with hands-on tinkering and experimenting with novel materials. Additionally, as the material falls into the category of a smart textile, it was critical to include professional researchers involve in the smart textile fields to understand their perspective and experiences with using the toolkit. Additionally, two Ph. D researchers from the material experience lab were used for the pilot study as they can provide great feedback for the test set up, yet also discuss their experiences with the toolkit.

Particpants 1 - 2: Pilot
Participants 3 - 5: Students from MDD course
Participants 6 - 7: Smart textile experts

Test Set-Up

- Toolkit Equipment: Modular Textile (2 x 2 patched textile), 5 actuators, electronics, and computer (UI interface) (Fig. 130).

- Other Equipment: Camera focused on table (showcase hands and interaction with toolkit).

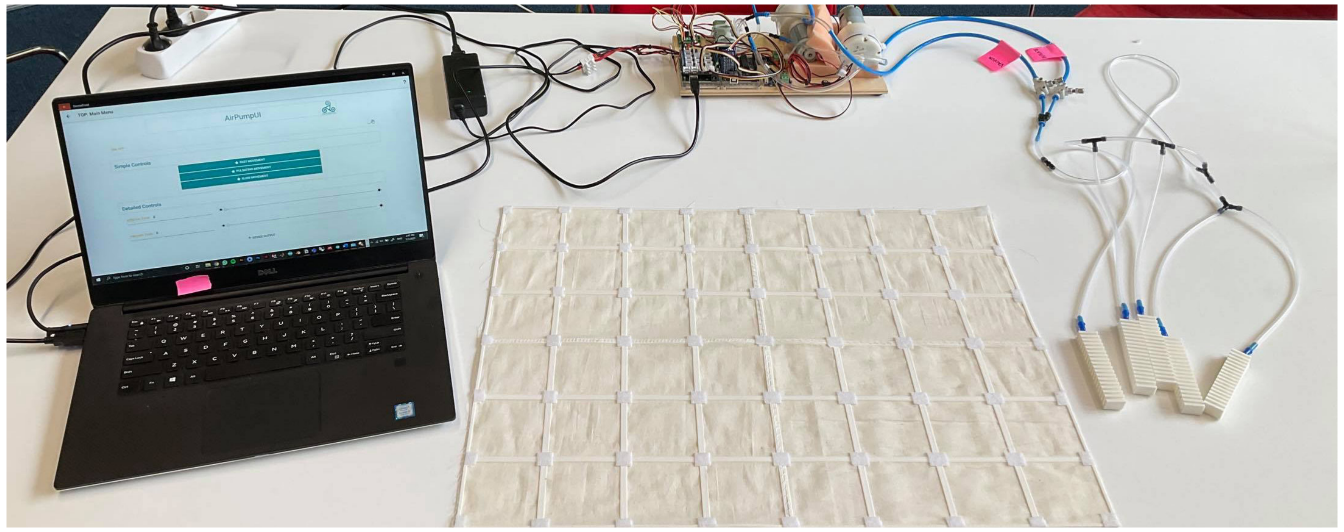


Figure 130
User study physical set-up

9.2 PROCEDURE

Introduction

Basic introduction showcasing inflating actuators, attaching to textile, and modifying kinetic parameters on computer interface and speed control valve.

Free Exploration

Give the user time to freely experiment with the set up without a set goal. Ask them to think aloud as they are interacting with the toolkit to understand their thought process.

Set Personal Design Challenge

Discuss with user to create a personal design challenge based on their own interest or current work. We are interested to see how and why users would like to use this toolkit, therefore, it is critical to leave the design challenge open as opposed to make it the same for all participants. If user has difficulty setting their personal design challenge, a set of cards with some inspiration/topic suggestions are provided to the users to aid in their challge creation (Fig. 131)

Conducting Design Challenge

User will use the toolkit to solve their design challenge by tuning the parameters. During the process, they will be asked to to think aloud as they are interacting with the toolkit to understand their thought process. Special attention will given to the following questions:

-How did they select the placement of the actuator?
-Did it produce their expected result?
-Why did they select the specific kinetic parameters?
-How many iterations did it take to achieve their goal?

Final Discussion

The user study will end with an open discussion of the toolkit mediated by the following questions: o How did the toolkit help you achieve your selected goal?

-(If experience with smart materials) How would you compare this to other method of prototyping smart materials?
-Can you imagine applications of shape changing materials after using this toolkit?
-Where in the design phase might you use this toolkit?
-Were there any limitations of the toolkit during your experimentation?

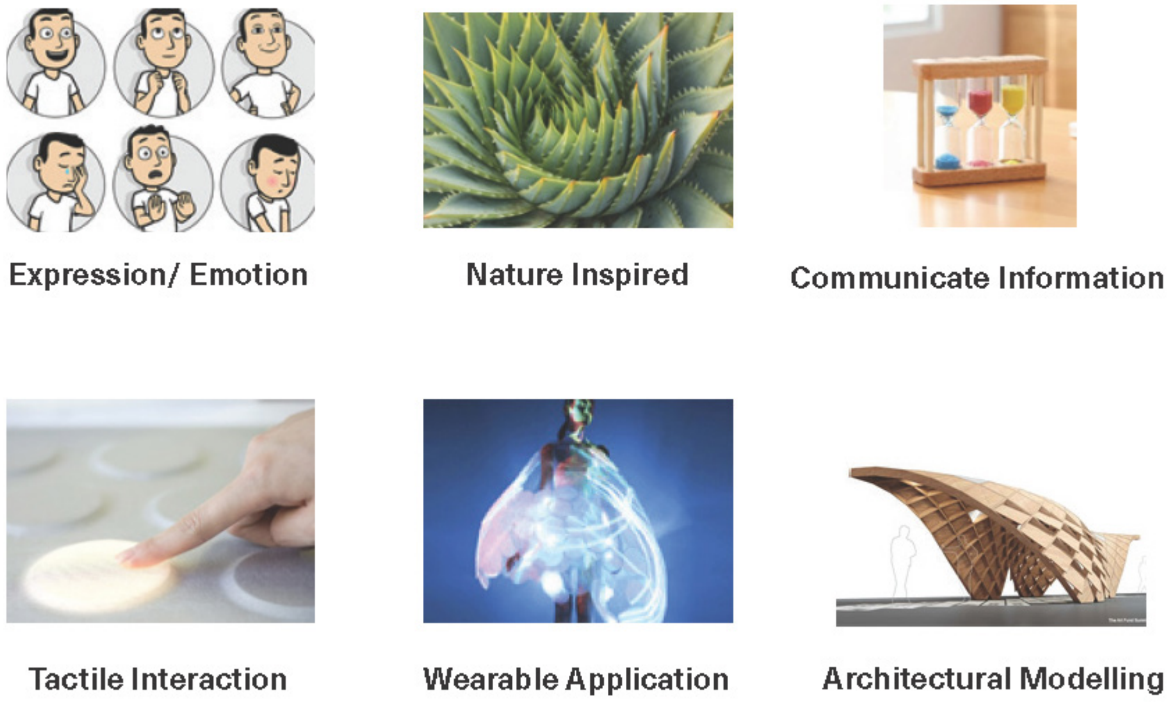
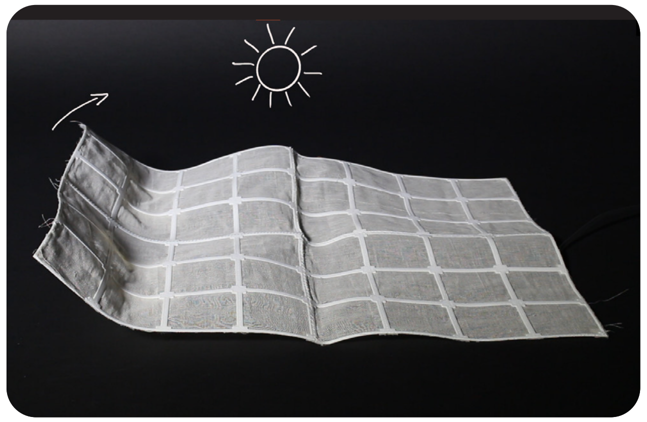


Figure 131
Aid for design challenge selection

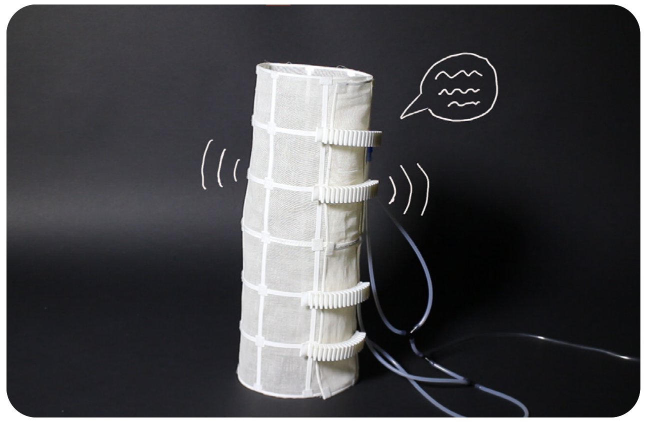
9.3 RESULTS

The resulting designs created by the participants showed a diverse variety of interfaces that are made possible with the toolkit. During the design challenge formulation phase, 3 out of 7 designers (including the pilot study) created designs without the need of the design challenge aid to test out personal designs from their own work and the other 4 used the aid to formulate their challenge. The resulting creations can be found in Figure 132 showcasing a recreation of the participant's design in a photo studio with some additional drawings to help bring the designs into context. The number assign to each design corresponds to the participant assigned numbers.



Living Algae Carpet (#1)

This concept consisted of a carpet with algae embeddded in the fabric that would rise up like a flower in response to the sun. The rising up of one side of the carpet invites the user to lie on the carpet to protect it when it has been exposed to too much sun. The movement was very slow (>10 s cycles) to simulate the slow movements of plants. The concept was evaluated by a roleplay scenario where the designer would leave the room and come back to check on the status of its living capet.



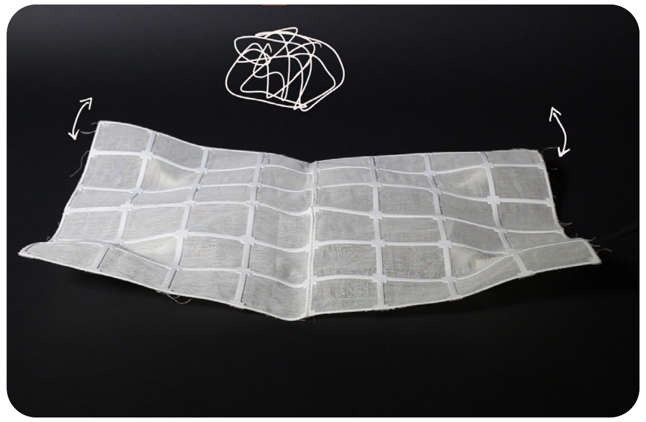
Breathing/Talking Lamp (#2)

This concept consisted of a lamp with very human-like qualities. Recreated from one of the participant's previous projects, the lamp was meant to move in a fashion mimicking human breathing (2 sec. cycles) and, in theory, was meant to speak a story to the audience while moving. The use of the actuators to create a cylindrical vase form was used to turn the 2D textile into a larger 3D volume.

Heart Rate Tempo Running Aid (#3)

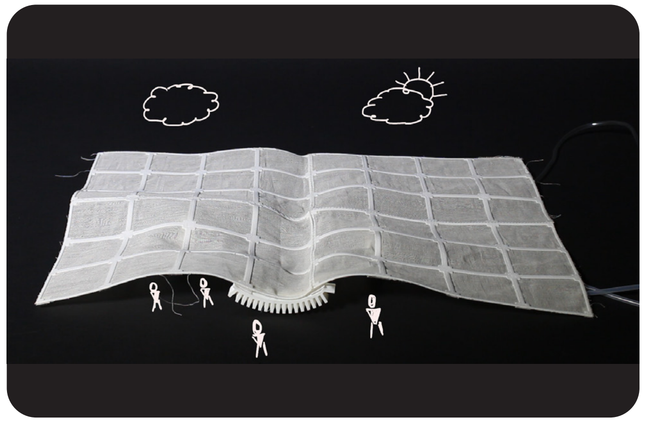
This concept consisted of a wearable fabric that would be placed around the chest of a runner to help them control their heartbeat and breathing. If the heartbeat of a runner would rise up, the actuators placed close to the center of the textile would create haptic feedback to the user and help them bring their heart rate down by mimicking their breathing and slowing it down over time. The participant would've liked to create a sequence of movements by controlling the actuators individually to simulate the flow of breathing from the bottom of the chest to the top of the chest.

Figure 132
Recreation of participant results from design challenge



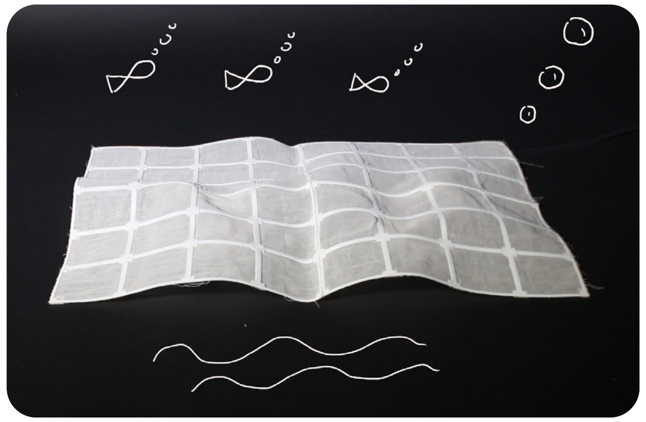
Stressed and Relief Emotion (#4)

This concept was meant to evoke an emotion/expression in two stages. The first stage consisted of a slow rising of the textile along the edges growing towards the centre expressing stress/anxiety. At the end of the rise, the textile would quickly deflate as it released all the stress mimicking relief. This concept really utilized the toolkit's ability to experiment with movement types. Ideally, the designer would have liked more actuators to be able to create wrinkles along the centre of the textile to express a larger sense of stress.



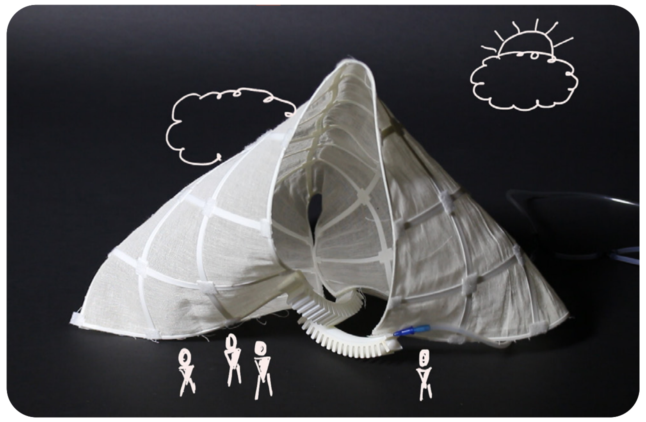
Responsive Architecture (#5)

This concept consisted of a large scale architecture that would open up along its edges when pedestrians walk close to it. This would create an interactive passage way under the textile for pedestrians to walk by that would be resposive to its surroundings. Additionally, they imagined the top part of the textile would work as a playground or interactive meeting space as people would interact with the changing terrain and topology. As this was meant to be an interactive exibit, the movement qualities were not deeply explored, but mostly focused on the form of the architecture.



Manta Ray / Sea Animal (#6)

From the beginning, this participant related the textile to a sea animal swimming along the bottom of the sea. They decided to recreate the movement of a manta ray with its wave-like, quick movements of its fins. They focused on creating small, pulsating movements (1 sec cycles) to simulate the swimming movement of the animal. Additionally, the actautors added to the sea animal analogy as they were reminded of an octopus's tentacles due to its shape and movement.



Breathable Architecture (#7)

This participant began exploring 3D forms that could be created with the toolkit before first deciding on a challenge to tackle. After creating this canopy-like design, they attached the meaning of a breathable architecture that would allow for improved flow of air through its structure thus creating comfort to the pedestrians in its surroundings. The unique ability to use the actuator connections as building blocks for 3D volumes is showcased through this design.

9.4 DISCUSSION (EVALUATION OF TOOLKIT)

The think out loud exploration and discussion with the participants brought a large number of insights into the user experience of the toolkit and the material.

Form Qualities

Ease of Use

Users found changing the form of the textile with the actuators and the velcro connection to be quite intuitive. It was common for users to begin experimenting with a reduced number of actuators or with actuators pointing in the same direction to first gain an understanding of the influence the actuators had on the textile. Once this initial understanding was captured, users began to freely place all actuators across the textile to create more complex shapes.

It was noticed that more than half of the participants wanted to place the actuators diagonally on the grid. While it was possible to place the actuators diagonally, the current length did create some limitations that can be fixed by increasing the actuator length by 1cm.

Possibilities

The forms explored showed great variability both in the toolkit's possibility and designer's interest. While some users chose to create large deformations on the edges of the textile, others aimed to create localized wrinkles or wave-like deformations. Others also attempted to bring the textile off the surface of the table and begin to mend it into their own desired 3D shapes to create larger volume structures.

Some users also found limitations due to the constraints of the material. It was found that large convex 3D curves are not possible with the textile, such as creating a dome shape in the centre of the textile.

Kinetic Qualities

Ease of Use

Users found the kinetic controls to not be as intuitive as controlling the form. The digital interface was proven simple to use to control the duration of the movements, yet the synchronization with the flow control valve to regulate the speed of movement was confusing to 5 of the users. That being said, 2 users actually enjoyed having the direct physical control of the speed to really fine-tune the movements of their design. Additionally, users found that since kinetic qualities cannot be perceived immediately (compared to the controlling the form), it required more patience and a longer adjustment period to comprehend the controls. This most likely had influence in some users focusing their efforts on controlling the form as it was a simpler, more interactive interface to use.

Possibilities

Controlling the duration cycles of inflation and deflation using the digital control was quite an essential part in all of the users' design even if the actuator speed was not as popularly used during their experimentation. Depending on the design challenge, users opted for creating a varied range of movement duration cycles combinations from rapid pulsating movements, to long, slow movements, and even to complex combinations of the two. During the free exploration cycle, one user created an interesting movement combination where the deflation valve was almost fully close and the inflation valve was fully open. When they set the movement cycle duration to "pulsating" (1s inflation, 1s deflation), it created an slowly growing, yet pulsating movement of the textile, which the user associated with "growth in nature".

The most critical limitations users found was the lack of individual control over the actuator to create individual, localized movements of the actuators. This can allow for more complex interactive designs possible with the textile. While this additional feature would enhance the kinetic possibilities, it might also present the user with additional complexity in the control interface. Finding the right balance between simplicity and control is an area to be explored in future research.

Design Challenges

The design challenges really showcased versatility and creative freedom that the toolkit allowed for. The design challenges formulated by the users consisted of (including the pilot study): 3 alive-like expressions/interfaces, 2 adaptable architecture scale models, 1 expression of emotion, and 1 haptic wearable clothing. It must be noted that the two participants from the pilot study already had a pre-existing idea of creating alive-like designs as the Material Experience lab focuses on biodesign and living interfaces as well.

The ability to create or prototype alive-like expressions and emotional expressions with this toolkit shows its potential for used in studying the material experience of livingness. The participants who used the toolkit to create expression tended to associate human or animal like qualities to the form and movement of the textile, which allowed for mimicking of alive-like qualities. Some of these alive-like qualities including breathing sensation, fluid movement of sea creatures, growth of plants, and building up of stress/anxiety. Additional discussion on these alive-like expressions is discussed further in the Material Experience section.

In the other end of the spectrum, the study also found usability for the toolkit to explore more traditional, functional products such as smart clothing and architecture. The use of the textile toolkit to prototype smart wearable clothing is expected as the use cues of textiles prompt designers to wrap the textile around the body. Due to the movement of both the actuators and textile, the shape change could not only be used as a visual interface, but also as a tactile/haptic interface to stimulate different parts of the body. The use of the shape changing textile as a tactile interface tool opens up the possibility of interactions possible with the tool that were not thought of previously.

In the architecture modelling case, the textile's ability to create complex "topology", but also be able to fold into larger 3D volumes allows the exploration and prototyping of dynamic, fluid architecture, which are otherwise hard to prototype in the real scale due to its moving qualities. Therefore, creating scale models of dynamic spaces using the toolkit proves to be a quite important use case due to the complexity of modelling such structures with moving parts using other means.

Applications of the Toolkit

As part of the discussion, participants were asked where they could see this toolkit being useful after their experience of designing with it. Participants found it practical to be used as an ideation tool for shape changing interfaces or an evaluation tool to verified that the shape changing qualities produce the result intended. It was found that the current ideation tools for such interfaces are not sufficient in showcasing the kinetic qualities (such as sketching) or can be difficult and time consuming (such as fabricating shape changing materials from scratch or 3D animation/simulation). This was especially important to the smart textiles experts as they expressed the difficulties in fabrication that smart textiles require, and how much quicker and accessible iterating with this toolkit was. This toolkit, while still having its own limitations, can still be a helpful addition to shape changing material researchers, interaction designers, and smart textile designers.

Besides the design implications of the toolkit, 3 users also expressed the toolkit's fun, playful qualities that gives it potential for use as an educational toy for children. Similar to other building block style games for children, a shape changing toy such as the toolkit can allow kids to express themselves not only through form, but also through movement, thus allowing for more diverse explorations and means of learning and expression for early age education.

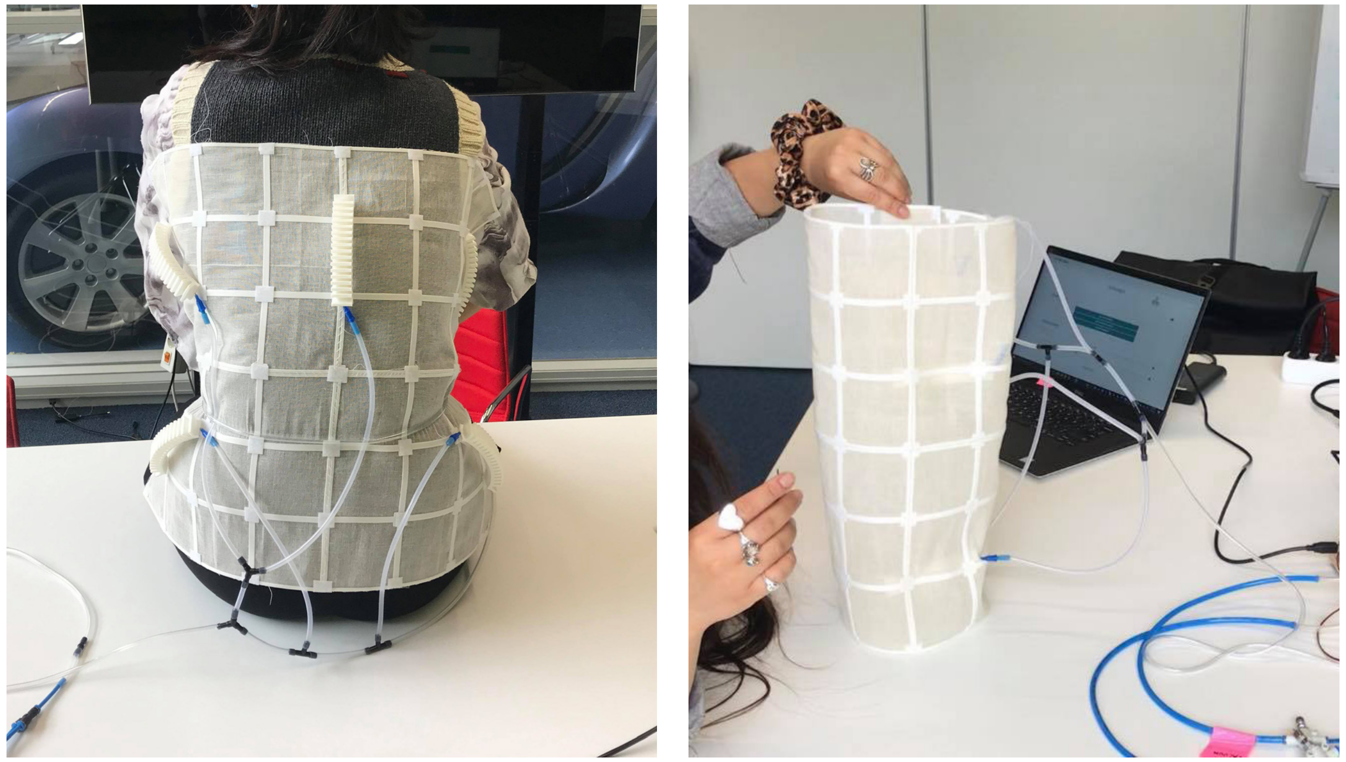


Figure 133
Display of new, creative ways to use the Textalive toolkit

Limitations

As per any toolkit meant for design and creative expression, it was expected that limitations of the toolkit would arise during testing. The most mentioned limitation was the toolkit's uniform movement qualities. The following discusses some of the limitations found during the study:

1. To create more complex movements, participants suggested the ability to add individual control over each actuator. This is theoretically possible by adding additional solenoid valves per actuator to selectively open/close the airway to each actuator. How this additional control can be translated to an easy-to-use digital interface is still to be explored in future research.

2. As was mentioned when discussing the ease of use of the kinetic controls, the majority of the users found it confusing to use the flow control valve manually to regulate the speed of the actuators. Ideally, users would prefer to regulate the speed directly through the digital interface.

3. Of special concern to the textile experts, the size of the actuators at the current state limits the toolkit's ability for prototyping wearables and clothing. As the trend of smart clothing is going in the direction of minimizing size and seamless integration within the textile, the size of the actuators should be minimized as much as possible.

4. Currently, only bending actuators are used with the textile toolkit. Expanding the range of available actuators by including other types of shape change can increase the shape change possibilities of the textile. Inspiration for expanding the toolkit can be taken from the MorpheesPlug project (Kim et al., 2021).

5. Many of the designers had trouble placing the actuators in the diagonal direction due to the length of the actuator. Simply by adding an additional 1 cm to the actuator length can make this connection easier.

Additional Features

As was seen during the user study, many of the participants wanted to use the textile in more versatile ways than just a tabletop interactive textile. The users imagined the textile toolkit to be used as a hanging textile, on the wall, as a 3D volume when folded, and even around the body (Fig. 133). To encourage more interesting user exploration, participants suggested providing props to help people achieve these results. Some of these props can include:

- Pins to hold the textile when folded

- Straps to allow the textile to be wrapped and constrained against the body

- Adhesive to attach to attach on walls

-String with pins to allow to hang the textile

With the addition of these simple props, designers would be able to add more functionality to their design to explore different kinds of interfaces aside from the tabletop textile.

9.5 DISCUSSION (MATERIAL EXPERIENCE)

Despite the user study not directly being a material experience test utilizing the Ma2E4 toolkit, it was still a secondary goal to gather insights from observation regarding how users experience the shape changing textile material. This discussion is not meant to be a conclusive experiential characterisation of the material, but instead aims to be a starting point for designing material experience user studies with the toolkit and other shape changing materials in the future.

Performative Level

The performative level asks the question: **what does the material make you do?**. This refers to how the user physically interacts with the material by touching, moving, and/or holding it various ways. The choice for using textile as the interface element of the shape changing toolkit was made due to humans' familiarity with the material.

During the study, it was observed that the participants began exploring the shape change of the textile from a distance while the textile was resting on the table, as per my introductory instructions of how to use the textile. As the users began to get more comfortable with using the toolkit, users started to test the tactile sensation of the material by pressing, compressing, caressing, and laying their arms on the textile during its movement. Users were specially surprised with how they could influence the local deformations and form of the textile by pressing and compressing it during its shape changing cycles.

While some users did not go beyond the touch stage and just allowed the textile to remain on the table, 3 users decided to explore move and hold interactions with the toolkit. In order to create 3D volumes with the textile, these 3 users began to bend and fold the textile to change its initial form from a 2D textile to a 3D shape (Fig 134).

Finally, due to textile's association with clothing in our society, 2 users prompted to wear the textile around different body parts such as their back, chest, and neck by wrapping the textile around their body to experience the haptic sensation of the textile (Fig. 133). Additionally, one user even prompted to lay down on the textile to test if the tactile sensation could still be felt against their own body weight, which was confirmed through their test.

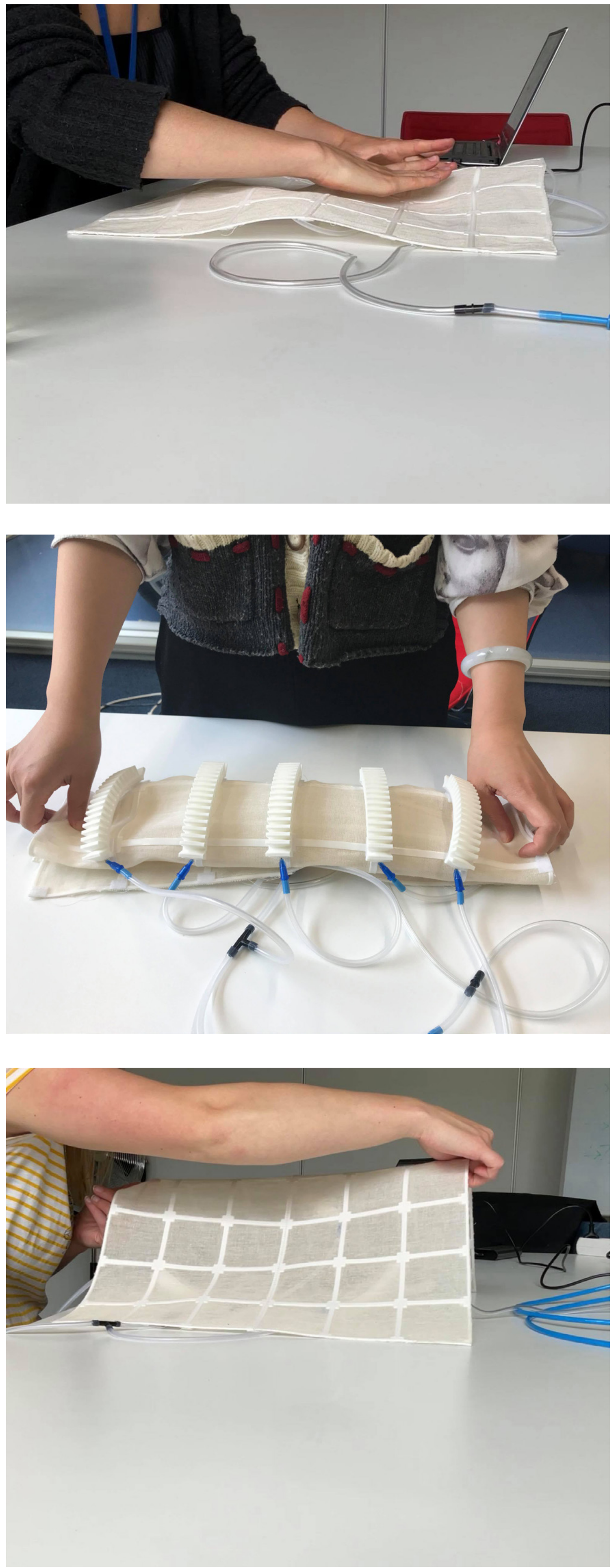


Figure 134
Examples of performative action of partipants during test

Sensorial Level

The sensorial level asks the question: **how would you describe the material?**. This description is on the most literal sense in terms such as hard vs soft, smooth vs rough, etc. As the material simply consisted of cotton textile and flexible plastic, there is not much novelty in the sensorial aspects of the material as people are already familiar with it. For this reason, the sensorial level was not explored in detailed during the study.

That being said, there is one important characteristics to note. One is that some participants initially perceived the material as being fragile during its shape change movmements and at first, neglected to touch the textile while it was moving. After reassurance that the textile toolkit was strong enough to touch, users proceeded to touch it. Additionally, users were surprised with how strong the resistance of the actuator to compression was when inflated. This perception of fragility and weakness is most likely related to their pre-exisiting perceptions of interacting with textile. When the material is reinforced with the 3D printing pattern and actuator, it becomes stiffer than expected.

Affective Level

The affective level asks the question: **what emotions does the material evoke?**. Although this question was not directly asked to users, some of the participants described the emotion they associated with the movement of the material without being prompted. The most common emotions as described by 4 participants was calm and soothing. These emotions were mostly attached to movement duration times that mimicked breathing pattern around 2-3 seconds. For faster movements (<2 seconds), one user described it as playful and mesmerizing.

Finally, there was one user who selected expressing an emotion as their design challenge. They selected **the transition from an emotional state of tension to a state of relief,** which was achieved by a slow inflating movement with the textile wrinkling up to a sudden, quick deflation. This variation in emotion based on movement and form, in addition with the ability to deliberately tune the parameters to achieve a specified emotion suggests that even within the same material, a variety of emotions can be expressed by manipulating the spatial-temporal form of the toolkit.

Interpretive Level

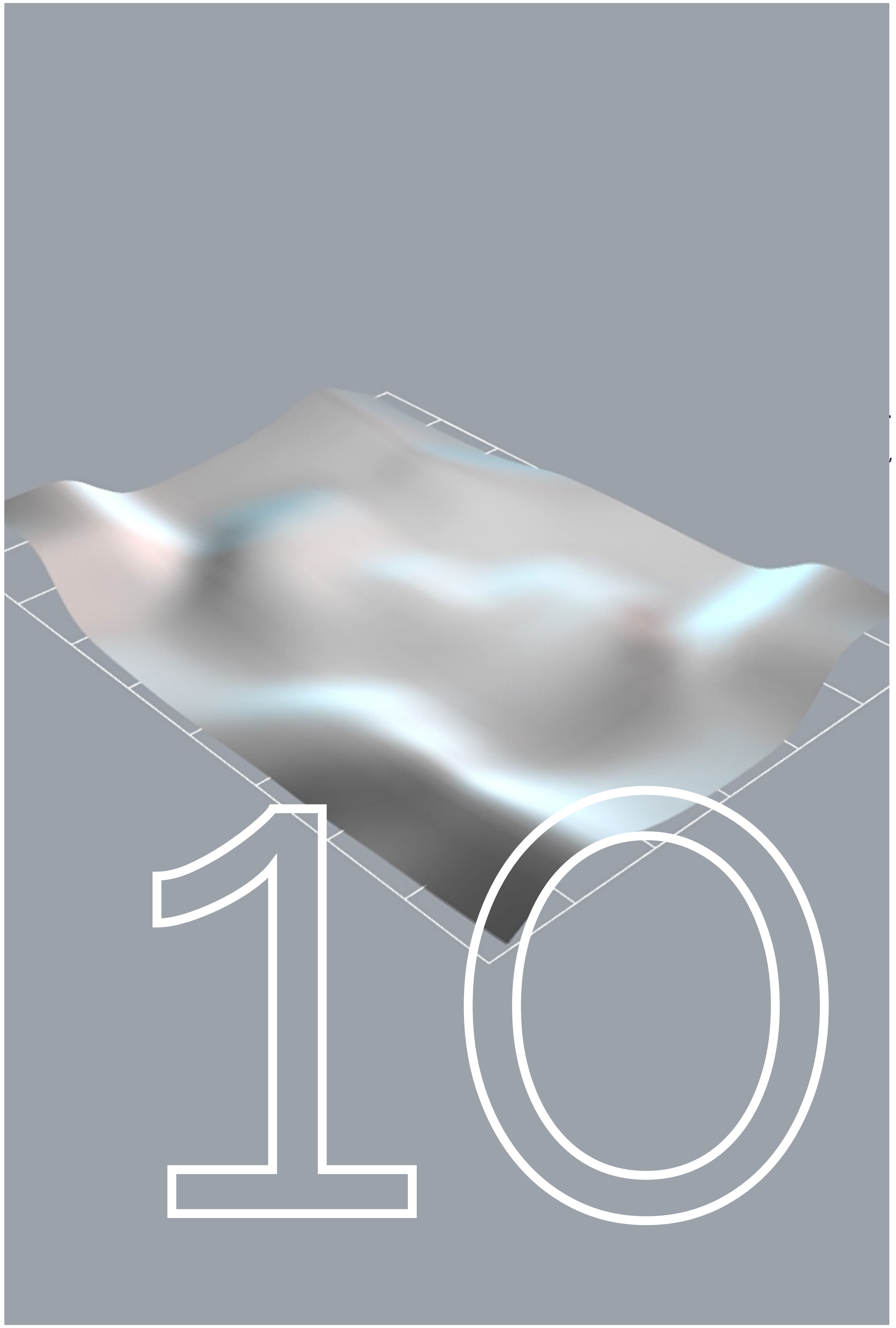
The interpretive level asks the question **What do you associate with the material?**. When studying livingness as a quality of material experience, this occurs in the interpretive level. In this level, people relate previous experiences with the behavior of the material. Despite the users not being introduced to the idea that the toolkit can be used to explore alive-like expressions, 3 of the 5 users in the study explicitly mentioned that the textile felt like it was alive and/or had alive-like behaviors such as breathing, growing, and fluid movement. This interpretation of the textile as alive was due to multiple layers of the interaction:

1. The actuators themselves reminded users of animal-like qualities. Some users even described the actuators as octopus tentacles or caterpillars. The organic form of the actuators created and interesting juxtaposition with the organized grid of the textile.

2. The organic forms produced by the textile created an abstract form of the shape change that was a translation of the movement of the actuators. This ended up creating associations with sea creatures for one user such as a manta ray or sea plants.

3. The different types of movements created different representations of livingness in people's mind. Slow movement were often associated with growth, medium and cyclic movements with breathing and sleeping, and pulsating movements with animal locomotion and a heartbeat.

4. The sound produced by the air compressors, despite initially thought to be an annoyance, was found to actually enhance the experience of livingness as it made some users feel as if the textile was breathing with the additional auditory sensation.



CHAPTER TEN

COMPUTATIONAL SIMULATION

To enhance the toolkit, a computational simulation of the forms created with Textalive was created. This chapter explains the programming behind the simulation to aid future designers in recreating the results and compares the simulated forms with the physical prototype as a means of validating the simulation tool.

10.1 COMPUTATIONAL MODELLING IN HCI

Throughout this project, we have showcased the importance of physical prototyping and testing in the exploration of novel shape changing materials through the creation of the toolkit using 3D printed pneumatic actuators. In our evolving design world, digital tools have also become an essential part of the design process. In the field of HCI research, it is common for novel shape changing materials to be enhanced with digital simulations tool that can aid designers in the prediction or fabrication process of the material allowing for faster iterations and decision making using the digital space. Similar to how CAD tools allow designers to create and visualize static forms and products before they are realized in the real world, simulation tools for shape changing materials help designers predict the dynamic shape change stages prior to fabrication. These simulation tools are of high importance for designers as the behavior of these new materials are often difficult to predict.

These computational tools can be separated into two main categories:

1. Direct Computational Design Tools: User inputs fabrication geometry and the tool produces a target shape change geometry.

2. Inverse Computational Design Tools: User inputs target shape geometry and the tool produces the fabrication geometry.

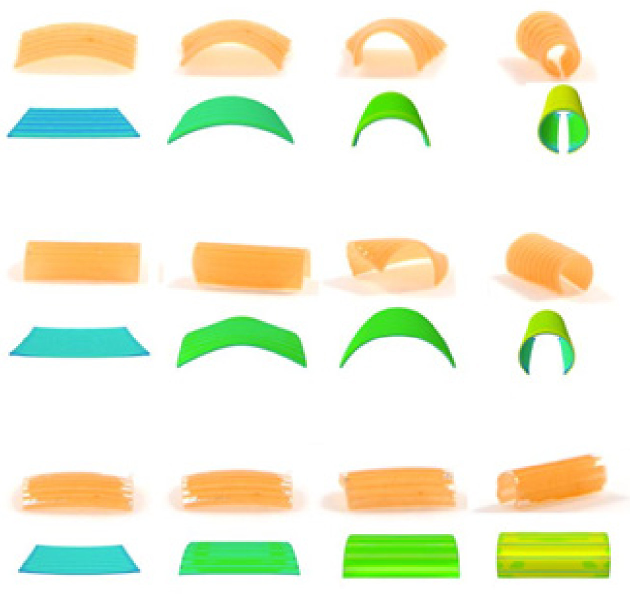


Figure 135
Example of direct design computational tool (Wang et al., 2017)

Direct Design Comp. Tools

These are tools where the designer creates an input geometry and feeds this geometry to into the simulation tool. The input geometry is related to the fabrication or set up process such as providing a 2D pattern of the heat sealed markings to be placed on the heat sealable fabrics as in the Aeromorph project (Ou et al., 2016). With this input geometry, the simulation tool then predicts the shape change behavior by displaying the result through 3D visualization or other means. New shape changing materials by the MIT Tangible Media Group are often accompanied with a direct computational design tool to aid designers in visualizing the shape change digitally. With these types of tools, designers can make slight adjustments to their fabrication geometry until they achieve the desired result. These style of tool allows for a creative collaboration between the designer and the computer to arrive to the final resulting shape change design similar to a generative design approach (Fig. 135).

The fabrication geometry that designer inputs into the simulation can vary. It can consist of a pre-designed 3D CAD model or a custom user interface where the designer uses building blocks to interactively create the input geometry. In these tools, it is common for there to be a controlling parameter or stimulus that affects the degree of shape change in the simulation. These parameters vary depending on the type of material such as air pressure for inflatables/pneumatics or temperature for SMAs. It is also possible that only the initial and final stage of shape change are provided to the designer for a set pre-determined value of the stimulus. With this stimulus determined, the simulation then runs a physics calculation using software such as Grasshopper to produce the final result.

Inverse Comp. Design Tools

A more advanced computational tool is the inverse computational tool design tools. Here the designer provides the tool a pre-determined 3D geometry of the desired final shape change state and the simulation runs a optimization algorithm to produce a fabrication geometry that will create the shape change. These types of tools are more advanced as they require a combination of a physics simulation and an optimization calculation to produce a result. The complexity of the input geometry required from the user can vary. For example, the Printflatables project allows the user to import a flat, bended sheet structure as input and produces the fabrication pattern plus the inflated simulation as seen in Figure 136 (Sareen et al., n.d.). More advanced computational tools can take in complex curvatures and surface geometry as input and a highly accurate optimize result as seen in Figure 137 (Panetta et al., 2021). It must still be noted that the complexity of the shapes possible from the simulation tool are not only dependent on the simulation tool, but also on the shape change possibilities the material allows. For this reason, not all shape change materials are necessarily well suited for inverse computation depending on their limitations.

Computational Tool Proposal

For this project, it was decided to create a direct design computational tool for the following reasons:

1. Inverse design tools require a higher level of computation knowledge.

2. The toolkit itself is similar to a direct design tool where the designer can change the input parameters (the actuators) and observe the resulting shape change. This type of behavior where the designer can selectively decide the location of the actuators can be mimicked in a digital environment to visualize the shape change before testing it with the physical toolkit.

The goal of the tool is, therefore, to allow the designers to test out the form of their designs digitally before testing out with the physical toolkit.

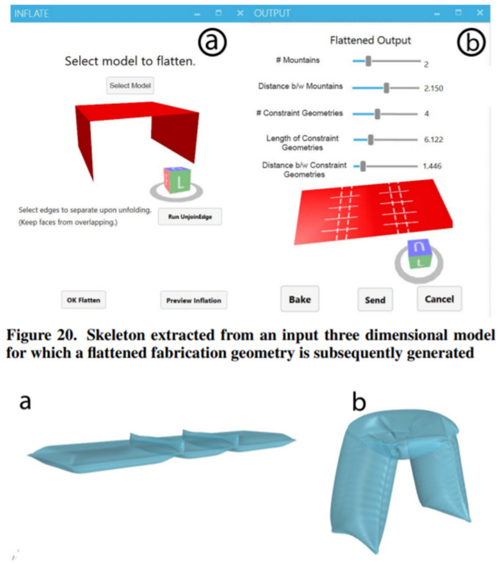


Figure 20. Skeleton extracted from an input three dimensional model for which a flattened fabrication geometry is subsequently generated

Figure 136
Example of inverse design computational tool (Sareen et al., 2017)

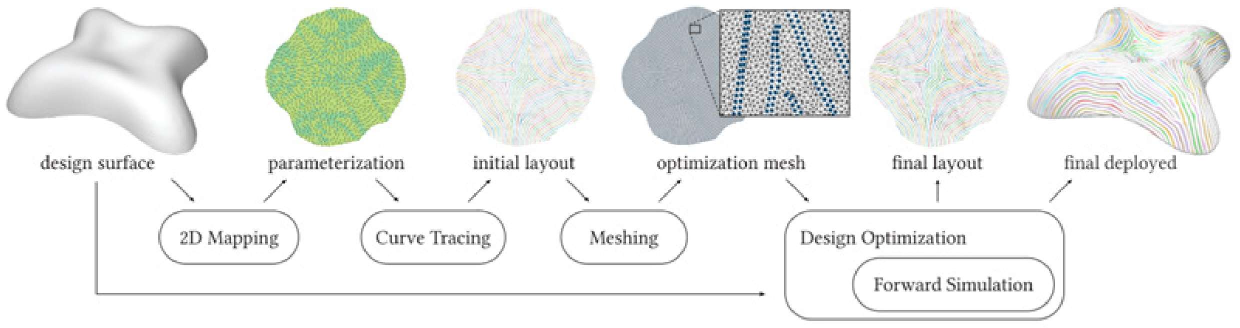


Figure 137
Example of inverse design computational tool workflow (Panetta et al., 2021)

10.2 COMPUTATIONAL SET-UP

Before starting the design of the simulation tool, the physical principles of the toolkit need to be explored. The computational tool does not need to be a true to life simulation of the toolkit such as modelling the complex inflation of pneumatic actuators. These sections will instead present the basics physics behind the materials of the toolkit and show how they can be simplified for easier simulation. The simulation tool was built using Grasshopper with the Kangaroo 2 plug-in for the physics simulation and the SelectablePreview plug-in for the user interface.

The 3D Printed Textile Composite

The textile used in the toolkit is a mesh cotton. The mesh cotton has a high stiffness yet can still be easily bent and folded. The 3D printed grid pattern consists of TPU 95A, which adds additional stiffness to the textile along the grid lines, yet still allows for bending without plastically deforming. Figure 138 shows the grid pattern of the 3D print. The textile interface can be simplified into two parts:

1. A flexible mesh that can fold and bend with variable stiffness

2. A structure of simple rods with variable stiffness

Using the Grasshopper and Kangaroo 2 plug-in components, a computational model of this structure can be created. First, a square grid pattern is created to the same size of the textile toolkit (8 x 6 squares).

Using the square grid line created, the boundary surface (outside edges of the grid pattern) are extracted to create a mesh of the same size. The mesh is then triangulated and connected to the Edge Lengths Kangaroo 2 physics component (Fig. 139). This component essentially turns the mesh into a flexible surface similar to a textile that can be folded and bent with a variable stiffness controlled by the Strength parameter. Figure 141 shows an example of the textile mesh being deformed manually with the mouse pointer in the simulation.

Next step is to create the support 3D printed grid pattern structure. Although it would be ideal to include the influence of the height and width of the 3D pattern as part of the simulation, it was found highly difficult to simulate this as it requires a beam bending simulation, which was not achieved successfully. As an alternative, the 3D print pattern can instead be simulated as an uniform rod structure with uniform axial and bending strength using the Rod component from Kangaroo 2. To allow for a degree of flexibility in the rod similar to the TPU material, the grid is first subdivided and then converted to a polyline (Fig. 140). Figure 142 shows an example of the textile being deformed manually with the mouse pointer with the new addition of the Rod support. The added support adds additional stiffness to the mesh making the simulation closer to the real physical prototype.

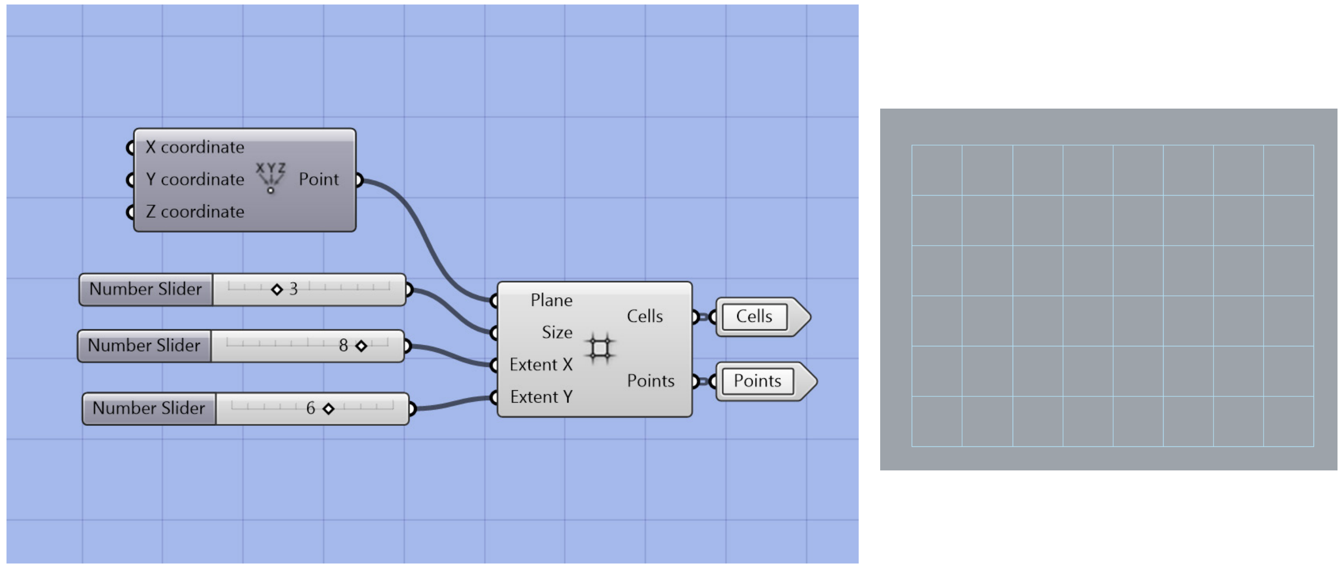


Figure 138
Grasshopper: creating the grid structure

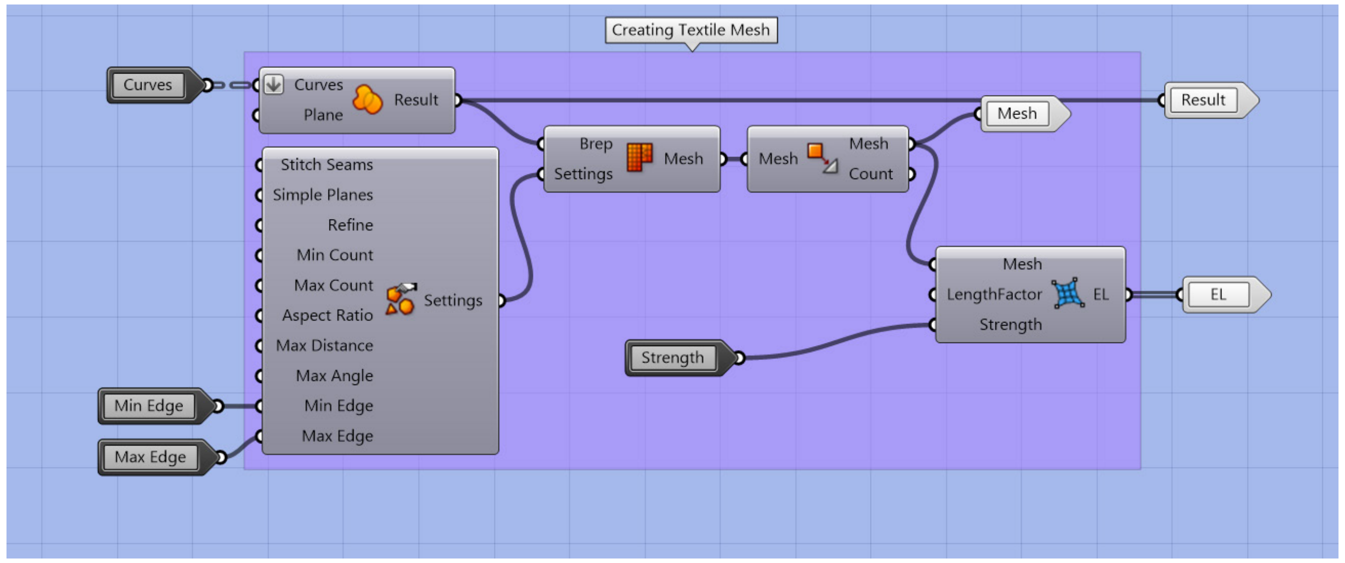


Figure 139
Grasshopper: Simulating the textile mesh

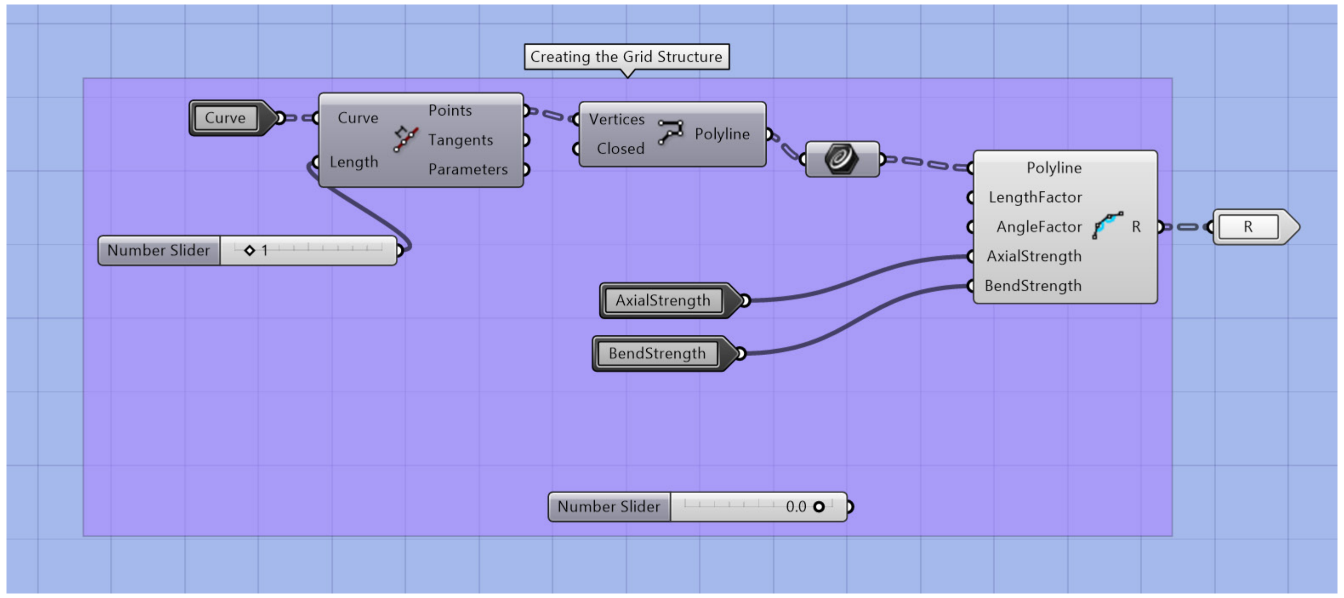


Figure 140
Grasshopper: simulating the 3D printed grid

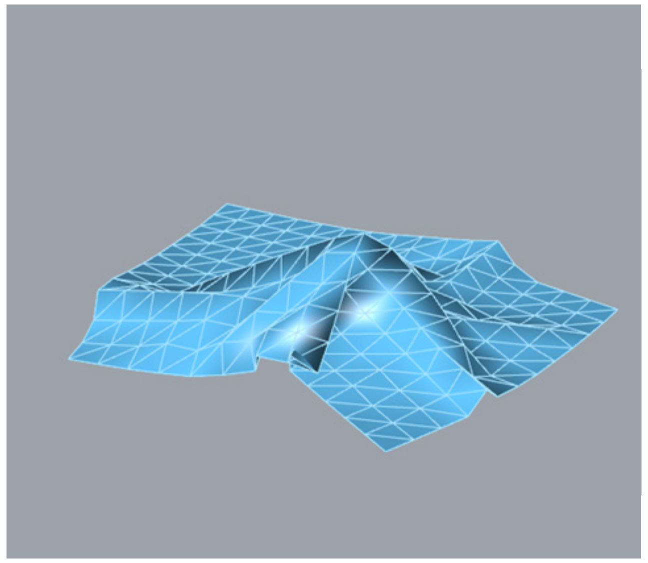


Figure 141
Simulation of textile mesh without 3D printed rod structure

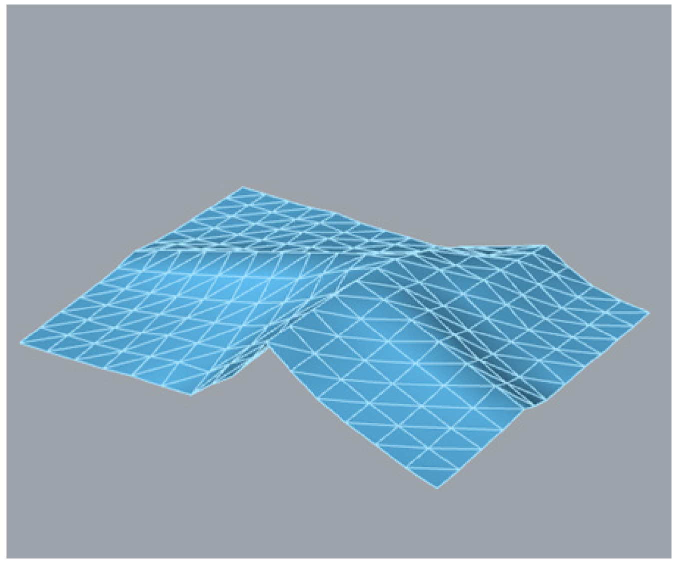


Figure 142
Simulation of textile mesh with 3D printed rod structure

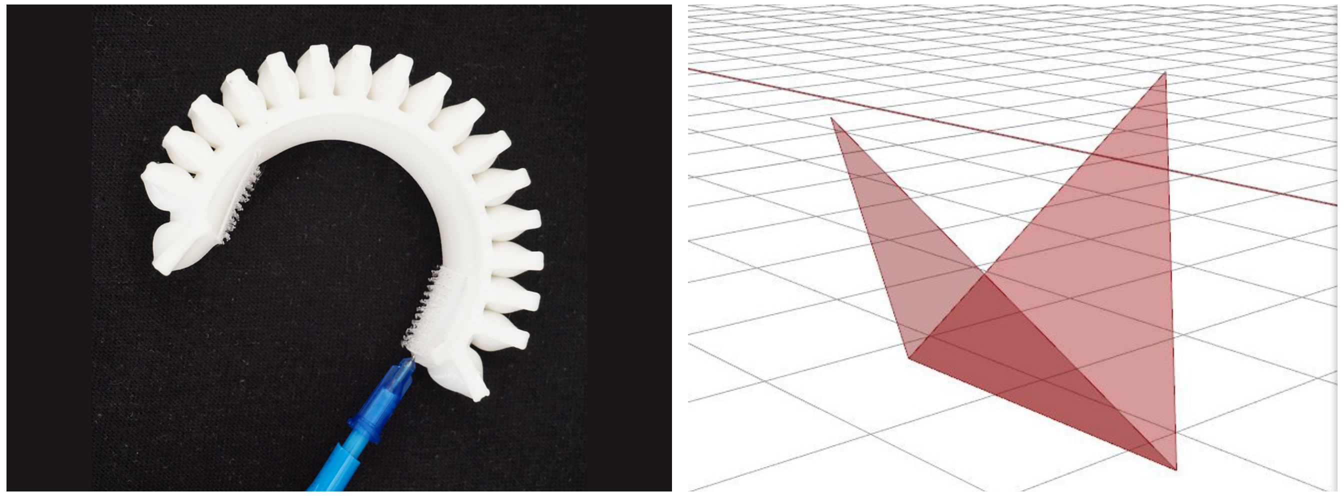


Figure 143
Simplification of actuator movement into Grasshopper hinge component

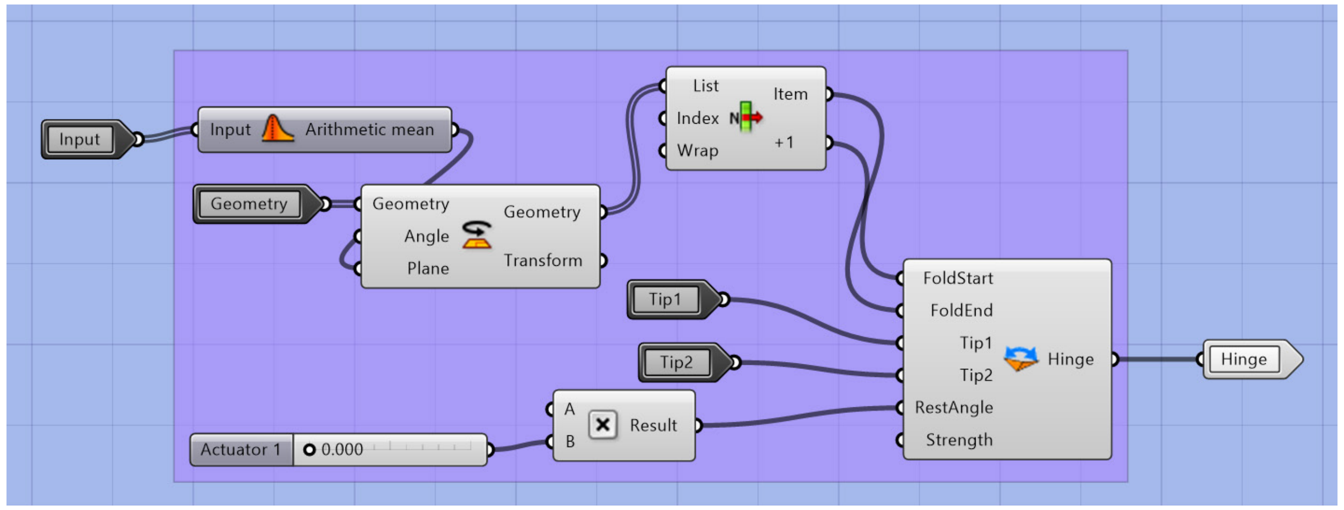


Figure 144
Grasshopper: Simulating the actuator as a hinge

The Actuators

With the textile mesh set up, the next step was to select the best method to mimic the movement of pneumatic actuators. As has been shown in Chapter 5, pneumatic bending actuators go from a straight, relaxed state into a bent, curved state when inflated. Simulating the entire inflation of the geometry and its corresponding movement and its collision with the textile mesh would be an overly complicated simulation of an otherwise rather simple movement. Instead the actuator can be simplified to a simple hinge movement where the hinge starts in a flat state when deflated and the hinge partially closes when inflated (Fig. 143)

By simplifying the actuator movement into a simple movement, the Kangaroo 2 Hinge component can be use to interact with the textile mesh. The hinge can be created by using two points along the grid where the actuator is connected to (similar to the Velcro connections in the physical prototype) and creating a hinge structure using the two actuator connection points as the tips (Fig 144). The hinge created thus has a fold along the midpoint between the two connection points and has a control input (e.g. Actuator 1) that controls the fold angle from 0 (fully open) to 180 degrees (fully closed).

When the hinge is connected to the textile mesh in the physics simulation along the actuator connection points, the following simulation is created when the hinge is folded as seen in Figure 145. This bending behaviour of the hinge component appears to be a simple, yet sufficient approximation of the curling of the bending pneumatic actuator.

The proposed hinge simulation can then be expanded to represent the 5 actuators used in the toolkit by duplicating the hinge component and applying it to different points along the grid of the textile mesh. Figure 146 shows an example of the simulation with 5 actuators hinge components.

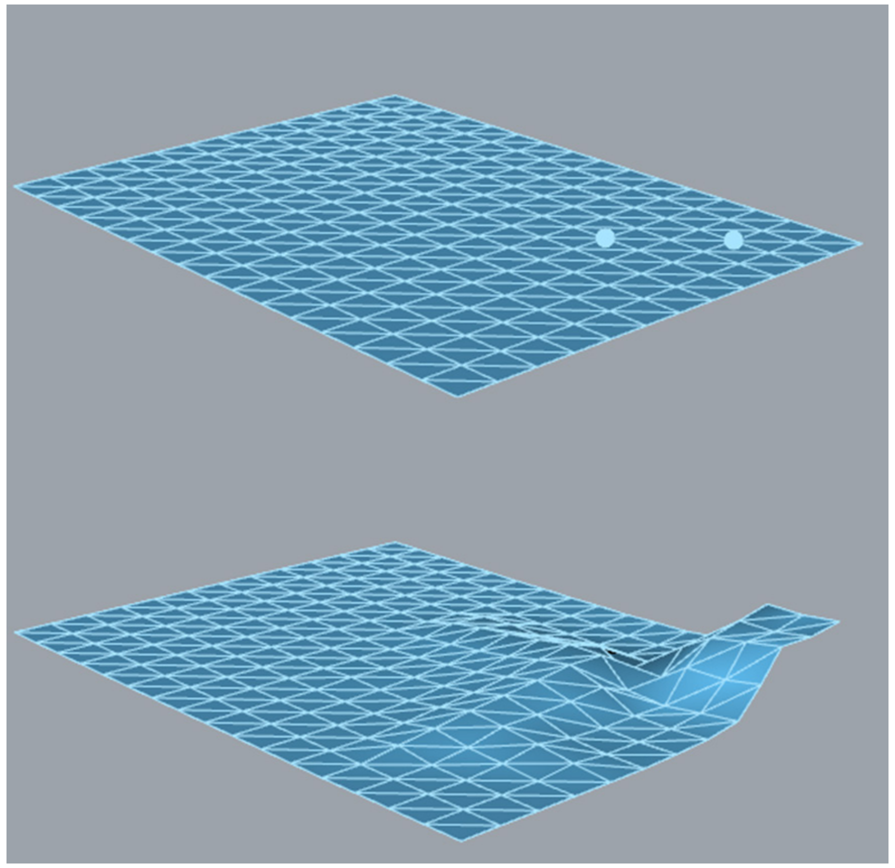


Figure 145
Simulation using single actuator

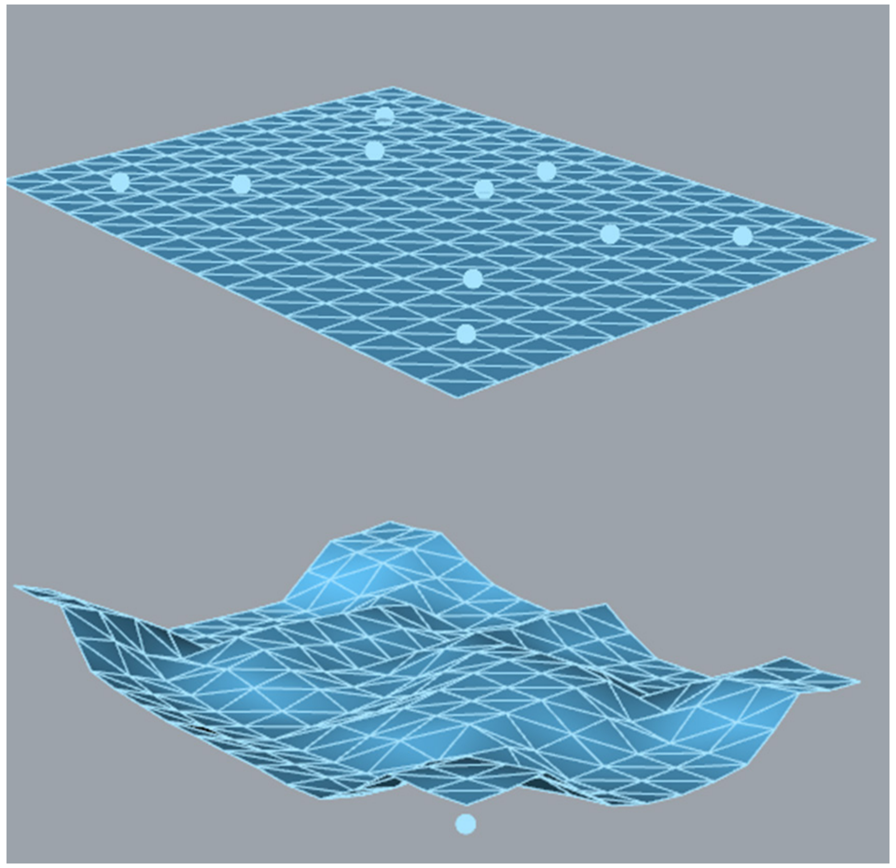


Figure 146
Simulation using multiple actuators

Constraining Hinge Component

During testing of the tool, it was found that the "Hinge" component faced an issue when the actuator was placed on the outer edges of the textile. This was because this would cause one of the folding points of the hinge to be on the outside of the mesh, thus disturbing the physics simulation. To fix this, the following logic algorithm was added to check if one of the folding points was outside the mesh, and to relocated to a point withing the mesh along the edges as seen in Figure 147. Figure 148 shows the folding points of the hinge with the color blue and it can be seen how the algorithm relocates the hinge location according to where the actuators are placed on the textile.

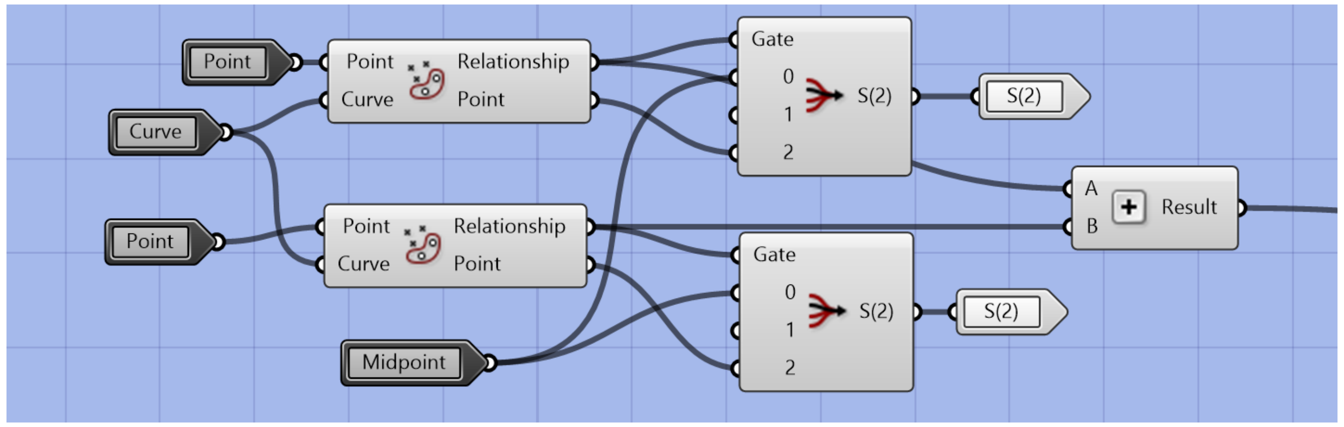


Figure 147
Grasshopper: Constraining the hinge component along the boundaries of the mesh

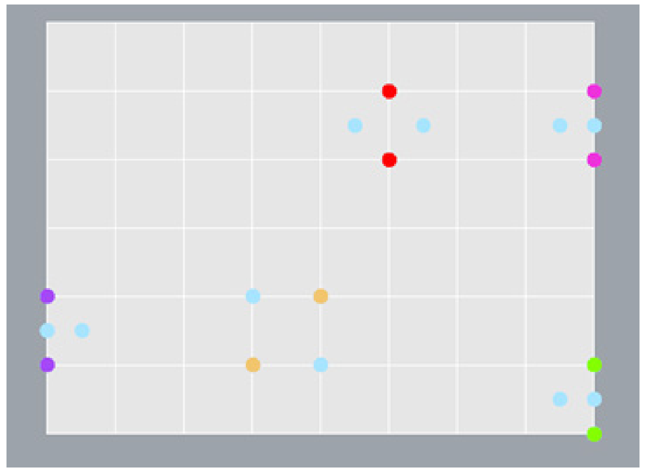


Figure 148
Example showing constrain of hinge folding line algorithm

External Factors

In the real-world scenario, the physical prototype is not an isolated object in space. The textile interacts with its environment and is bounded by the constrain of forces such as a gravitational force and the normal reaction force from the table. The simulations shown previously already included these components into consideration, therefore, this section will just describe the Grasshopper components used to achieve these results.

First, there is the gravitational force. The gravitational force ensures that the entire textile mesh has a constant downward force to prevent the textile from floating in the simulation. This is achieved by using the Kangaroo 2 component "Vertex Loads" with a small negative force. The input "Mesh" of the "Vertex Loads" components is the flexible mesh created to represent the cotton textile (Fig. 149).

Secondly, there is the normal reaction force of the ground or table. This ensures that the textile mesh does not move in the negative z direction and is constraint by a ground object. This is achieved by using the "Solid Points Collide" component and using a rectangular surface to constrain the points of the mesh from going below the surface (Fig. 150 & 151).

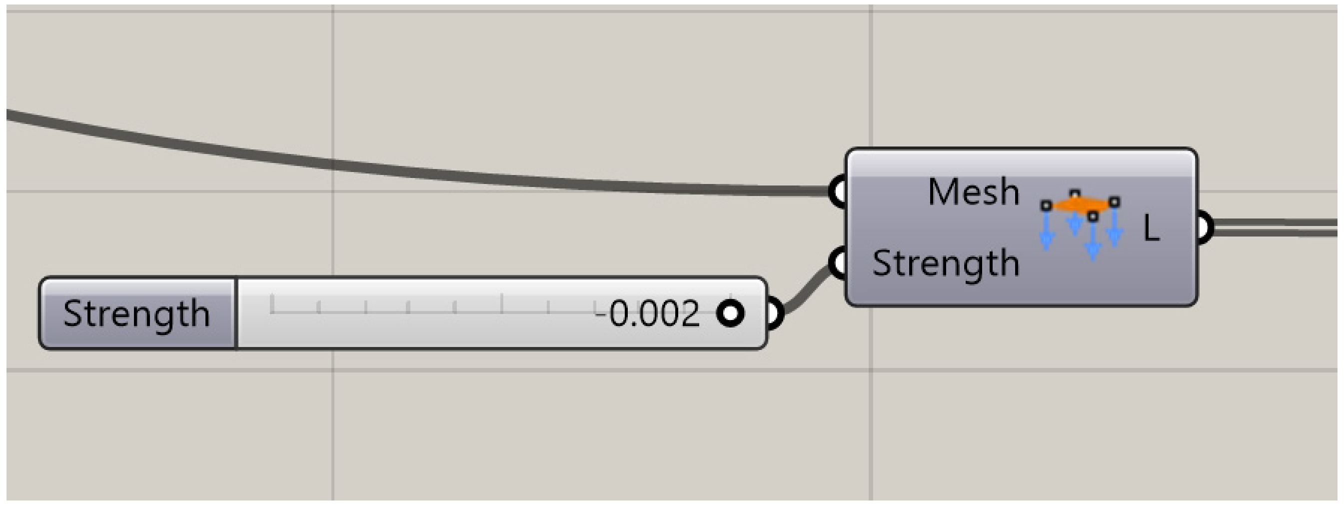


Figure 149
Grasshopper: simulating gravity

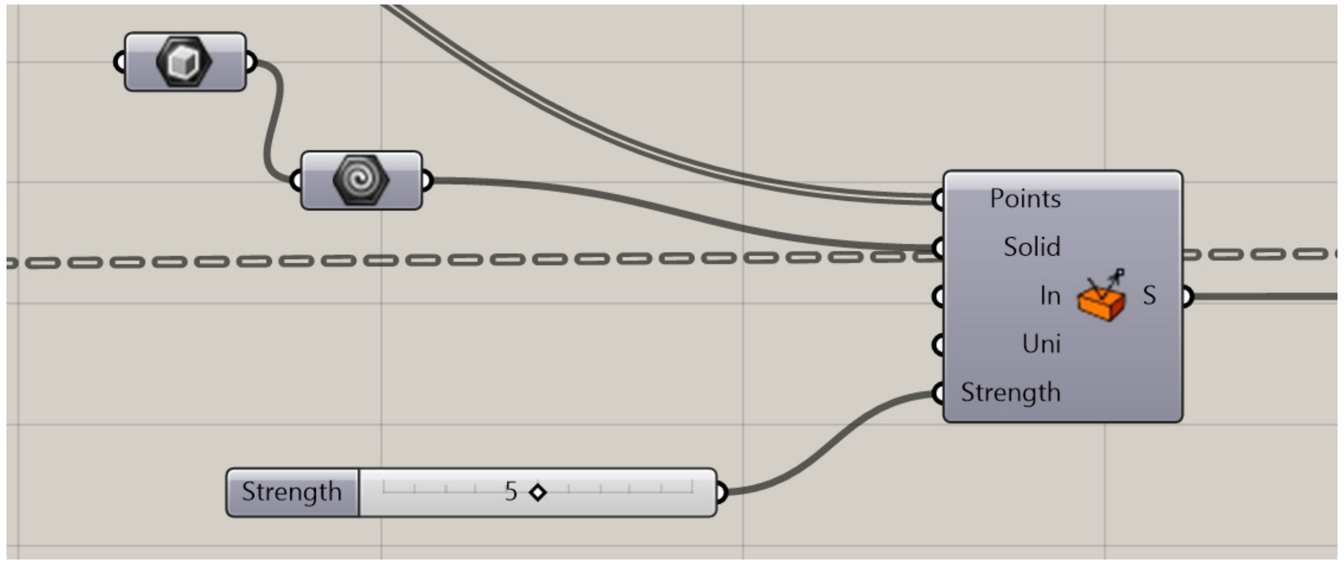


Figure 150
Grasshopper: simulating table top reaction force

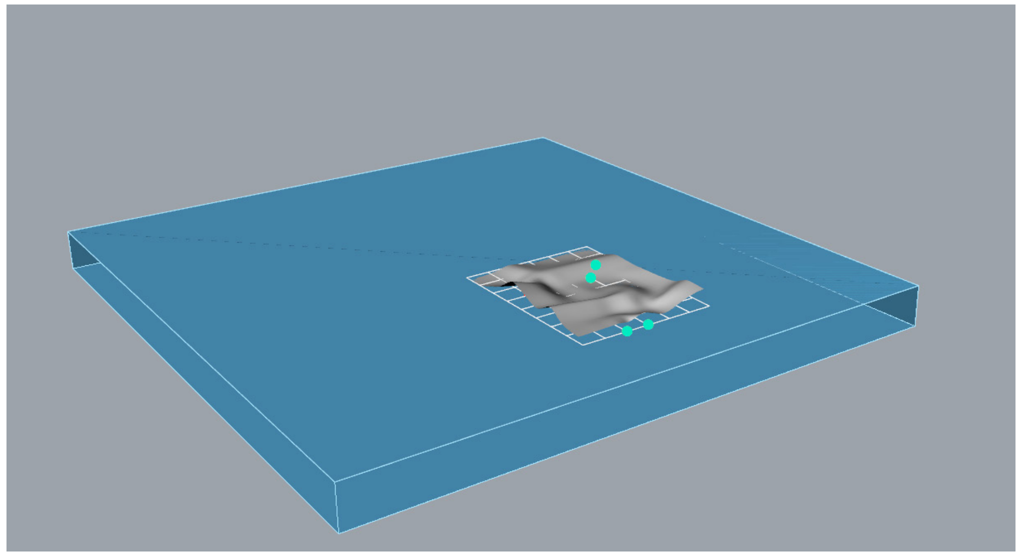


Figure 151
Input geometry (blue rectangle) for reaction force component

Additional Features

To finalize the design of the computational tool, some additional features were added to make the tool easier to use for both the validation of the tool with the real prototype and also for other users to test the tool in the future. These two features were:

1. Interactive selection of actuator location

2. Remote control panel of simulation

The interactive selection of actuator location was done using the "SelectablePreview" component from the plugin with the same name. This component allows the free selection of points within a given geometry. By using the points of the grid square structure as input to this component, the user can interactively select the two points where the actuators would be placed along the textile mesh for quicker iterations and testing. Additionally, each actuator is color coded, for easy identification from the user (Fig. 152 & 153).

Secondly, there is the Remote Control Panel. This panel allows the Grasshopper designer to publish certain controls to the Rhino interface for easier, direct manipulation of specific parameters. To simplify the use of the simulation, the control panel in Figure 154 was created. This includes the following features:

1. On/Off switch to turn on/off the simulation

2. Reset button to start the simulation from the beginning

3. Individual actuator control to change the inflation of each actuator individually

The combination of these two additional features turns the complex Grasshopper algorithm into a simpler interface to give the user direct control over the parameters. In the next section, the simulation tool is validated against the shape change of the real toolkit prototype using the new user interface design for easier control of the toolkit parameters.

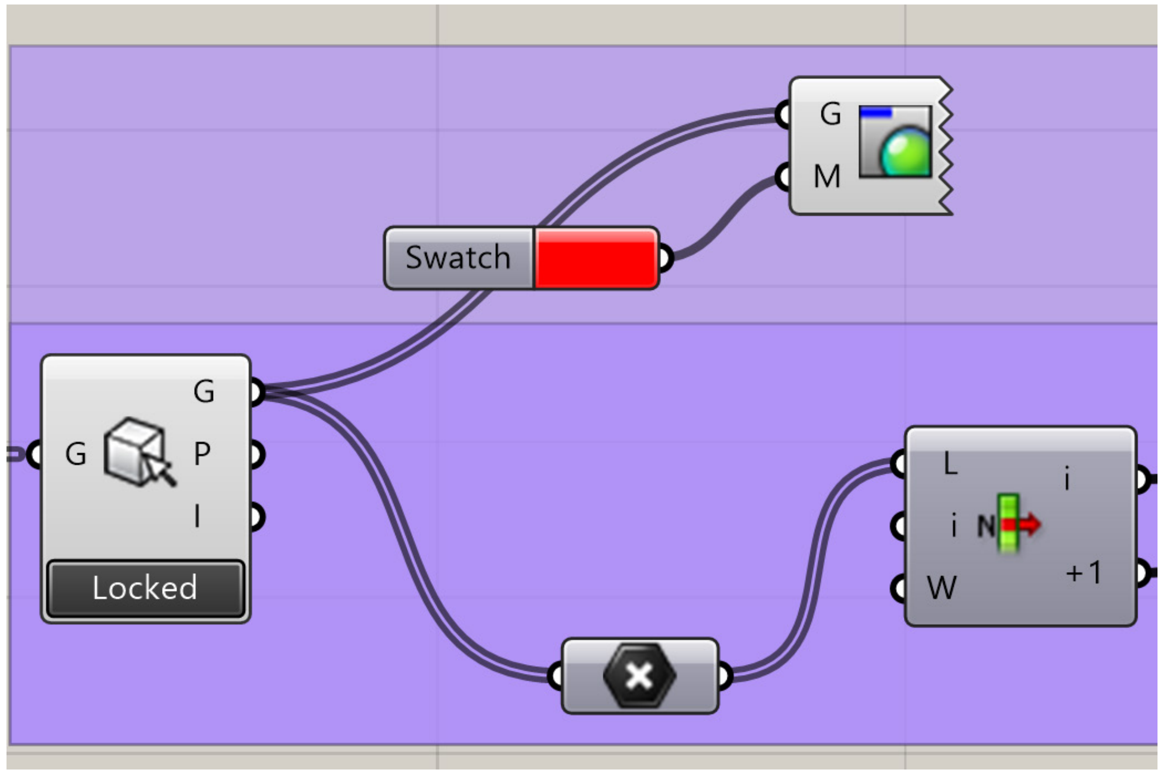


Figure 152
Grasshopper: SelectablePreview component with color coded actuator points

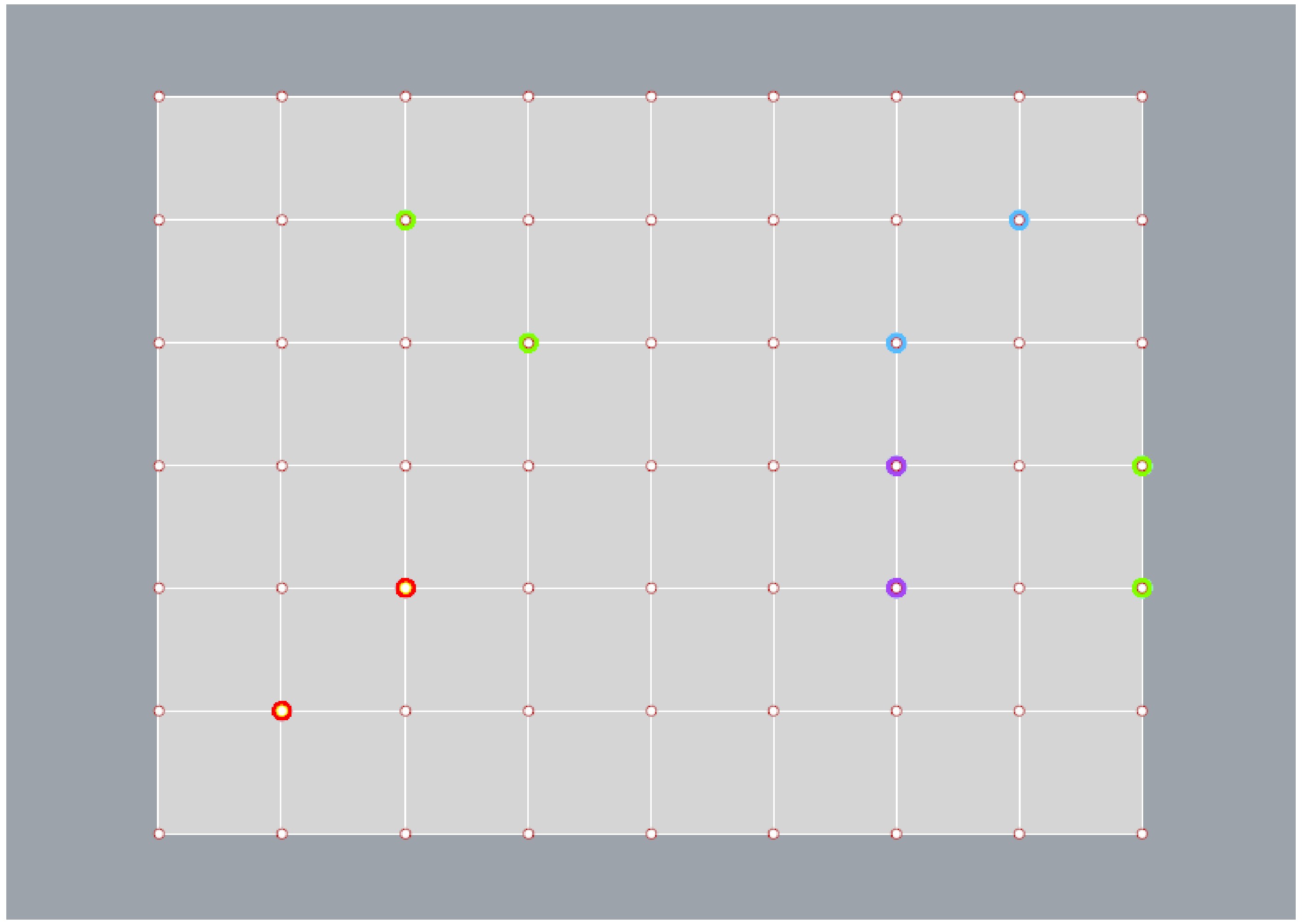
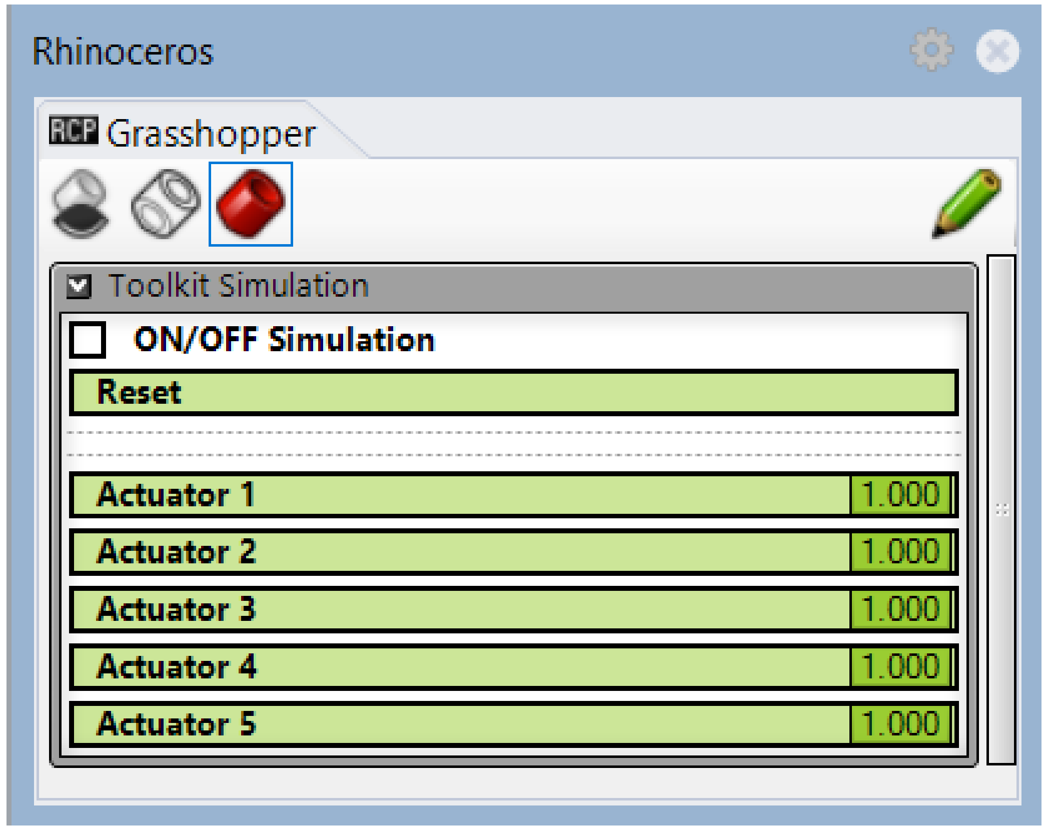


Figure 153
Example of user selecting actuator points using SelectablePreview



Rhinoceros

Grasshopper

☑ Toolkit Simulation

☐ ON/OFF Simulation

Reset

Actuator 1 1.000

Actuator 2 1.000

Actuator 3 1.000

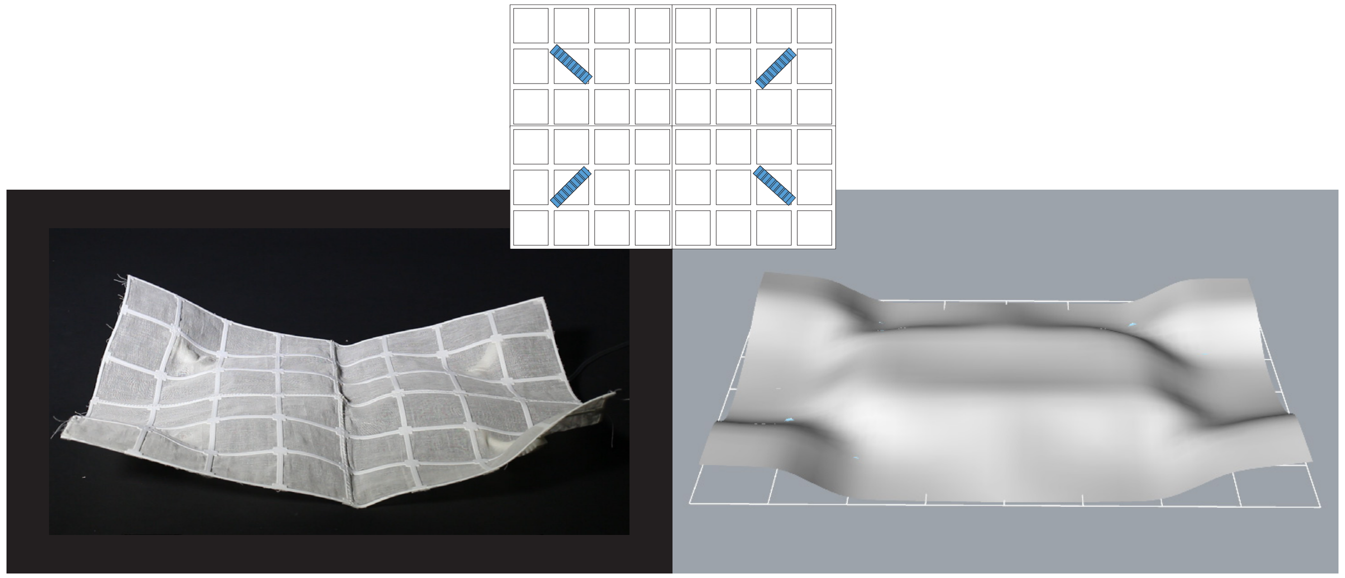
Actuator 4 1.000

Actuator 5 1.000

Figure 154
Remote control panel to control simulation

10.3 VALIDATION OF SIMULATION TOOL

With the simulation tool completed, the next step was to make some direct, visual comparisons between the simulation and the physical prototype. The physics parameters of the simulation such as the Mesh Strength and Rod's Axial and Bending Strength were adjusted to visually match the simulation and the prototype as close as possible. Figure 155 shows the comparisons using the final simulation tool. The evaluation was conducted with 4 actuators instead of 5 due to some technical issues with the 5th actuator during time of testing. The results of the simulation proved to be very promising as it is visually similar to the what is seen with the toolkit. It is noticeable that some of the curvatures created by the textile appear to be more sharp angled on the simulation than in real life. As the parameters were only manipulated through visual trial and error, it is recommended that future development of the tool can find a mathematical equation between the physical and digital simulation for improved results.



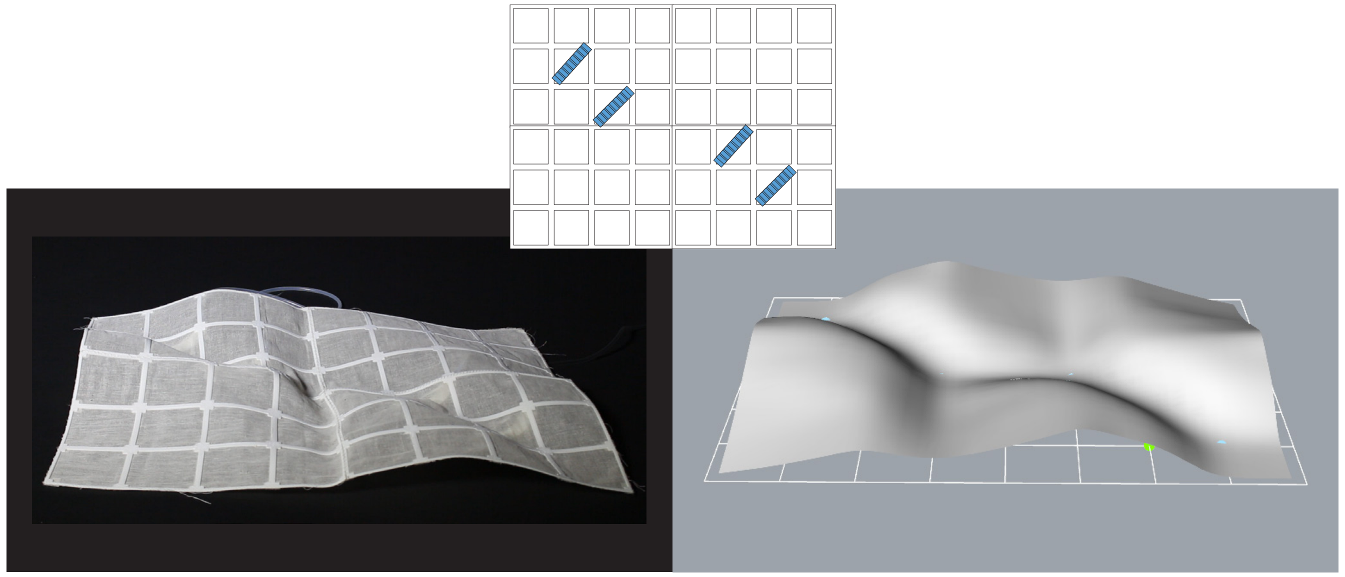
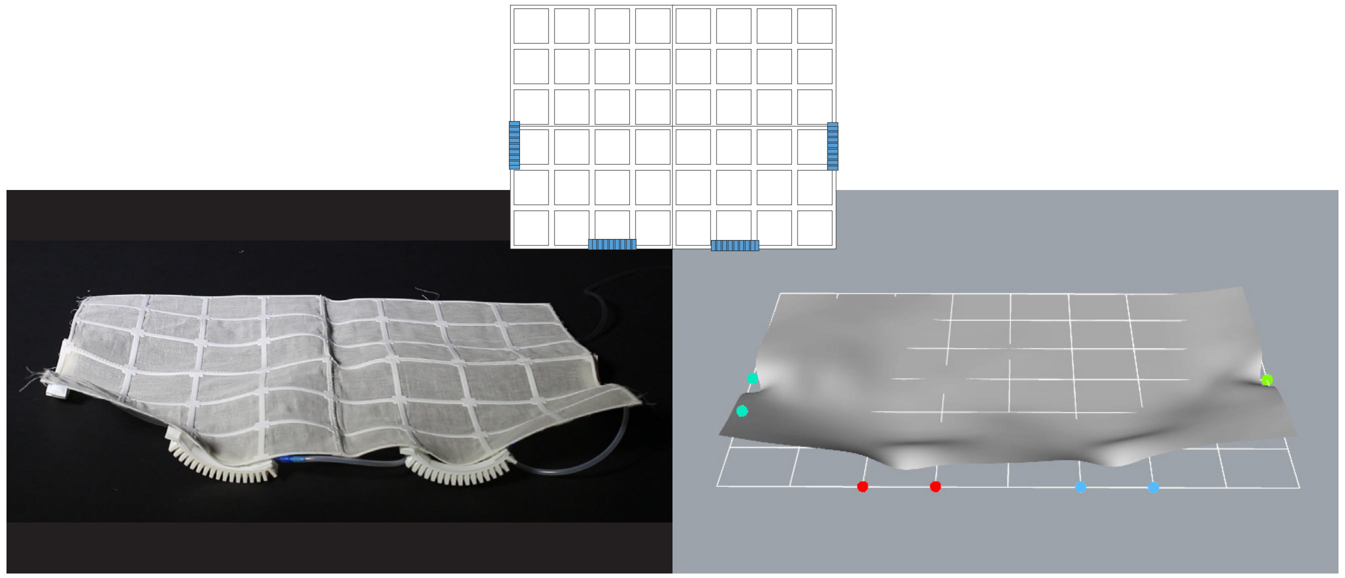
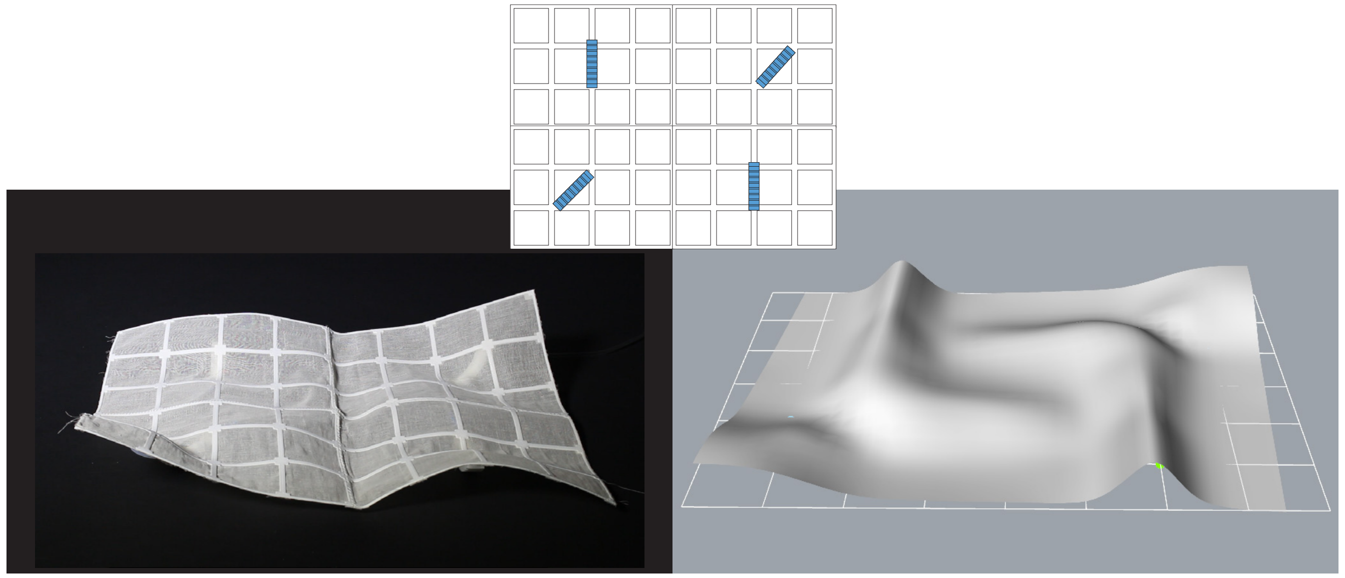


Figure 155
Comparison of simulation with physical prototype





The compurational simulation tool is a great final addition to the toolkit as it allows designers to explore forms in the digital environment before testing out in real life. While the toolkit still allows quick and easy iterations to explore new forms, the simulation tool showcases the computational possibilities that such a material has. With such a digital tool, designers could develop explore larger textile interfaces or custom design patterns and experience the shape change in the digital world in future development. Additionally, it is recommended that an animation tool be develop alongside the simulation to allow the designers to also vary the movement qualities of the simulation similar to how it is done in the real prototype. Development of such digital tools will help designers better understand and create new shape changing interfaces by allowing designers to experiment in a digital environment for faster and better iterations.

CHAPTER ELEVEN

FINAL REMARKS

As a finale to the project, this chapter concludes with final remarks on the desirability, feasibility, and viability of the project followed by future recommendations in studying shape changing interfaces. Finally, a short personal reflection is included alongside a thank you message to all the people involved with the project.

11.1 CONCLUSION

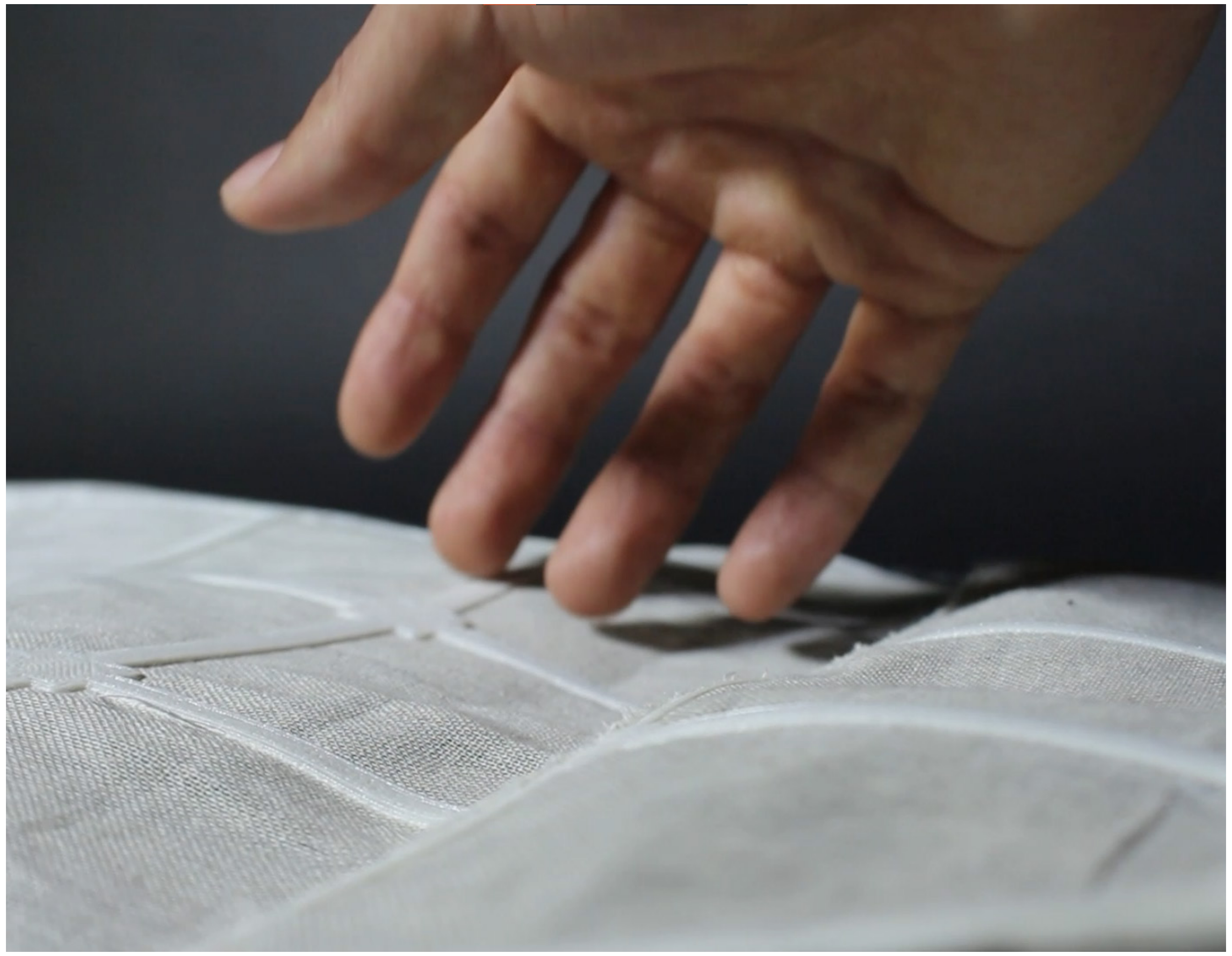


Figure 156
Interacting with Textalive (from movie clip)

Throughout this project, shape changing interfaces have been explored beginning with its infancy studying literature for inspiration and insights, conducting a material driven design process on the selected material, developing a material concept in the form of a physical toolkit, and evaluating it with potential users. As a final discussion on the project, the research and outcome are assessed in terms of desirability, feasibility, and viability.

Desirability

Our current digital world is filled with interfaces and screens that push us to interact with our environment in unfamiliar ways. Shape changing interfaces show promise in creating more interactive, engaging systems with our environment. Currently, studying shape changing interfaces in the design space is faced with a technical barrier due to the difficulty in fabricating and controlling these new materials. Toolkits, such as Textalive, allow for easy and quick physical exploration of shape changing interfaces by removing those barriers. As not many designers outside this research space have previously been introduced to shape changing interfaces, toolkits also serve as an introduction in education to inspire and teach the future generation.

The Textalive toolkit was evaluated with designers from varying levels of expertise in smart materials and textiles. The evaluation showcased the wide range of applications and ideas developed using the toolkit. Additionally, it showcased the importance of how physically prototyping and creating with shape changing materials helps designers in understanding the material experience qualities of the material.

Feasibility

Shape changing materials have been shown to be difficult to fabricate and to control. This project uses 3D printing to create shape changing inflatable materials. By using 3D printing following the process shown by the guidelines and insights displayed during the material tinkering, it has been proven that fabrication of these materials can be accessible using inexpensive FDM printers.

By creating the toolkit, the feasibility of controlling these shape changing materials has also been shown through exploring variations in the shape change morphology of the tool in the lab and during the user evaluation. Additionally, the kinetic qualities of the shape change can be controlled with the proposed hardware and digital interface. This is made possible by the unique characteristics of pneumatic/inflatable materials that allow for precise control over speed, forward/reverse movement, and range of motion. Finally, the simulation tool developed showcases the materials and the toolkit's computational potential helping designers explore shape changing forms digitally before testing them in the physical prototype.

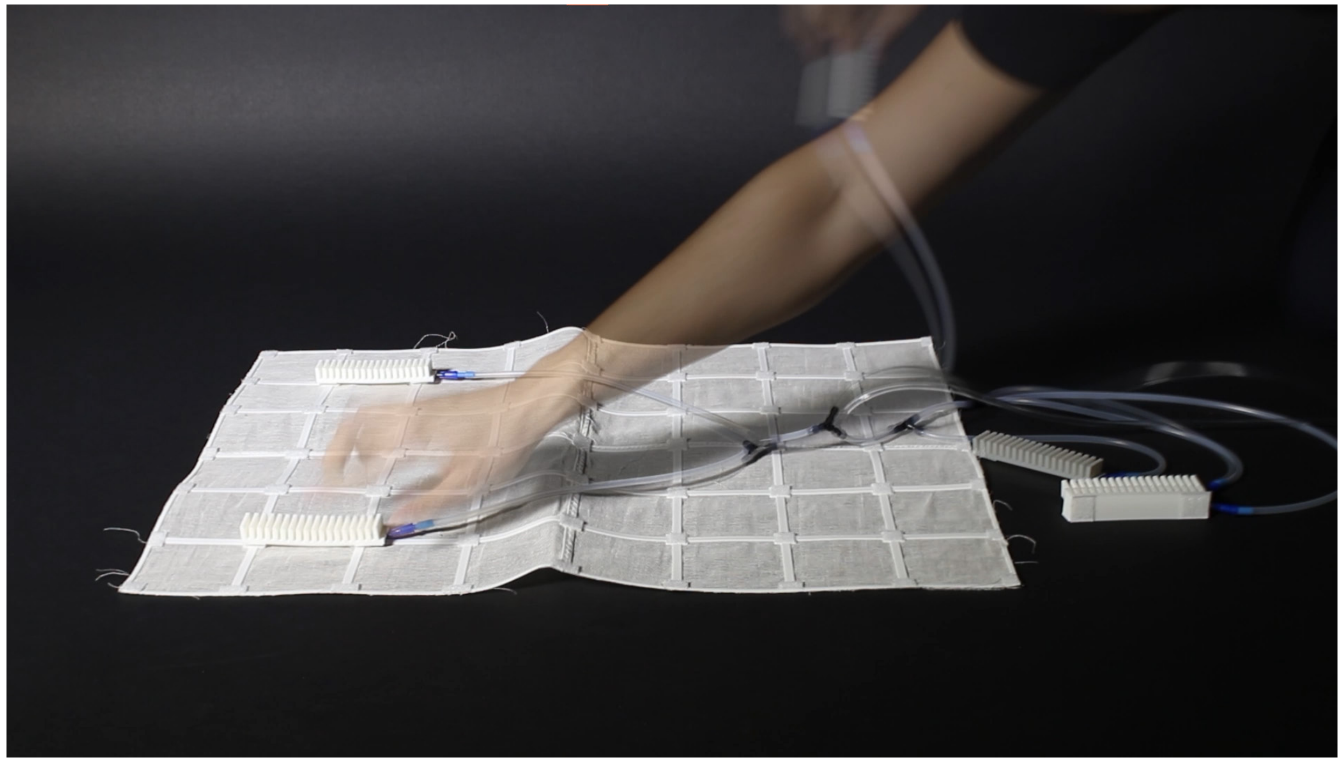


Figure 157
Applying actuators on Textalive (from movie clip)

Viability

Using readily available materials (textile, 3D printing, off-the-shelf electronics), specially in a research environment, makes this toolkit highly accessible to other researchers and designers to recreate and test. Additionally, the electronics can be substituted for a more, inexpensive alternative such as manual syringes or other pneumatic mechanism to vary the type of interaction the designer has with the system. By increasing the accessibility to shape changing materials, the gap between material research and the design field can be bridged to aid in the inclusion of these new materials in our future products.

11.2 FUTURE RECOMMENDATIONS

Beyond the scope of this project, there are a few recommendations and open research questions that are still left to answer. This section will discuss my vision for the future material possibilities and toolkit possibilities,

Material Possibilities

As was shown in this project, 3D printing inflatable structures using Ninjaflex TPU can create promising shape changing actuators as long as the printing guidelines are followed. Although only bending actuators were explored in this project, 3D printing allows for an endless number of geometrical possibilities as long as the material constraints are respected. It is recommended that more complex geometries exhibiting other types of shape change, such as the ones described by MorpheesPlug, be explored in the future (Kim et al., 2021). Of special interests are auxetic pneumatic structures following the work of Lisanne van Leijsen to fully understand their potential from a technical and material experience perspective.

As for 3D printing on textile, it is recommended that the next step for this project would be to create a process that allows for printing of the pneumatic actuators directly on the textile. Using a modified version of the guidelines presented should help future researchers in developing a printing process to make the structures work and improve on the work initiated by the Fabricflation project (Arnellou et al., 2015). Additionally, as was recommended by experts during the evaluation of the toolkit, it would be interesting to explore how the 3D printed pneumatic structures can be minimized in size while still maintaining sufficient deformation. Finally, there was one parameter of 3D printing textiles that was not studied during this project, which is pre-tension of the fabric during printing. Pre-tension of fabric during the printing process produces localized deformations after the prints is removed due to the internal stresses created. By combining a new printing process to printing pneumatic structures directly on textile with pre-tension of the textile, more complex shape changing textiles could be explored in future work.

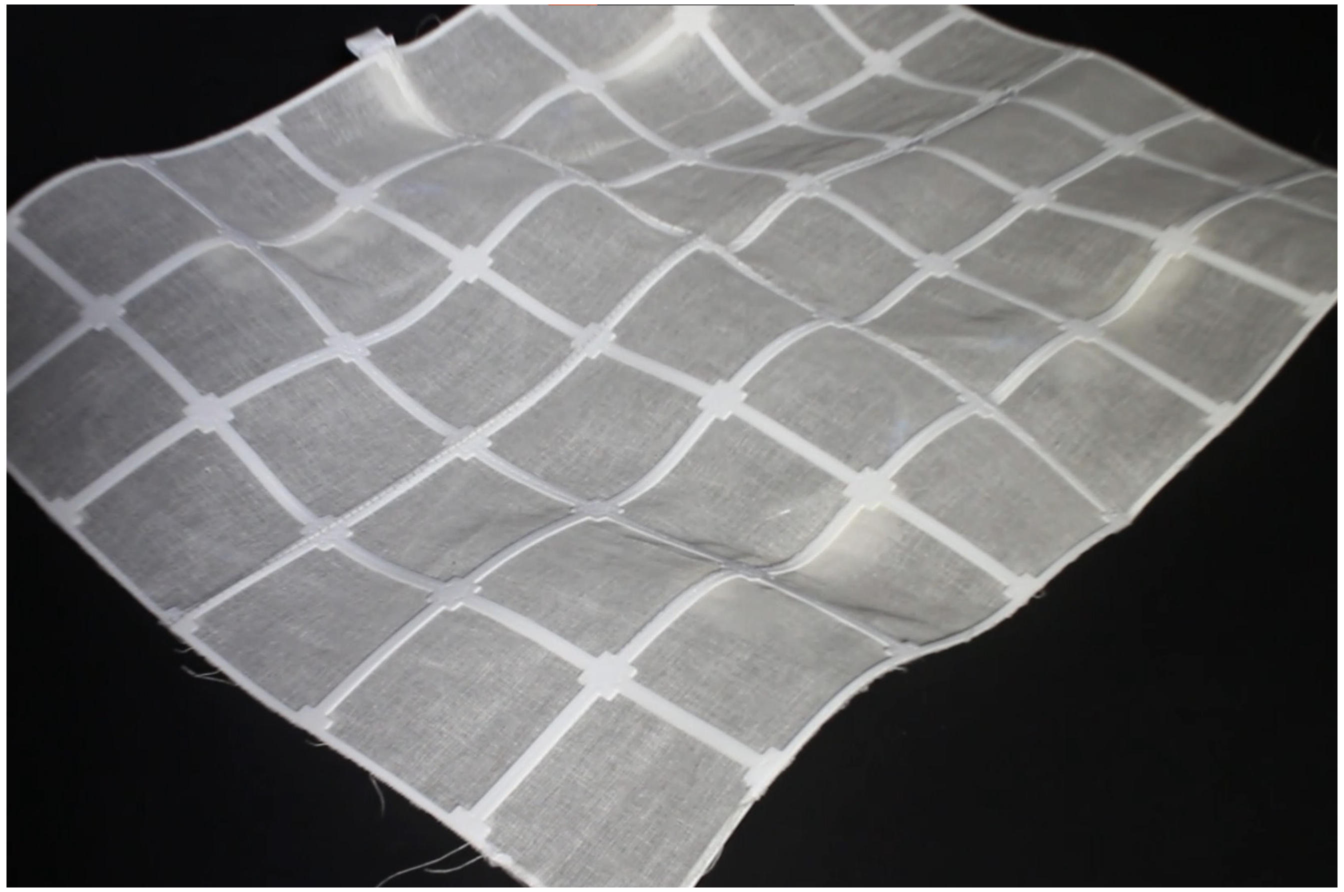


Figure 158
Close up of Textalive prototype in action (from movie clip)

Toolkit Possibilities

The evaluation of Textalive showcased its promise in helping designers explore shape changing interfaces. That being said, there is still room for future exploration and improvements on the design that can further help in better understanding the material experience and livingness of shape changing interfaces.

Primarily, it is recommended that a proper material experience study using the Ma2E4 toolkit be conducted to gain a more systematic understanding of the material experience. The user evaluation of the toolkit paved the way for the beginning of understanding the material experience based on user insights. A more controlled, directed study on material experience though, would help designers answer specific research questions. The type of material experience studies to be performed can vary from testing variations in shape morphology, variations in movement speed, etc.

Secondly, it is recommended to perform a systematic categorization of the shape changing morphologies of the Textalive toolkit with respective insights from the material experience study. This can help better understand what types of meanings and interpretations are attached to various forms and movements of the textile. Appendix A showcases examples of the varying morphology of the textile, yet it is not yet well understood which forms are most relevant to designers using the toolkit and how a shape morphology guide might assist them in their exploration. It is also noted that the shape morphologies cannot be properly captured through images and should be in the very least experience through video to fully understand the entire range of motion of the material. For this reason, a digital categorization or catalogue of the shape morphologies would be preferred to truly serve as a guide for the future of the toolkit.

Finally, the user evaluation revealed some shortcomings of the toolkit that could be improved in future iterations and additional features that would enhance the experience of exploring shape changing interfaces. The recommended improvements for the toolkit include:

1. Easier control over kinetic qualities: while some users managed to master the kinetic controls of the toolkit, some found them to be confusing. It is recommended that the flow control valve to vary the speed of the actuators be electronically control in the future and included as part of the digital interface. This can be possible by connecting servo motors to the valves that can open/close the valves remotely through the Arduino.

2. Individual control over the actuators: currently, the actuators all move in synchrony. To create more complex movements, it is recommended to expand the electronics to include individual control over the actuators. This can be done by adding additional sets of solenoid valves per each actuator to the electronic set-up that can allow the flow of air to be open and closed individually.

3. Expansion of actuator types: the current system only offers bending actuators, yet with 3D printing, the possibilities of new types of shape change are also possible. It is recommended to explore these new types of actuators and study how they interact with the textile interface.

4. Include props: some of the users in the study found that they wanted to explore new ways of interacting with the textile such as wearing it on their body, hanging it on the ceiling or wall, etc. It is recommended that simple props that can aid in this exploration of using the textile away from the table be explored in the future.

5. Interactivity: One aspect not mentioned in the user study that can bring value to the toolkit is the ability to create interactive interfaces through sensors. By including a set of sensors that users can prototype with, new interfaces that respond to their environment and people around them can be created with the toolkit.

11.3 PERSONAL REFLECTION

This thesis project was one of the most rewarding experiences so far of my academic career as an Industrial Designer. Throughout this project, I got the opportunity to experience a new design methodology (material driven design), learn how to be self sufficient during an individual design project, had the pleasure of collaborating with wonderful professors and colleagues along the way, and have gain a better understanding of what it means to be a design researcher. Through following the MDD process, I learned that material design research can be quite unpredictable, and yet rewarding in unexpected ways as it is a process that begins with a material and not a specified context as seen in traditional design processes. I experience how the project and the material explored kept morphing and changing through the iterations leading to the final decision to create the toolkit presented, which I could have never predicted from the beginning. Because of this unpredictability, there were moments in the project of doubt and uncertainty, yet thanks to the help of my great supervisory team who always pushed me to trust the process, we reached a result I am quite proud of.

Additionally, I experience how in research, the research question itself must keep evolving and adapting to the project throughout the process. We began with quite ambitious and far-reaching research question of exploring livingness in shape changing interfaces. Through the material research, we realized that this question needed to be reassessed into a smaller chunk that we could contribute to in the time of a master thesis leading us to the creation of a toolkit. Now that I have completed the process of attempting to study livingness in shape changing interfaces, I have realized that the creation of a toolkit was inevitable and only the first step towards truly understanding this question. I hope that in the future, a new designer will be able to take the tools provided or their own variation of it to continue the journey of understanding livingness as a material experience quality.

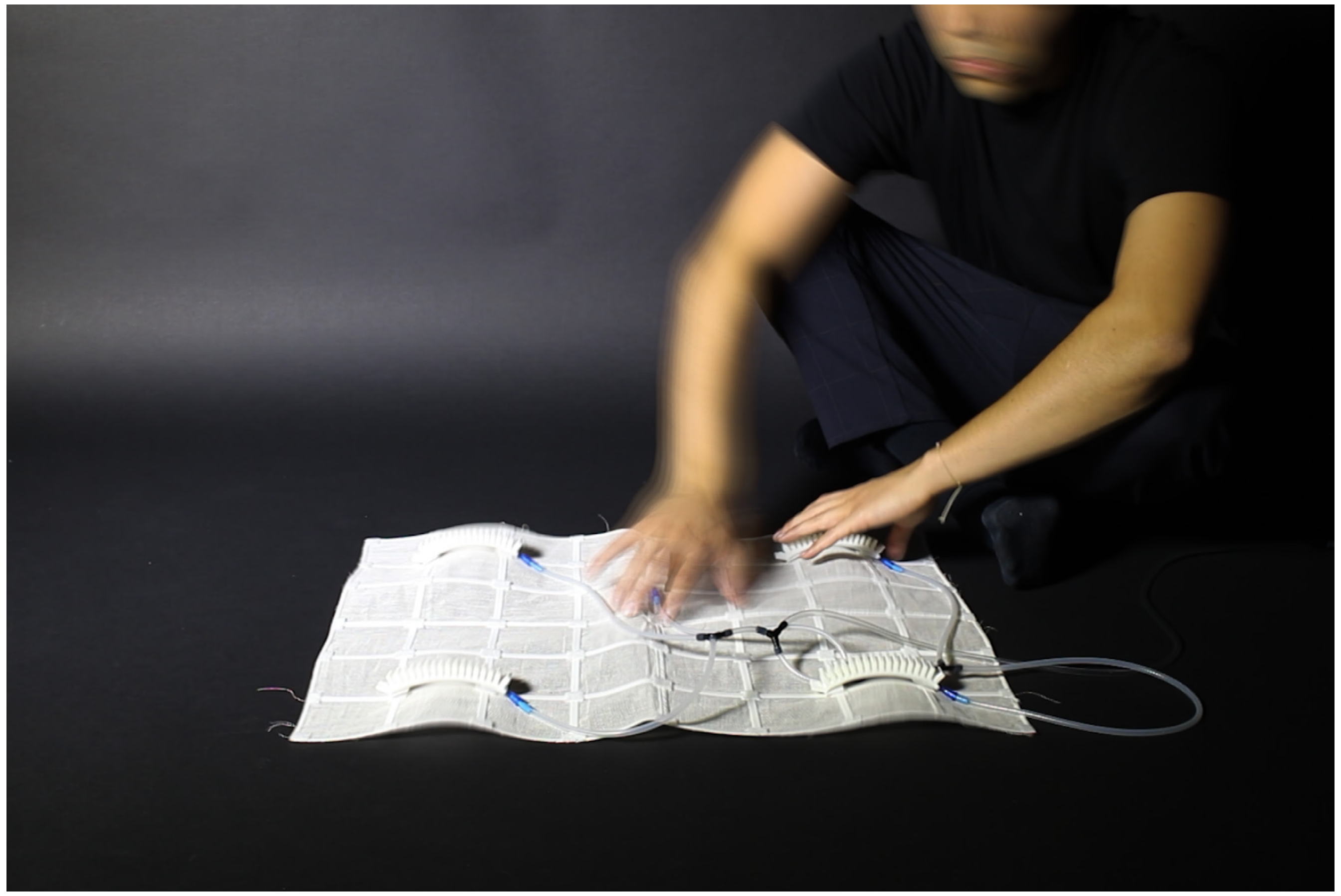


Figure 159
Self portrait of me and Textalive (from movie clip)

11.4 SPECIAL THANKS

While this project constitutes my master graduation thesis, it could have not been possible without the guidance and inspirations of the people that collaborated with me during this process.

Special thanks to my supervisory team: Elvin Karana, Jun Wu, and Alice Buso for teaching and guiding me through a new methodology of design research, motivating me to always keep iterating and adapting to new challenges in the project, and for making a welcoming environment during all our meetings to keep things fun and exciting every week.

Thanks to the members of the Material Experience Lab for letting me join your weekly meetings and inspiring me with your amazing projects.

Thanks to Rob Scharff for inspiring me during my material exploration through your previous research with pneumatic actuators.

Thanks again to Alice Buso for developing the hardware that made the toolkit possible.

Thanks to Dimitra Tsoli who aided me in developing the printing method for printing TPU on textile.

Thanks to all the participants in the user study who helped me in validating the toolkit and showed me new, creative ways of using my own design.

Thanks to all my friends and family for always supporting through the process.

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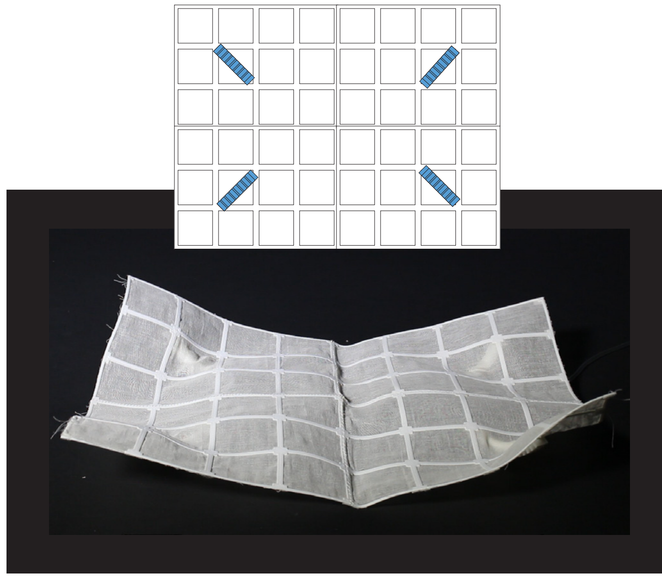
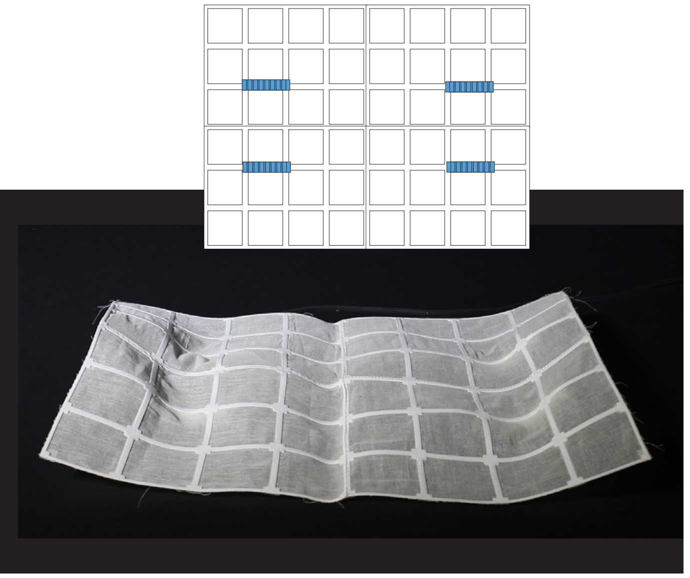
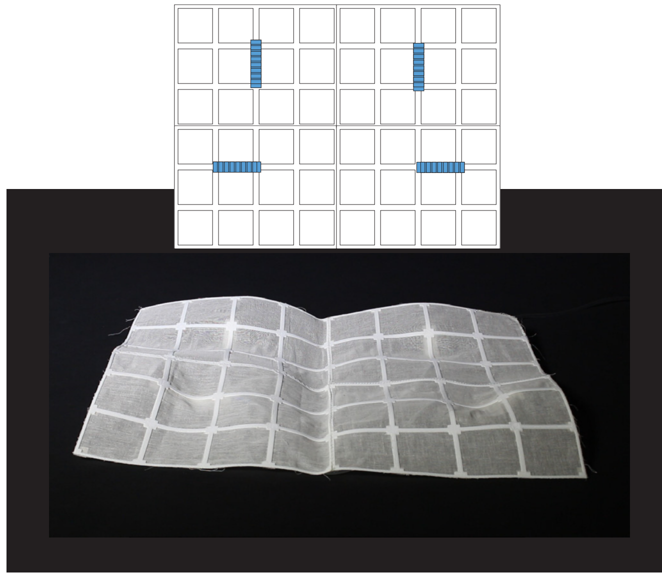
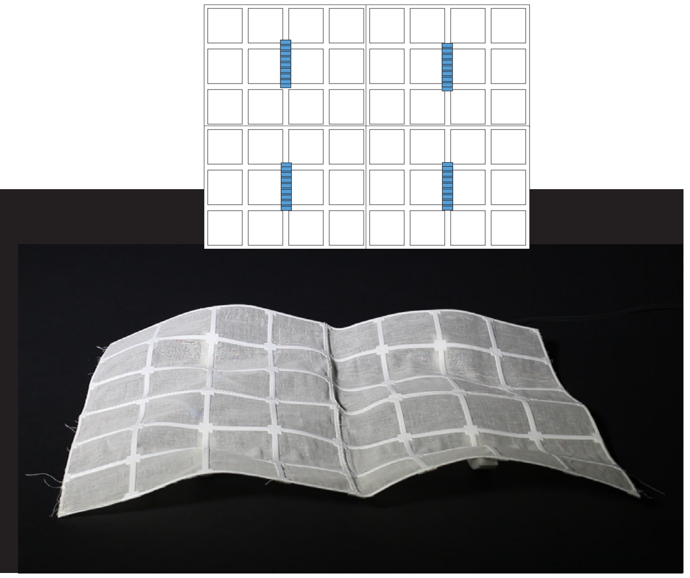
APPENDIX A

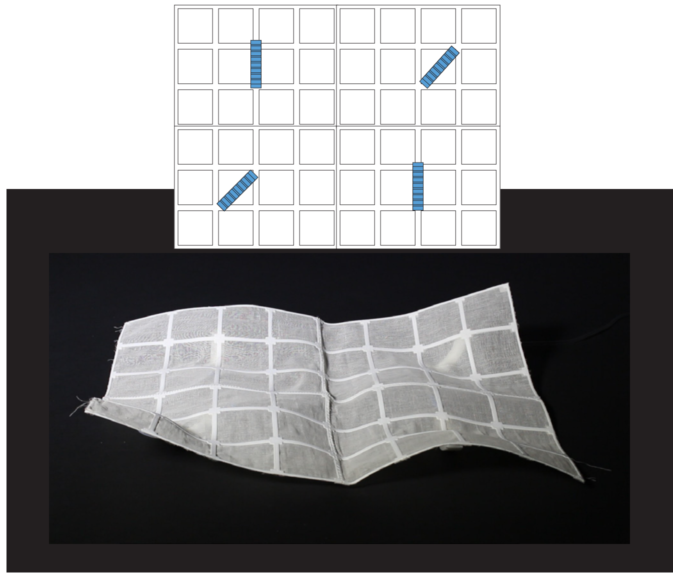
SHAPE MORPHOLOGY EXAMPLES

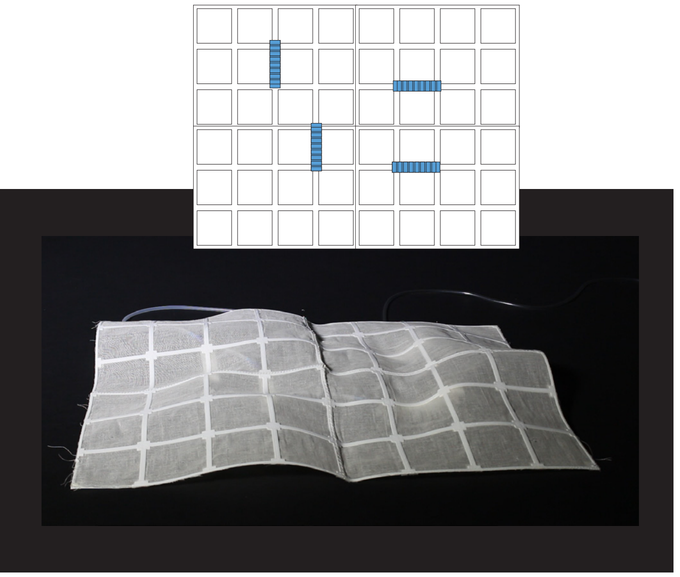


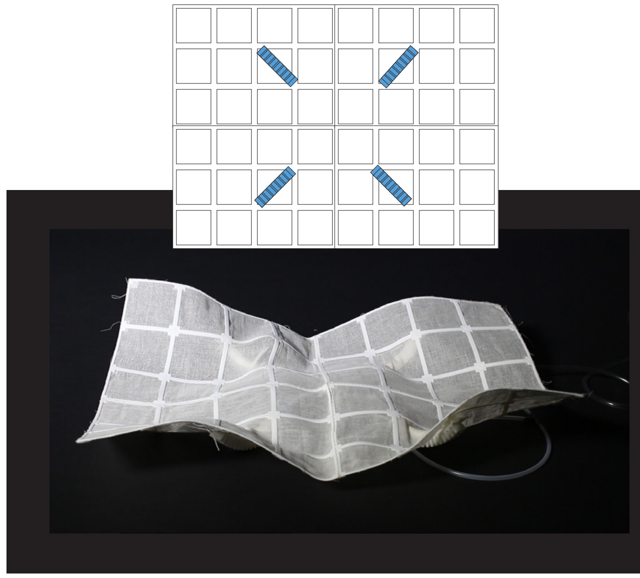


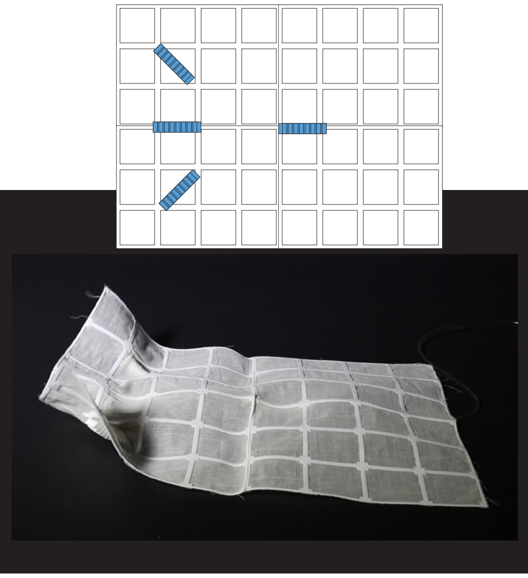


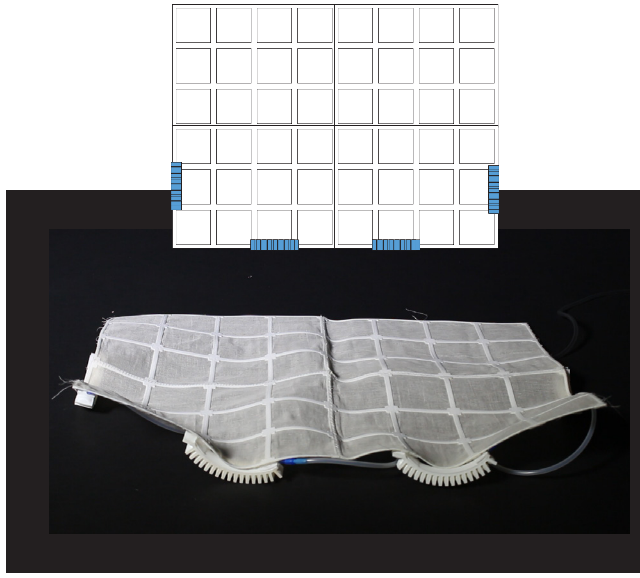


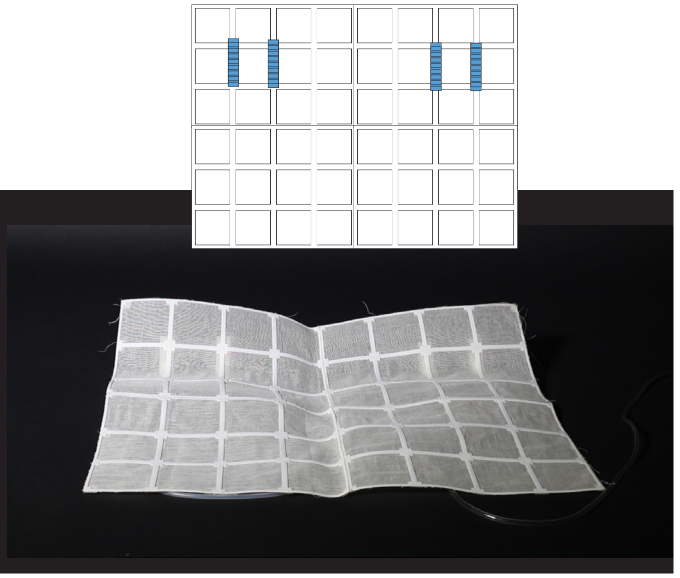


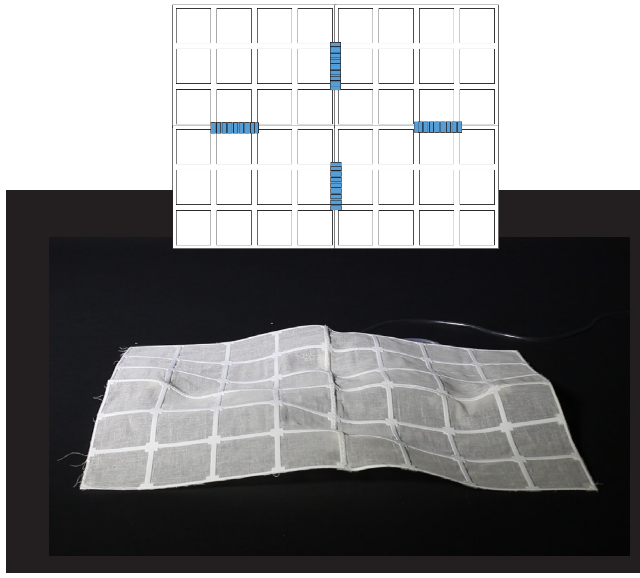


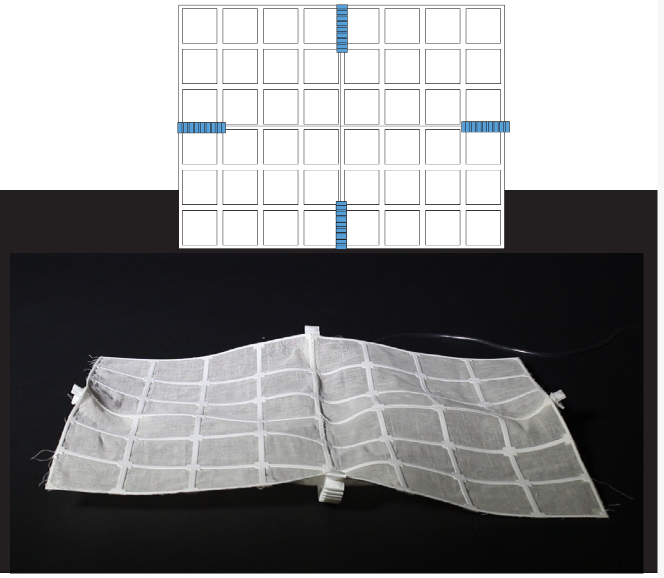


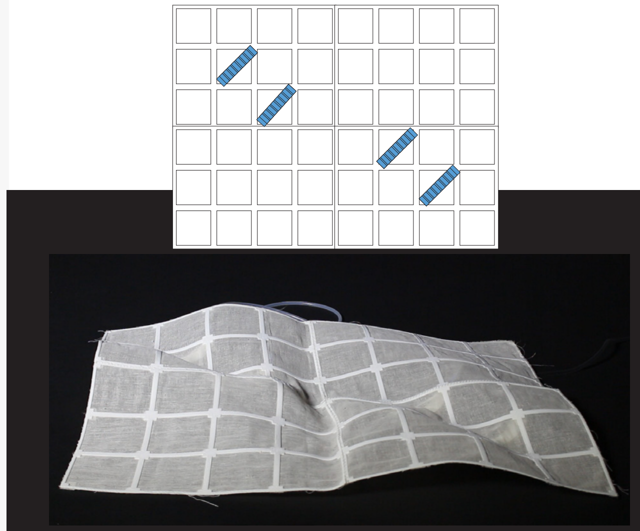


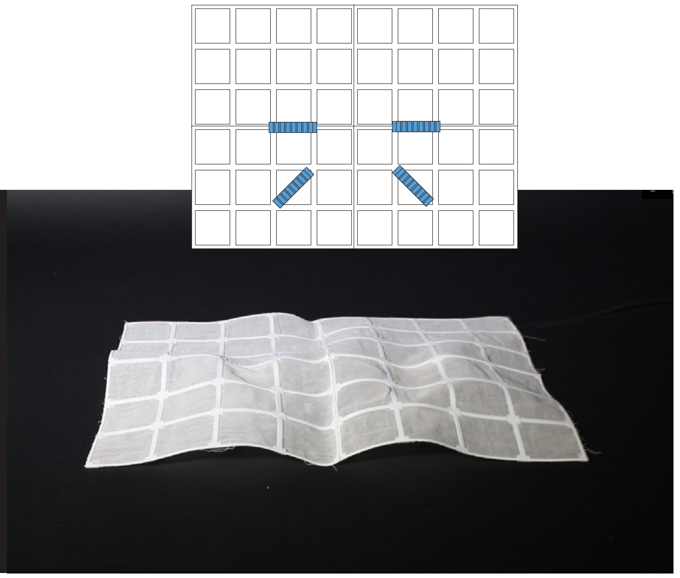


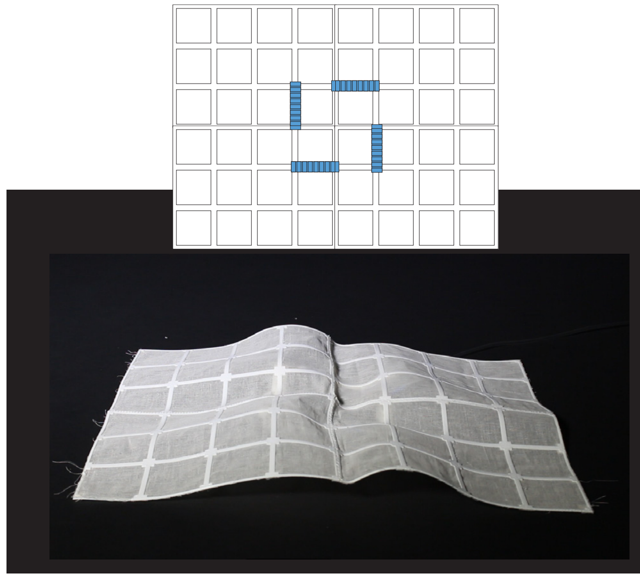


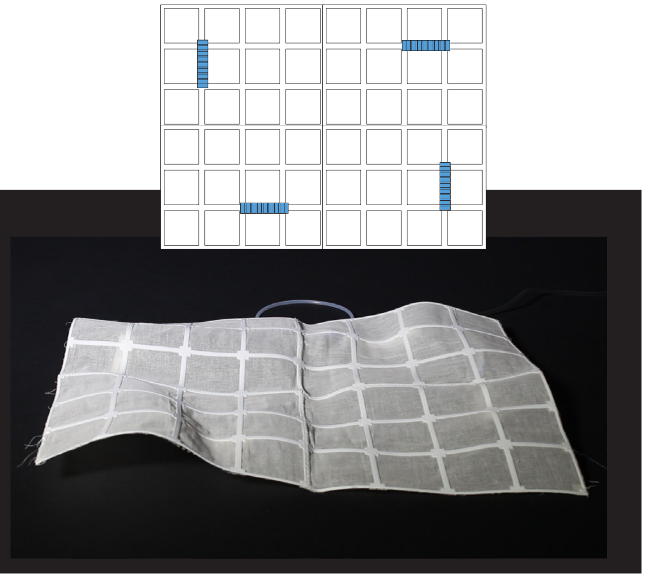


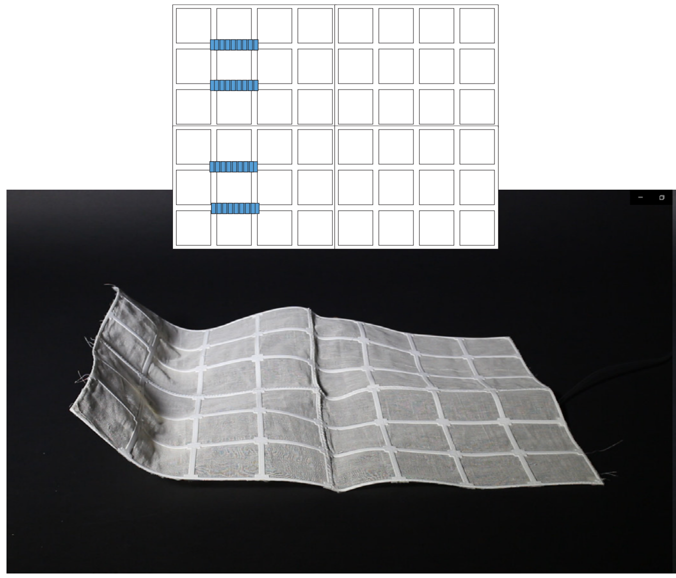


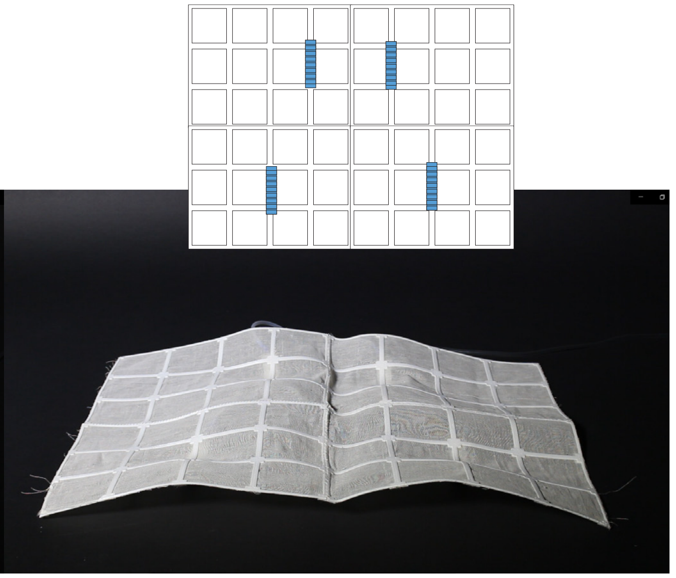






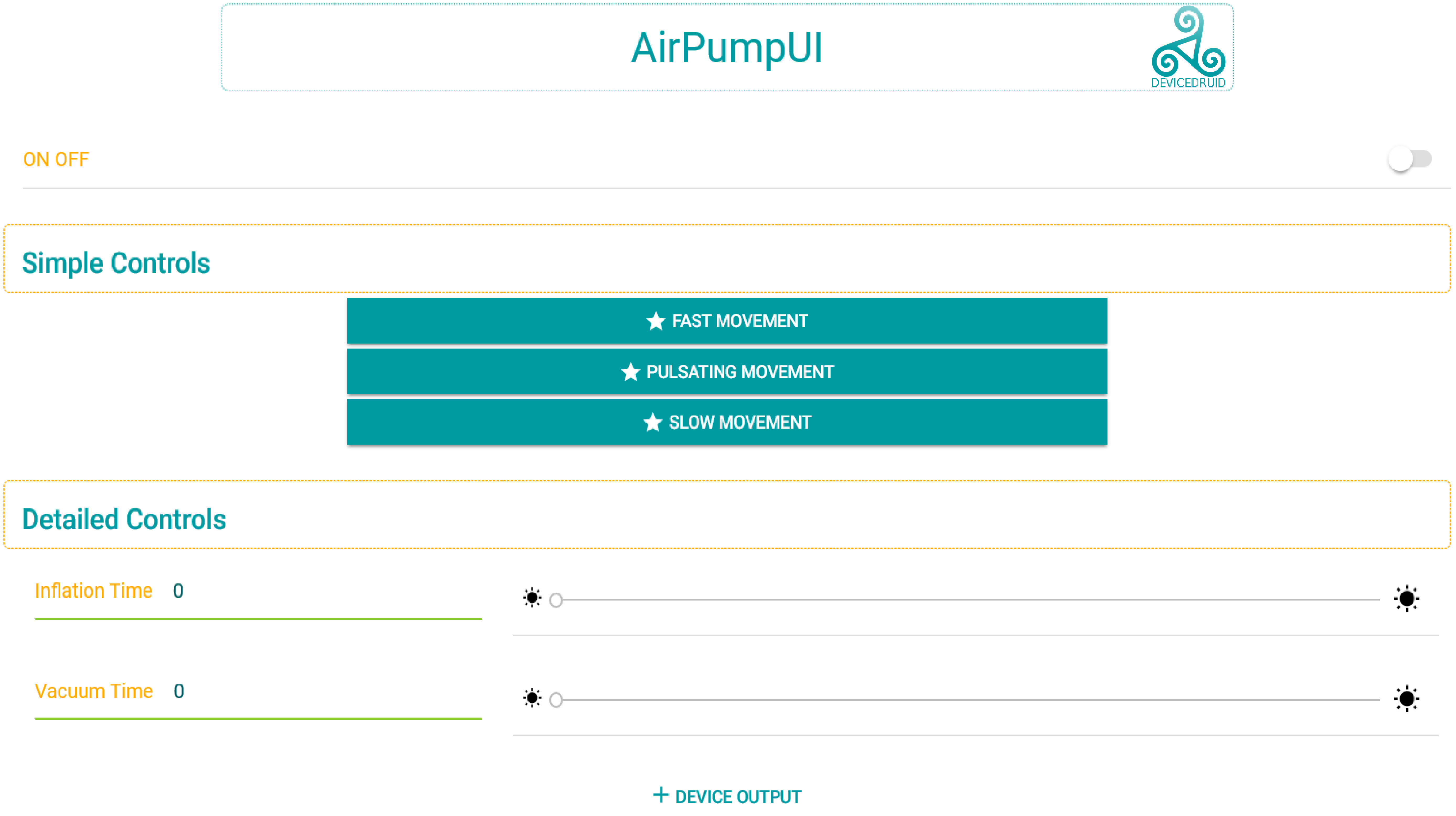






APPENDIX B

ARDUINO CODE



AirPumpUI

Simple Controls

Detailed Controls

Inflation Time 0

Vacuum Time 0

```
/*
 * AirPumpUI.ino -- part of the AirPumpUI project.
 * Setup of SerialUI and menu system
 * Jose Martinez Castro
 * TU Delft
 *
 * Copyright (C) 2021 Jose Martinez Castro
 *
 * Generated by DruidBuilder [https://devicedruid.com/],
 * as part of project «ec94fada4b2f442eb6d64ca7bc6e4a81yeLo0heVtn»,
 * aka AirPumpUI.
 *
 * Druid4Arduino, Device Druid, Druid Builder, the builder
 * code brewery and its wizards, SerialUI and supporting
 * libraries, as well as the generated parts of this program
 * are
 *           Copyright (C) 2013-2019 Pat Deegan
 * [https://psychogenic.com/ | https://inductive-kickback.com/]
 * and distributed under the terms of their respective licenses.
 * See https://devicedruid.com for details.
 *
 *
 * This program is distributed in the hope that it will be useful,
 * but WITHOUT ANY WARRANTY; without even the implied warranty of
 * MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.
 * THE ENTIRE RISK AS TO THE QUALITY AND PERFORMANCE OF THE
 * PROGRAM IS WITH YOU. SHOULD THE PROGRAM PROVE DEFECTIVE,
 * YOU ASSUME THE COST OF ALL NECESSARY SERVICING, REPAIR OR
 * CORRECTION.
 *
 * Keep in mind that there is no warranty and you are solely
 * responsible for the use of all these cool tools.
 *
 * Play safe, have fun.
 *
 */


/* we need the SerialUI lib */
#include <SerialUI.h>
#include «AirPumpUISettings.h»

/* our project specific types and functions are here */
#include «AirPumpUI.h»

// constants won't change
const int PUMP_PIN = 5;  // the Arduino pin, which connects to the IN pin of relay
const int VACUUM_PIN = 6;  // the Arduino pin, which connects to the IN pin of relay
const int PUMP_VALVE = 4;  // the Arduino pin, which connects to the IN pin of relay
const int VACUUM_VALVE = 7;  // the Arduino pin, which connects to the IN pin of relay

// Generally, you should use «unsigned long» for variables that hold time
// The value will quickly become too large for an int to store
unsigned long previousMillis = 0;        // will store last time LED was updated
unsigned long currentMillis = millis();

/*
 * In addition to any custom globals you declared,
 * here you have access to:
 *
 * *** MySUI -- the SerialUI instance.
 * Use it as you would the Serial device, e.g.
```

```
 *          MySUI.println(F(«Helloooo...»));
 *
 *
 * *** MyInputs -- a container for
 * values submitted by users. Contents:
 *
 *    MyInputs.ONOFF (Toggle)
 *    MyInputs.InflationTime (BoundedLong)
 *    MyInputs.VacuumTime (BoundedLong)
 *
 *
 *
 *
 */


// generated for usbserial platform

#if SERIALUI_VERSION_AT_LEAST(3,2)
// all is well, you have a valid SerialUI lib installed...
#else
#error «Need SerialUI version 3.2 or greater»
#endif


/* **** standard setup() function **** */
void setup() {

        if (!SetupSerialUI()) {
                DIE_HORRIBLY(F(«Problem during setup»));
        }

        pinMode(PUMP_PIN, OUTPUT);
  pinMode(VACUUM_PIN, OUTPUT);
  pinMode(PUMP_VALVE,OUTPUT);
  pinMode(VACUUM_VALVE,OUTPUT);

}


void loop() {

  /* We checkForUser() periodically, to see
  ** if anyone is attempting to send us some
  ** data through SerialUI.
  **
  ** This code checks at every pass of the main
  ** loop, meaning a user can interact with the
  ** system at any time.  Should you want to
  ** check for user access only once (say have a
  ** N second wait on startup, and then forgo
  ** allowing SerialUI access), then increase the
  ** delay parameter and use checkForUserOnce(), e.g.
  **
  **    mySUI.checkForUserOnce(15000);
  **
  ** to allow 15 seconds to connect on startup only.
  **
  ** Called without parameters, or with 0, checkForUser
  ** won't delay the program, as it won't block at all.
  ** Using a parameter > 0:
  **        checkForUser(MAX_MS);
```

```
  ** will wait for up to MAX_MS milliseconds for a user,
  ** so is equivalent to having a delay(MAX_MS) in the loop,
  ** when no user is present.
  */
  if (MySUI.checkForUser()) {

    /* Now we keep handling the serial user’s
    ** requests until they exit or timeout.
    */
    while (MySUI.userPresent()) {
      // actually respond to requests, using
      MySUI.handleRequests();

        currentMillis = millis();
       if(MyInputs.ONOFF == «ON» && MyInputs.InflationTime > 0 && MyInputs.VacuumTime > 0)
        {
          previousMillis = currentMillis;
          currentMillis = millis();
          VACUUMOFF();
          delay(200);
          PUMPON();

            while ((currentMillis - previousMillis) <= long(int(MyInputs.InflationTime) * 1000) && MyInputs.ONOFF ==
«ON»){
            currentMillis = millis();
            delay(100);
            MySUI.handleRequests();
          }

          previousMillis = currentMillis;
          currentMillis = millis();

          PUMPOFF();
          delay(200);
          VACUUMON();

        while ((currentMillis - previousMillis) <= long(int(MyInputs.VacuumTime) * 1000) && MyInputs.ONOFF == «ON»){
            currentMillis = millis();
            delay(100);
            MySUI.handleRequests();
          }
        }
        else
        {
          PUMPOFF();
          VACUUMOFF();
        }



                // you could add a quick task here, to perform
                // after *every* request, but it’s better to use
                // the setUserPresenceHeartbeat-related methods
    }
  } /* end if we had a user on the serial line */

  // add code here to run when no ones around


}
```

```
void PUMPON(){
   analogWrite(PUMP_PIN, 255);
   digitalWrite(PUMP_VALVE, HIGH);
}

void PUMPOFF(){
   analogWrite(PUMP_PIN, 0);
   digitalWrite(PUMP_VALVE, LOW);
}

void VACUUMON(){
   digitalWrite(VACUUM_VALVE, HIGH);
   delay(200);
   analogWrite(VACUUM_PIN, 150);

}

void VACUUMOFF(){
   analogWrite(VACUUM_PIN, 0);
   digitalWrite(VACUUM_VALVE, LOW);
}
```

APPENDIX C

PROJECT BRIEF

DESIGN FOR our future

TUDelft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT
Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy".
Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name Martinez Castro
initials JF given name Jose Francisco
student number 5045282
street & no.
zipcode & city
country
phone
email

Your master programme (only select the options that apply to you):
IDE master(s): ● IPD ○ DfI ○ SPD
2nd non-IDE master:
individual programme: - - (give date of approval)
honours programme: ○ Honours Programme Master
specialisation / annotation: ○ Medisign
○ Tech. in Sustainable Design
○ Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair Prof. Dr. Elvin Karana dept. / section: Emerging Materials
** mentor Dr. Jun Wu dept. / section: Materials Manufacturin
2nd mentor Alice Buso- Phd Candidate on Smart Textiles (TU Delft)
organisation: TU Delft
city: Delft country: Netherlands

comments (optional)

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

Procedural Checks - IDE Master Graduation

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair Prof. Dr. Elvin Karana date 02 - 03 - 2021 signature

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: EC
Of which, taking the conditional requirements into account, can be part of the exam programme EC
List of electives obtained before the third semester without approval of the BoE

○ YES all 1st year master courses passed
○ NO missing 1st year master courses are:

name date - - signature

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: ○ APPROVED ○ NOT APPROVED
Procedure: ○ APPROVED ○ NOT APPROVED

comments

name date - - signature

Shape Changing Alive-like Pneumatic Textile Interfaces project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 22 - 02 - 2021

16 - 07 - 2021 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The context of the project is shape changing alive-like textile interfaces using pneumatic meta materials. Meta materials are artificial structures that are defined by their macro structure rather than their microscopic chemical structure. The pneumatic aspect of these materials is that their shape can be controlled with variation of high and low pressure within its internal structure of channels. This pneumatic actuation principle is similar to the masters research on pneumatic soft robotics and student research on pneumatic chiral meta structures [7][10]. Refer to Figure 1 for visual examples of pneumatically actuated shape shifting interfaces.

"Alive-like" user interfaces that are inspired by natured can, therefore, be achieved by using the unique kinetic properties of this meta-material to create structures that move like living things. Studio Drift's Shylight is an example of product concept that uses kinetic elements to create a kinetic installation that mirrors the circadian rhythm of real flowers. Other works in the department have explored the "alive-like" interfaces using shape memory alloys, such as mimicking the movement of caterpillars or giving everyday objects, such as a fruitbowl, "alive-like" kinetic qualities using SMAs [1][8]. Pneumatic meta-materials have the possibility of solving some of the complications found with SMAs by using a single elastic material that is actuated by a controlled pneumatic input. Refer to Figure 2 for visual examples of shape morphing structures displaying "alive-like" qualities.

Textiles are one of the oldest human-used materials and provide a sense of familiarity for interaction (Ex: stretch, fold, etc.). When combined with the pneumatic meta-materials, textiles have the potential to display alive-like qualities that are more approachable to people. Our idea is, therefore, to use textiles as the medium of introducing new smart interactions to people since they already feel comfortable with the material's behavior.

My main stakeholders are Dr. Jun Wu, who specializes in computational and generative design, and Dr. Elvin Karana, who specializes in material experience and the material driven design methodology. Dr. Wu and Dr. Karana have previously collaborated on graduation projects such as Interwoven, a project using a combination of digital fabrication and material experience with plant roots to study the material's potential in product design [12].

Dr. Jun Wu has experience with the technical specifications and computational design of these materials with his previous work on the soft robotics and pneumatic chiral meta structures [9][10]. His expertise in this project will help me to characterize the technical specifications of the material, so that its behavior and performance can be predicted for use in product design.

Dr. Elvin Karana has experience in characterizing both the technical and experiential aspects of novel materials with recent works exploring the experience created by materials and the possibilities of materials that are/or feel "alive" to induce "livingness" as a quality of everyday products [2]. Her expertise in this project will aid in providing support for the use of the Material Driven Design method to characterize the experiential aspects of the meta-material focusing on "alive-like" expressions and identify the context for the best use of this material.

Currently, the main limitation is the lack of knowledge about the technical and experiential properties of this meta material concerning the predictability of its shape changing behavior, fabrication methods, and "alive-like" interfaces and expressions. My goal is to fill this knowledge gap to open up the possibilities for the use of this material as a design material.

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introduction (continued): space for images

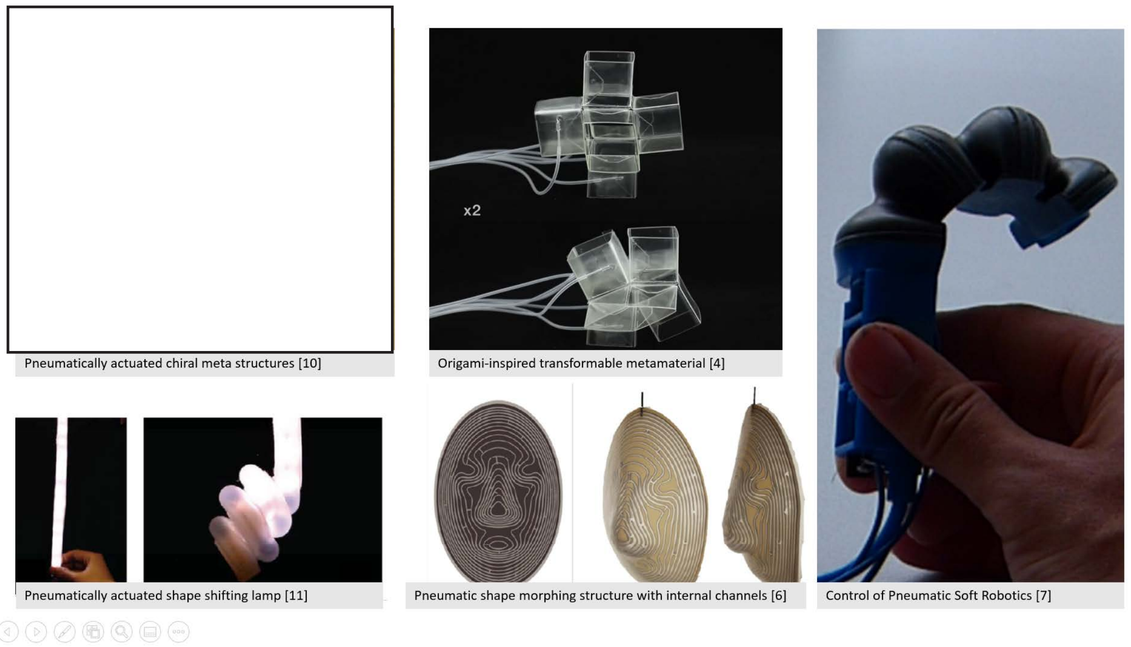

Pneumatically actuated chiral meta structures [10]
Origami-inspired transformable metamaterial [4]
Pneumatically actuated shape shifting lamp [11]
Pneumatic shape morphing structure with internal channels [6]
Control of Pneumatic Soft Robotics [7]

image / figure 1: Pneumatically actuated shape shifting interfaces

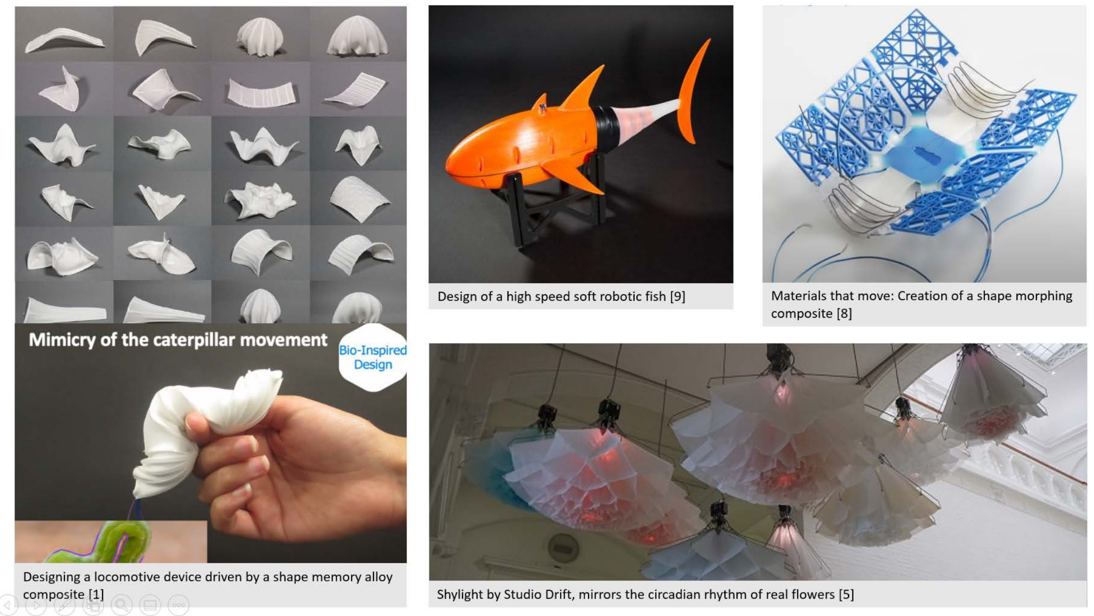

Design of a high speed soft robotic fish [9]
Materials that move: Creation of a shape morphing composite [8]
Designing a locomotive device driven by a shape memory alloy composite [1]
Shylight by Studio Drift, mirrors the circadian rhythm of real flowers [5]

image / figure 2: Shape morphing structures displaying "alive-like" qualities

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

This project aims to explore the possibilities that a new material poses for creating "alive-like" interactions that can be integrated into our daily products. The problem constitutes of characterizing pneumatic meta materials combined with textiles in its technical and experiential properties for the use of "alive-like" interfaces. Specifically, the structure type to be research will be on 2D manufactured structures that can be actuated to form a 3D form with variation in air pressure. The characterization properties to be researched include:

- Shape changing principles and how to predict the 3D form that is created from the 2D structure
- Fabrication techniques related to the prototyping of the final concept
- Shape changing user interfaces and alive-like expressions

Once the material properties are known, a context will be selected and a product concept will be created using the meta-material to best display its most important physical and experiential qualities.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in “problem definition”. Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

The assignment is to use the Material Driven Design Method to characterize the pneumatic textile meta material and produce a product concept that displays its most important qualities. This will be focused on portraying the materials kinetic properties to create "alive-like" interfaces that can be interacted with. The aim of the final concept is to displays these special properties to the public and educate on its possibilities for future design works.

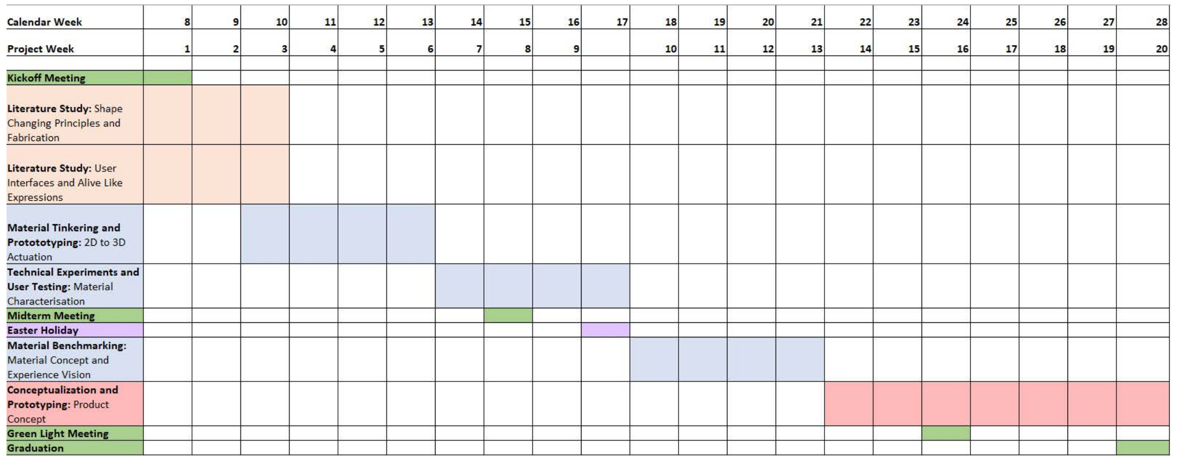
The expected solution is an interactive, "alive-like" product that is inspired by a natural phenomenon created by using the properties of the pneumatic meta-materials. As the capabilities of the pneumatic textile meta-material still require further specification, which will be carried out during the project, the final concept outcome will be defined later in the project after the Material Concept and Experience Vision have been defined as guided by the MDD method. The final product category will be a public interactive installation or product concept (with the ultimate goal of being displayed in an exhibit at Dutch Design Week) and does not need to be mass manufactured.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 22 - 2 - 2021

16 - 7 - 2021 end date



Calendar Week	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Project Week	1	2	3	4	5	6	7	8	9		10	11	12	13	14	15	16	17	18	19	20
Kickoff Meeting	🟩																				
Literature Study: Shape Changing Principles and Fabrication	🟧	🟧	🟧																		
Literature Study: User Interfaces and Alive Like Expressions	🟧	🟧	🟧																		
Material Tinkering and Protototyping: 2D to 3D Actuation			🟦	🟦	🟦	🟦															
Technical Experiments and User Testing: Material Characterisation							🟦	🟦	🟦	🟦											
Midterm Meeting								🟩													
Easter Holiday										🟪											
Material Benchmarking: Material Concept and Experience Vision											🟦	🟦	🟦	🟦							
Conceptualization and Prototyping: Product Concept															🟥	🟥	🟥	🟥	🟥	🟥	🟥
Green Light Meeting																	🟩				
Graduation																					🟩

The project schedule follows the Material Driven Design method to characterize the material in its technical and experiential qualities [3]. Similar past Masters projects, such as Interwoven and the caterpillar SMA project, used a similar task division throughout the semester [1][12]. The project begins by literature study of the technical capabilities of the meta-material and exploration of alive-like expressions possibilities. It then continues to a tinkering phase consisting of iterative 3D modeling and 3D printing prototyping to test the insights found during the literature review. Once the material has been tinkered with, technical experiments will be conducted to characterize the material and user testing will be carried out to evaluate its alive-like expression potential. These results will be then be presented in the midterm meeting. Next, a material concept and experience vision will be created that will determine the scope for the final product concept to be created. Finally, using the combination of the technical/experiential specifications of the material with the proposed vision, a final conceptualization stage will be carried out to showcase the material's qualities as an interactive product concept/installation.

The uncertain Covid situation will have some impact on the project compared to previous graduation projects. Thankfully, the early parts of the project will require minimal lab equipment, only using 3D printing, textiles, and a pneumatic pump, which will be available through the Applied Labs. The rest of the early work such as literature studies and 3d modeling can be done remotely if necessary. Additionally, I will have a workplace at the faculty two days a week, which will allow me to collaborate with peers. There will, nonetheless, be some drawbacks to the situation. As opposed to previous years, many of the early meetings with supervisors might have to be conducted online, such as the kickoff meeting. In the later stages of the project, a creative, remote method for user testing might need to be created if F2F meetings are not possible, such as showcasing the material prototypes through video. Despite some drawbacks, the project is still well suited for adjusting to remote work, if necessary.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

I want to use my previous knowledge in biomechanics to create designs that can inspire and educate people about new sustainable materials and nature-inspired innovations. The project has the perfect balance of technical research and nature inspired design, which is what I am hoping to be working on in my future career.

For the research phase, I will use my experience in research lab work to study and experiment with this novel material. My recently acquired skills in user testing and interviewing will be useful to perform user testing during the experiential characterization of the material. For the tinkering and prototyping phase, my skills in 3D modeling and 3D printing (from mechanical engineering internships and previously owning a personal 3D printer) will help me to quickly iterate between designs to better understand the material behavior. As per the design concept phase, I will use the VIP tools learned during the Advanced Concept Design course (in combination with the MDD method) to find the best application for the meta material for product design. Additionally, I have extensive experience in electronics and software design, which will be useful when designing the interactive and control system aspects of the final concept.

I will also be able to pursue my own personal learning goals by studying computational design with the guidance of Dr. Wu and an exploration of material driven experiences guided by nature with the guidance of Dr. Karana. Since I hope to work with sustainable materials and nature inspired designs in the future, I want to master the Material Driven Design method by the end of the graduation project. Finally, as mentioned before, it would be an ultimate goal to showcase such a design project in an exhibition like DDW, therefore, I would love to learn more about bio-inspired installations.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.