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Conveying Emotions through Movements and Materials of Soft Robots in the Context of Smart Jewelry

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Abstract

Humans have been wearing jewelry for thousands of years. We convey versatile information to the environment by wearing jewelry, such as our position in society or aesthetic preferences. Enhancing jewelry with movable parts could open up new channels of communication, as previous research has shown that shape-changing objects generally possess the ability to convey emotions to the observer. Soft robots would be well-suited to giving jewelry the ability to change shape because of their organic movements. Moreover, they could be worn safely and comfortably on the body due to their soft and pliable nature. In our study, we present a prototypical shape-changing necklace. It was presented to participants in a user study, varying the outer material as well as the shape, frequency, and amplitude of the movement, to investigate whether the necklace could convey discernible emotions to the viewer. Our results show that specific shapes as well as variations in frequency and amplitude determine how a movement is perceived. However, we were not able to provide evidence that the material influences the emotions conveyed. Furthermore, we observed that the presented shape-changing necklace was often associated with human-related concepts such as facial expressions, gestures, and social interactions. Additionally, we provide a detailed description of the fabrication process used for fiber-reinforced soft robots and improvements we made to said process as well as a description of the controller used for actuation. Our results can help designers establish shape-changing abilities in smart jewelry as a channel for communicating emotions by utilizing soft robots. Furthermore, we believe that our findings apply to other application areas, for example, social robots.

Überblick

Menschen tragen seit Tausenden von Jahren Schmuck. Durch das Tragen von Schmuck übermitteln wir der Umwelt vielfältige Informationen wie unsere Stellung in der Gesellschaft oder ästhetische Vorlieben. Die Erweiterung von Schmuck mit beweglichen Teilen könnte neue Kommunikationskanäle eröffnen, da vorherige Forschung gezeigt hat, dass sich formverändernde Objekte grundsätzlich dazu eignen, dem Betrachter Emotionen zu vermitteln. Soft Robots würden sich aufgrund ihrer organischen Bewegungen dazu eignen, Schmuckstücken die Möglichkeit zu geben, ihre Form zu verändern. Außerdem könnten sie aufgrund ihrer weichen und nachgiebigen Beschaffenheit sicher und angenehm am Körper getragen werden. In unserer Studie stellen wir eine prototypische Kette vor, welche in der Lage ist, ihre Form zu ändern. In einer Nutzerstudie wurde diese Teilnehmern präsentiert, wobei das Außenmaterial sowie die Form, Frequenz und Amplitude der Bewegung variierte, um zu untersuchen, ob die Halskette dem Betrachter unterscheidbare Emotionen vermitteln kann. Unsere Ergebnisse zeigen, dass Variationen in Frequenz und Amplitude und bestimmte Formen dazu geeignet sind, unterscheidbare Emotionen zu kommunizieren. Darüber hinaus fanden wir heraus, dass die präsentierten Bewegungen oft mit menschenbezogenen Konzepten wie Mimik, Gesten und sozialen Interaktionen assoziiert wurde. Wir konnten jedoch nicht nachweisen, dass das Material die vermittelten Emotionen beeinflusst. Außerdem lieferten wir eine detaillierte Beschreibung des verwendeten und verbesserten Herstellungsverfahrens für Fiber-Reinforced Soft Robots und der von uns für deren Betätigung verwendeten Steuerung. Unsere Ergebnissen können Designern dabei helfen, sich in der Form veränderbare Schmuckstücke zu entwerfen, welche in der Lage sind, Emotionen zu kommunizieren. Darüber hinaus sind unsere Erkenntnisse auch für andere Anwendungsbereiche wie beispielsweise Social Robots hilfreich.

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Finally, thank you, Oma!

Conventions

Throughout this thesis we use the following conventions.

The whole thesis is written in American English.

The singular *they* is used to include people of any gender identity. We also use it to prevent attribution to a specific person.

All files linked to the GitLab repository "thesis-digital-appendix" were additionally handed in on a flash drive together with the printed versions of this thesis.

Chapter 1

Introduction

Wearing jewelry as a way of communication

One of the main purposes of conventional jewelry like rings, necklaces, brooches, and others is to adorn the wearer. In addition, jewelry communicates with the environment by conveying certain information about the wearer [Versteeg et al., 2016]. For example, it can tell something about the wearer's wealth, relationship to another person, taste, or other aspects of their personality.

Electronic components complement smart jewelry

The communicative capabilities of jewelry increased vastly over the past decade due to the incorporation of electronic components, as shown by the research field of *smart jewelry* (often also called *computational jewelry* or, in British English, *smart jewellery*) [Silina and Haddadi, 2015; Jarusriboonchai and Häkkilä, 2019]. The variety, capabilities, and miniaturization of electronic components enabled designers to create smart jewelry with novel output channels compared to conventional jewelry [e.g., Fortmann et al., 2016; Pateman et al., 2018; Inget et al., 2019; Buruk et al., 2021].

Smart jewelry is capable of changing surface texture and shape

The changeability of its shape [Kao et al., 2017] and surface texture [Jarusriboonchai et al., 2020] are smart jewelry capabilities that offer great potential for novel interactions. Shape change allows for dynamic adjustment of the smart jewelry's outer appearance. For example, a piece of jewelry could adjust its appearance according to the situation or the wearer's clothing.

Shape change can convey emotions

In other fields, especially in the area of *(social) robotics*, shape change has been researched as a way of communicating emotions [e.g., Desai et al., 2019; Bucci et al., 2018; Vekemans et al., 2021]. Strohmeier et al. [2016], Hu and Hoffman [2019], Davis [2015b], and others have discovered that modifying specific characteristics of an object's shape change (such as frequency, amplitude and the shape itself) can convey different emotions.

Soft robots are well suited for use in smart jewelry

One way of achieving shape change in objects and surfaces is through *soft robots*. Soft robots are a subgroup of robots that are characterized by soft materials like silicone [e.g., Ilievski et al., 2011; Galloway et al., 2013; Gohlke et al., 2016; Hu et al., 2018] or fabric [e.g., Davis, 2015b; Albaugh et al., 2019] as a primary material. Furthermore, soft robots often move in an especially natural and organic manner. The aforementioned properties of soft robots make them ideal components for smart jewelry design.

Can emotions conveyed by shape-changing smart jewelry be controlled?

We can conclude from prior work that shape change can be utilized to communicate emotions, that it is in the nature of jewelry to communicate, and that soft robots fit the context of smart jewelry. However, the intersection of these three fields has not been well explored. Therefore, in this work, we investigate whether the emotions communicated by a shape-changing soft robot used in smart jewelry can be controlled by manipulating the properties of the movement.

Does the material influence the conveyed emotion?

The selection of the materials used for a piece of jewelry is a crucial part of the design process [Koulidou and Mitchell, 2021]. When designing smart jewelry meant to convey certain emotions, the material likely influences the way a particular movement is interpreted [van Waveren et al., 2019]. Thus, our second point of interest is on whether the surface material of a soft robot used in smart jewelry can influence the emotions conveyed by its shape change.

Chapter 2

Related work

In this work, knowledge primarily from three major research fields is combined and supplemented by new insights. First, we combine approaches from the fields of smart jewelry and soft robotics. These fields both have their roots in human-computer interaction, and combining knowledge from these areas allows us to create a prototypical shape-changing piece of smart jewelry. The third field, psychology, equips us with methods to make well-founded statements regarding emotions conveyed.

This work aims for contribute to existing knowledge on the intersection smart jewelry, soft robotics, and psychology

2.1 Prior Theses

This thesis builds on the work of prior research conducted by our chair. Results presented in bachelor and master theses are not considered of the same quality as peer-reviewed work published in conference papers or journal articles. Therefore, we want to distinguish these two types of related work. However, to show which prior work served as a basis for this work, we have chosen to present the connected theses in this Section.

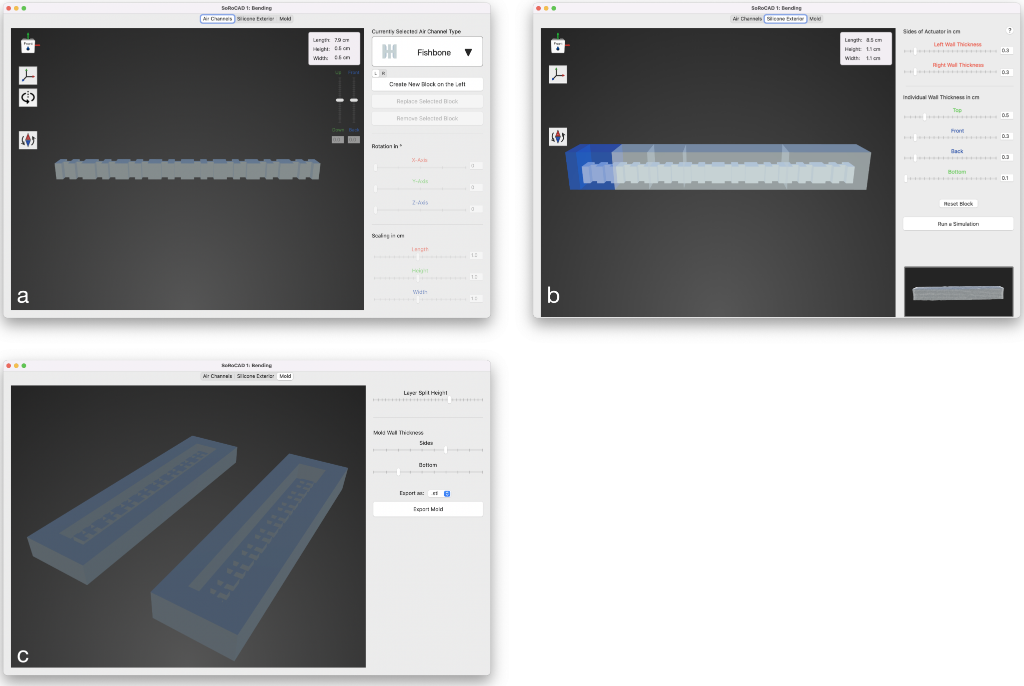

Figure 2.1: SoRoCAD consists of three stages. First, the air chambers are defined *(a)*. Second, the exterior (i.e., the wall thickness around the air chambers) is configured *(b)*. Finally, the molds are exported *(c)*. The software is shown in the version published in the thesis by Sahabi [2021].

2.1.1 SoRoCAD

In order to facilitate the process of manufacturing soft robots actuated by compressed air, SoRoCAD, a software for designing and generating molds, was developed. The software was developed [Timchenko, 2019], evaluated [Strüver, 2020], and improved [Sahabi, 2021] throughout three theses.

SoRoCAD is a tool for creating silicone-based soft robots

SoRoCAD is a tool for creating silicone-based soft robots. The software allows the user to design a soft robot in three steps. First, the internal structure of the soft robot's air chambers is defined (cf. Figure 2.1a). They define which inner part of the soft robot can later be inflated. The second step defines the soft robot's exterior around the air chambers (cf. Figure 2.1b). The software allows the definition of different wall thicknesses for the soft robot. By varying the thickness of the walls, the soft robot can be deformed in a certain way when pressurized. For example, two opposing walls with different thicknesses cause the soft robot to bend toward the thicker wall. This principle also allows for more complex designs. Before exporting the final molds, the user can view a simulation of the expected movement of the soft robot when it is pressurized.

The software is primarily focused on, but not limited to, finger-shaped actuators [Sahabi, 2021]. This focus is partially due to the subsequent manufacturing process. The exported molds are used to cast two halves of the soft robot (cf. Figure 2.1c). This approach is simple, but it limits the designs in their geometries. For example, fabricating a design that consists of air chambers that cannot be cut by a plane into two convex shapes might be impossible.

Finger shaped actuators with simple air chambers are the main target of SoRoCAD

The molds used to cast the silicone can be fabricated with a 3D printer. The process for casting silicone is detailed in Section 3.5.1). After the silicone is fully cured, the halves are removed from the molds and glued together with liquid silicone. By only using silicone on the edges, the cavities in the halves form a hollow air chamber. After curing the added silicone, the soft robot can be punctured with a cannula to be supplied with compressed air.

2.1.2 Thesis on Shapes and Movements

Nedorubkova [2021] investigated possible shapes and movements for soft robotic actuators made from silicone in their thesis. They performed multiple brainstorming sessions to let participants imagine possible shapes and movements of soft robots. Their brainstorming sessions resulted in 36 distinct shape ideas with corresponding movements. They assigned each shape idea to one of six categories according to movement type (“Expanding and elongation”, “Bending” , “Waving” , “Twisting and Rotating”, and “Compression” [Nedorubkova, 2021]) and created virtual 3D models of them (cf. Figure 2.2)

User study to explore possible soft robot designs

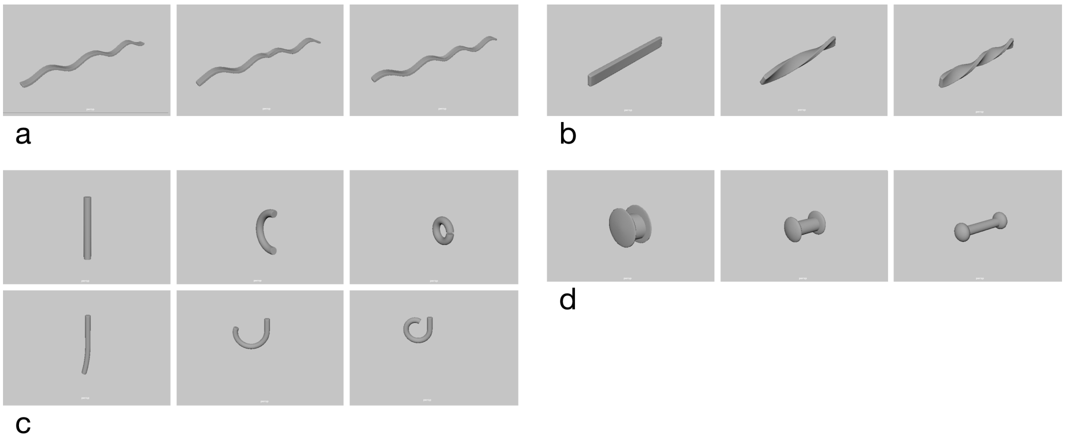

Figure 2.2: In their study Nedorubkova [2021] categorized the soft robots from their brainstorming session and created 3D animations (e.g., *a-d*). As inspiration for our design, we used soft robots from the categories *Waving (a)*, *Twisting and Rotating (b)*, *Bending (c)*, and *Expanding and elongation (d)*.

Soft robots are often associated both with living beings and with rigid objects

Results from this thesis are valuable starting points for our research

In the subsequent user study, Nedorubkova [2021] presented animations of the 3D models to participants and asked them what they associate with the shapes, and whether they could imagine real-world applications for the shapes. They discovered that participants often associated soft robots with living organisms and everyday objects. Furthermore, they reported that the soft robots were also often associated with rigid objects. Some figures were apparently perceived as more ambiguous than others, as Nedorubkova [2021] reported some shapes were associated with the same objects by nearly all participants. When being asked for real-world applications for the presented soft robot, the participants reported jewelry as one potential application for soft robots. This finding supports our goal of embedding soft robots into smart jewelry. The identified movement groups provide a valuable base for our study.

2.2 Smart Jewelry

Smart jewelry is used in human-computer interaction to describe a subgroup of wearable devices. The spectrum ranges from functionally driven smart jewelry [Pateman et al., 2018] to unique artistic pieces [e.g., Versteeg et al., 2016; Koulidou and Mitchell, 2021]. In functional smart jewelry, the pieces are often seen as an interaction surface [Koulidou and Mitchell, 2021; Arora et al., 2019] to control the jewelry itself (e.g., *IlluminEar* and *Rhythm Shoes* by Buruk et al. [2021], *Kino* by Kao et al. [2017], and the *Tangible Apps Bracelet* by Fortmann et al. [2016]), or other devices [Kao et al., 2015; Patel and Hasan, 2018]. This area of smart jewelry must still be distinguished from *wearables*. The line distinguishing the concepts is not always clearly defined, but for *wearables*, the focus usually lies exclusively on interaction and not on external appearance [e.g., Chen et al., 2013; Chan et al., 2013].

Several terms describe the fusion of jewelry and technology, focusing on characteristics typical of jewelry

In the existing body of research, the terms *Interactive Jewelry* [Versteeg et al., 2016], *Digital Jewelry* [Miner et al., 2001], and *Art Digital Jewellery* [Koulidou and Mitchell, 2021] have emerged. They often describe similar concepts but differ in their focus and design approaches. They all share an emphasis on their delimitation from wearables by focusing on properties associated with conventional jewelry. Versteeg et al. [2016] defined *Interactive Jewelry* similarly to our definition of *smart jewelry* as a "crossing of wearable technology and jewelry." This is quite similar to the definition of *Digital Jewelry*, one of the earliest terms in this field. Miner et al. [2001] describes it as wearable technology that does not appear futuristic or overloaded with technical components. Instead, these objects should offer characteristics typical of jewelry, like an attractive and aesthetic appearance. *Art Digital Jewellery* [sic] is a relatively new concept that Koulidou and Mitchell [2021] introduced. Their approach describes on-body jewelry crafted in an artistic process which focuses on the wearer's personality and is enhanced by electronics. Koulidou and Mitchell [2021] therefore offer a narrower term focused on art to define this smart jewelry subsection.

Smart jewelry incorporating shape-change are rare

Smart jewelry often provides an output either privately for the wearer [e.g., Fortmann et al., 2016; Versteeg et al., 2016; Rantala et al., 2018; Inget et al., 2019] or perceivable for others [e.g., Koulidou and Mitchell, 2021; Buruk et al., 2021; Häkkilä et al., 2020; Inget et al., 2019]. However, not many examples exist utilizing shape change as an output chan-

Figure 2.3: "Kinetic wearables transitioning from brooch to necklace[a]", by Jimmy Day, licensed under CC BY-NC-SA 4.0[b] shows how multiple Rovables units [Dementyev et al., 2016] can be utilized to create a shape-changing composition by moving from a necklace-like arrangement *(left)* to a brooch-like arrangement *(right)* [Kao et al., 2017].

[a]www.media.mit.edu/projects/kino-kinetic-wearable/overview/
[b]creativecommons.org/licenses/by-nc-sa/4.0/

nel. Kino by Kao et al. [2017] utilized Rovables [Dementyev et al., 2016] to create other shape-changing jewelry attached to the wearer's clothing. The Rovables enabled the jewelry pieces to move around the cloth's surface to incorporate new shapes (cf. Figure 2.3).

Emotional bond to smart jewelry through personal data or rituals

Smart jewelry research on its connection with emotions has already been conducted. Most of this research is concerned with the emotional bond or the meaning jewelry can provide for the owner. This is, for example achieved by storing valuable personal data on the jewelry. This approach was chosen for the jewelry pieces *Pix*, *Memento*, and *Leth* described by Versteeg et al. [2016] and by Rantala et al. [2018]. Another approach is the communication of intimate information between two people as done by *Fibo* which communicates fetal movements to the partners jewelry [Patel and Hasan, 2018]. Furthermore, an emotional bond to a piece of smart jewelry can be established through habitually wearing a piece of smart jewelry close to the body and using or experimenting with it over an extended period [Koulidou and Mitchell, 2021]. These examples all share a common focus on the emotional connection of the wearer to the object or something it represents.

Figure 2.4: Picture by Jarusriboonchai et al. [2020] showing the *multi-wear pins* that can be used to communicate the wearer's own emotional state to the partner's pin through rotation of a dial

An example of communicating one's emotional state is provided by the *multi-wear pins* presented by Jarusriboonchai et al. [2020] (cf. Figure 2.4). Each pin consists of an electrochromic display with a dial attached to the back. *Multi-wear pins* are intended to be worn by couples and provide the ability to send visual patterns to one wearer that encode the other wearer's emotional state. The patterns are sent by turning the dial in a certain way. Jarusriboonchai et al. [2020] did not state whether the patterns are predefined or generated dynamically. In both cases, the communication involves two people who know each other well, which likely does not require a universal language of emotion-conveying patterns. Due to the intimate setting, wearers may not want the meaning of the pattern to be deciphered by others.

Multi wear pin allows communicating emotional state by surface texture change

In addition, there is evidence that preferences for the placement of smart jewelry on the body are influenced by its communication intentions. Inget et al. [2019] showed that smart jewelry intended to be used in a social context is often placed on the head and neck or the arms and hands. In

Smart jewelry intended to communicate public information can be placed higher on the body their workshop, they let participants place imaginary smart jewelry on different parts of the body. Afterward, they performed two rounds of relocating the jewelry.

In the first round, participants were to assume that the previously imagined jewelry displayed public information. With this assumption in mind, the participants were to then relocate the pieces to appropriate positions on the body, or remove them. The pieces that were left on the body were mainly located on the upper part, most of which were already there initially. In the second round, Inget et al. [2019] had the participants perform the same task again. This time it was assumed that the jewelry displayed private information. This resulted in jewelry being moved to the hands and fingers. Combining these two findings suggests that jewelry intended to show public information is best placed on the head and neck [Inget et al., 2019]. This is both for visibility and to keep areas like the hands and fingers free for jewelry providing private information.

2.3 Soft Robotics

The field of soft robotics incorporates several disciplines, including robotics [e.g., Polygerinos et al., 2015], elector mechanics [e.g., Suzumori et al., 1991], human-computer/robot interaction [e.g., Hu and Hoffman, 2019; Bucci et al., 2018], and material science [e.g., Narang et al., 2018]. Soft robot designs are often based on models in nature. Since the movements executed by soft robots mimic those of living organisms, they appear smooth and natural.

Soft robots consist mainly of soft materials

As the name suggests, an essential factor shared among soft robots is the absence of rigid materials. Instead, they are made of soft materials like textiles or elastomers. These soft materials constitute a substantial part of the soft robots to ensure a flexible nature overall. However, soft robots also combine these softer materials with stiffer ones to achieve the necessary composition for the desired shape.

Soft robots are allowed to be less complex

Soft robots, like conventional rigid robots, are programmable objects created to carry out specific, often com-

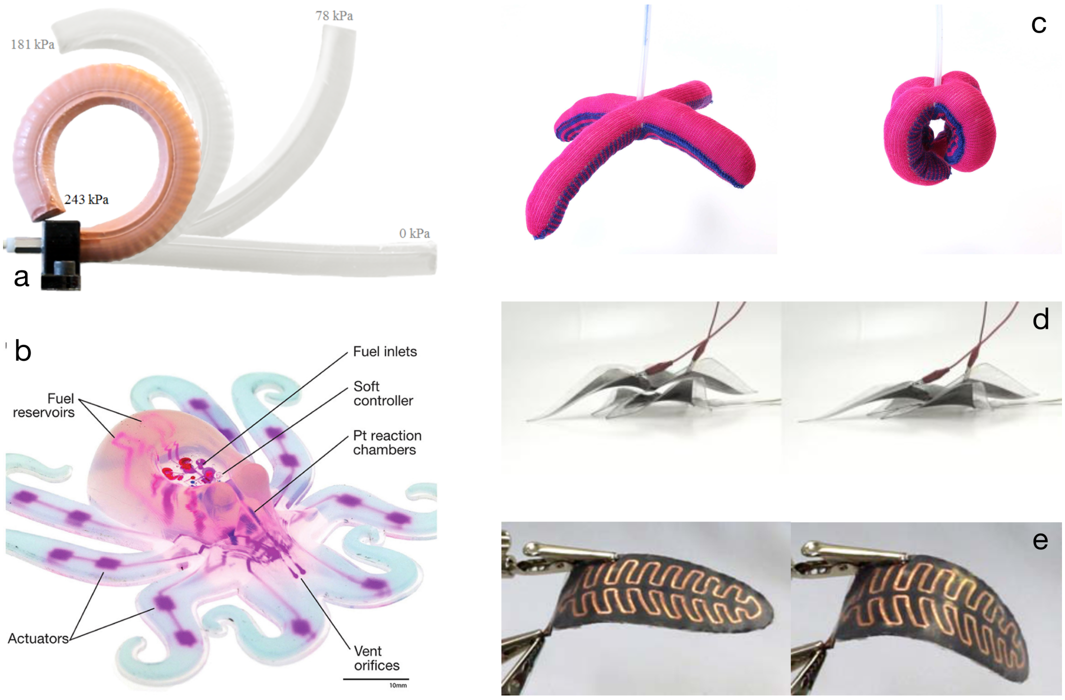

Figure 2.5: Soft robots made of silicone are often actuated by compressed air *(a)* [Galloway et al., 2013] or liquids *(b)* [Nakajima et al., 2018]. For robots made out of fabric mechanical forces applied by tendons are suitable *(c)* [Albaugh et al., 2019]. Electricity can be used to generate electrostatic forces *(d)* [Franinović and Franzke, 2019] or heat *(e)* [Du et al., 2018], both of which can actuate soft robots.

plex tasks. Rigid robots typically need complex feedback systems, for example, to evaluate their current position relative to another object. A soft robot can be less complex due to its adaptability to the environment [Laschi and Cianchetti, 2014]. If a soft robot grabbed something fragile, for example, its flexible material would naturally yield instead of damaging the object.

2.3.1 Actuation Methods and Materials

Soft robots can be actuated in different ways

Soft robots can be actuated in a variety of ways, e.g., through the use of compressed air [Ilievski et al., 2011; Nakayama et al., 2019], pressurized liquids [Wehner et al., 2016], mechanical forces [Davis, 2015b; Albaugh et al., 2019], electricity, [Franinović and Franzke, 2019] or heat

[Du et al., 2018] (cf. Figure 2.5). The choice of actuation method often depends on the purpose of the application and the materials used.

Compressed air is a typical force for actuation of soft robots

Soft robots are often operated with compressed air. Due to its airtightness and flexibility, silicone is a good manufacturing material for these soft robots. Using compressed air for actuation is a matter of a counterbalance of forces. The pressured air's force is countered by the forces of the materials constituting the soft robot. The desired deformations can be realized by selectively strengthening or weakening the materials at specific points [e.g., Ilievski et al., 2011; Polygerinos et al., 2015]. A special way to selectively reinforce the material is by combining it with a non-stretchable material [Galloway et al., 2013; Nakayama et al., 2019]. Combining the two materials prevents stretching at these points, and the actuation gives the soft robot the desired shape. The importance of air pressure-based systems for the field of soft robotics is demonstrated by the vast variety of generalized control systems that have emerged in recent years [e.g., Ou et al., 2016; Holland et al., 2017; Shtarbanov, 2021].

Multiple control systems have been developed over the last decade

Sensing counterpressure in air actuated soft robots

Pressure-based systems provide a particular advantage when measuring counterpressure. As previously mentioned, the forces applied to another object by a soft robot do not need to be measured to prevent damage. Nevertheless, there are cases where it is necessary to know the level of pressure which is applied against the soft robot [Park et al., 2011]. Since the pressure is equal in the whole system, the sensor does not necessarily have to be placed at the contact point. A corresponding sensor can be placed outside the soft robotic actuators. This allows for a more flexible system design, which can then be adapted to different requirements.

Vacuum-based material changes between soft and rigid state

A less frequently used approach is decreasing the pressure in the actuator. Narang et al. [2018] showed a flat soft robotic material that can change its rigidity. The material consists of multiple layers packed in an airtight envelope. The robot changes from being soft, flexible, and bendable to being stiff and rigid by creating a vacuum in the envelope, preventing the layers from slipping [Narang et al., 2018].

Another way of actuating soft robots is to use mechanical forces applied to the actuators by tendons, ribbons, or other movable physical connections. For example, Albaugh et al. [2019], Davis [2017], and Forman et al. [2020] showed soft robots that can be actuated in this way. Their work presents a tendon-based actuation method for knitted soft robots [Albaugh et al., 2019] and structured textile surfaces [Davis, 2017].

Mechanically actuated soft robots

Albaugh et al. [2019] provide a way to encapsulate the tendons used for actuation in the soft robot during the manufacturing process. They stated that one advantage of these soft robots is that they fit better into clothing and provide a more natural feeling on the skin than silicone, which is often used in pressure-based soft robots.

Knitted soft robots

Forman et al. [2020] showed that common materials for building rigid objects, such as plastic used by fused deposition modeling (FDM) printers, can be used to create a tulle-like material that appears woven.

Use of plastic to create soft materials

Franinović and Franzke [2019] showed how high-voltage electricity could be used to build soft actuators from electro-active polymers. The use of high voltage raises problems when used in immediate proximity to the skin, requiring extra effort to isolate the actuators from their surroundings. Du et al. [2018] used thermal energy to actuate shape-memory alloys. As with the electro-active polymers, the use of thermal energy in proximity to the skin raises issues that do not exist for pressure-based and mechanically actuated soft robots.

Soft robots actuated by electricity are not suited for our use-case

2.4 Communication and Measurement of Emotions

The communication of emotions is an ongoing field of research in human-computer integration. Particular interest in communicating emotions can be found in the field of social robots and interaction [e.g., Bucci et al., 2018; Song and Yamada, 2017; Hu and Hoffman, 2019]. Since social

Emotions can be conveyed by social robots

robots often possess anthropomorphic or zoomorphic features, expecting them to communicate an emotional state is plausible. However, there is also research on objects not generally expected to communicate emotions, such as textile structures [Davis, 2015b] or tactile displays [Vekemans et al., 2021].

2.4.1 Measurement of Emotions

Circumplex model is often used to measure emotions

The measurement of perceived emotions is a topic in behavioral science with a relatively long history compared to the history of human-computer interaction. Therefore, we can benefit from the experience gained and models created from this field [e.g., Russell, 1980; Crawford and Henry, 2004; Scherer et al., 2015].Due to the interdisciplinary nature of human-computer interaction, these methods and models have already been introduced in the field. They have been used in multiple studies [e.g., Davis, 2015b; Strohmeier et al., 2016; Hu and Hoffman, 2019], and have been discussed by researchers [Coyne et al., 2020]. Owing to its reliability [Russell et al., 1989] and simplicity, the *circumplex model* by Russell [1980] has been used widely in recent years in the human-computer interaction research community [e.g., Posner et al., 2005; Strohmeier et al., 2016; Song and Yamada, 2017; Vekemans et al., 2021].

The circumplex model consists of valence and arousal

The circumplex model by Russell [1980] consists of a two-dimensional space, which is constructed by the two orthogonal axes of valence and arousal (cf. Figure 2.6). Emotions are denoted in this space by a linear combination of these two dimensions. Whereas valence describes whether an emotion is positive or negative, its arousal level informs whether it is calm or excited [Davis, 2015a]. Compared to other categorical approaches, [e.g., Crawford and Henry, 2004] the circumplex model better represents the emotional state [Coyne et al., 2020]. On the other hand, the dimensional position in the model is not intuitive to interpret [Coyne et al., 2020].

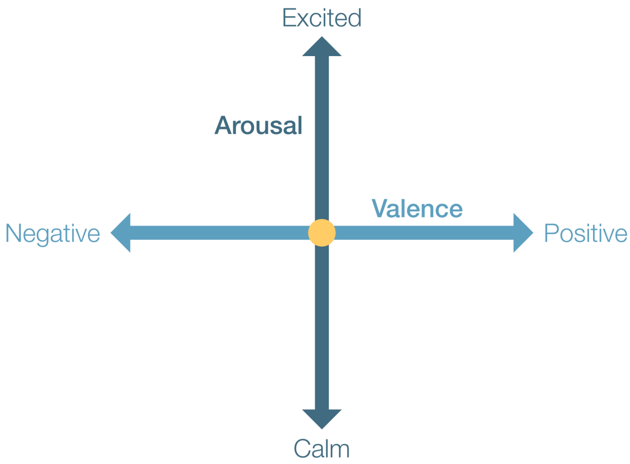

Figure 2.6: Reproduction of the circumplex model by Russell [1980] places emotions in a 2-dimensional space which is created by the two orthogonal axes *valence* and *arousal*. Extremes as used by Davis [2015b] in their study on conveying emotions.

2.4.2 Shape Change as Communication

The term *shape-changing* is an attribute for objects that can change their outer appearance, dimensions, or other physical characteristics somehow. Previous work has investigated whether these objects convey emotion through observation or touch [e.g., Davis, 2015b; Hu and Hoffman, 2019; Vekemans et al., 2021]. The assumption that this is possible is apparent since movements such as gestures or postures are also used in interpersonal communication to convey moods and emotional states.

Shape-change was investigated for conveying emotions

One example of shape-changing materials are *computational textiles*, as presented by Davis [2015b]. They determined that the emotion conveyed by a shape-changing textile depends on the observers' associations with the observed and their personal experience and attitude towards these associations. However, they also supported the theory that different shapes can convey different emotions. Furthermore, they showed that the valence and arousal ratings increase if the shape moves.

Emotions were conveyed by shape-changing textiles

Characteristics of shape-change influence the communicated emotion

The results from Hu and Hoffman [2019] align with the findings of Davis [2015b], who showed that textures moving with a higher frequency are perceived with a higher level of arousal. In their study, Hu and Hoffman [2019] further showed that different combinations of texture type, actuation amplitude, and frequency conveyed different emotions across the modalities of observing and feeling. Furthermore, they showed that the shape of the surface, whether it was round or pointed, had higher effects on the valence [Hu and Hoffman, 2019].

A follow-up study by Vekemans et al. [2021] used the textures presented by Hu and Hoffman [2019] and created a tactile display that is worn on the wrist. Their study confirmed the connection of low frequency with less aroused emotional states such as calm, sleepy, and sad. At the same time, the higher frequency was connected with more excited emotions.

Shapes created by participants to convey emotions resembled symbols

Strohmeier et al. [2016] tested another approach for establishing a connection between emotions and shape. They let participants design shapes by using a planar object the size of a smartphone for given emotions. They report that participants use symbols like a heart to convey a particular emotion. Additionally, they demonstrated that shape often corresponded to valence, while the movement properties such as speed, amplitude, and area in motion often corresponded with arousal. Both findings fit the results of Hu and Hoffman [2019], Vekemans et al. [2021], and Davis [2015b].

2.4.3 Conveying Emotions with Material

Material may influence how shape-change is perceived

Since material is an essential aspect of jewelry design, knowing whether it influences the conveyed emotion is crucial. Van Waveren et al. [2019] showed in their work that a variation in the materials on robots caused how warm and therefore positively they were perceived. According to the effect size reported by van Waveren et al. [2019], the effect may not be that large.

During the literature research, no further publications on how the material of robots or movable objects influences the conveyed emotion. Therefore, we believe that gaining further knowledge in this area is critical.

Chapter 3

Soft Robots Design and Fabrication Process

This chapter describes the soft robot's design as well as the fabrication process to create the soft robots used in the user study. To identify the best approach, we first list the user study's requirements for soft robots and their manufacturing process. We then explain why *SoRoCAD* [Timchenko, 2019] and *fiber-reinforced* actuators [Galloway et al., 2013]) were chosen for a detailed validation regarding the requirements. This comparison is followed by our implementation of the production process of *Fiber-Reinforced* soft robots, [Galloway et al., 2013] including several adjustments to better fulfill our requirements. The process report contains the presentation of an openSCAD based design tool, an explanation of the mold production, and a description of the casting of the soft robots.

3.1 Requirements

In order to make an informed decision about which process is most appropriate, we state several requirements the soft robots and their production process need to fulfill. They are presented in the following and used for validation in the subsequent section.

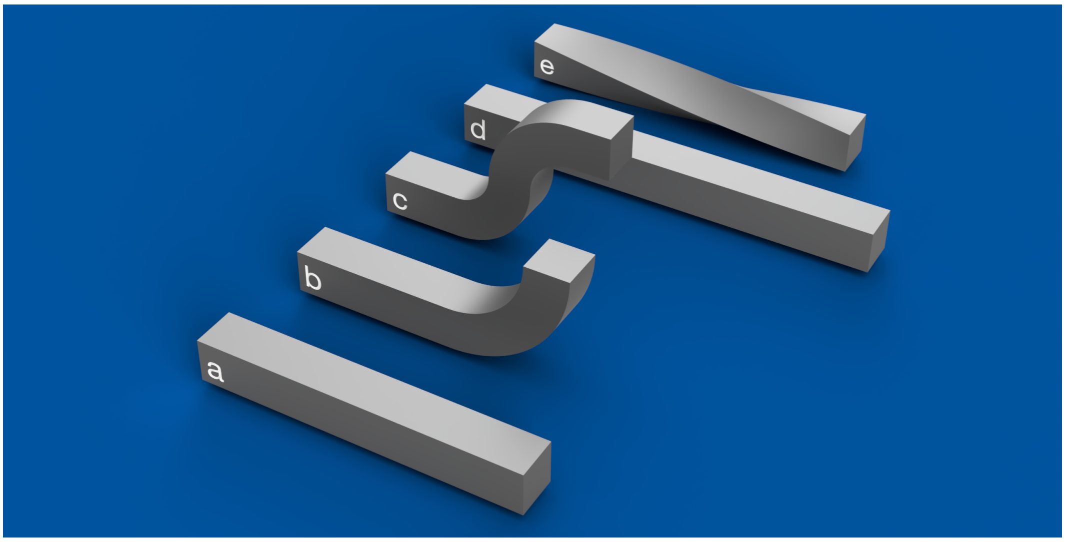

Figure 3.1: All soft robots must have the same initial shape (a) in the non-activated state. In the activated state, they will bend once (b) or twice (c) along the transverse axis or elongate (d) or twist (e) along the longitudinal axis, depending on the design.

Exterior appearance should always be the same

The soft robots used in the study must all have the same external appearance when not actuated. This concerns the overall base shape (i.e., the shape of the soft robot when no pressure is applied) as well as the soft robot's surface structure, color, and other visual features that are perceptible from a distance of approximately 1 meter.

The size of the soft robots must fit the jewelry in which they are used

Moreover, the soft robot must be small enough to fit optically and dimensionally in the composition of prototypical smart jewelry. We selected a necklace as the smart jewelry type for our study since it is more extensive than other jewelry (e.g., rings, bracelets, or earrings). This allows us to use larger soft robots, which are easier to manufacture while maintaining coherent proportions of the necklace. The selection of the chest as a location for displaying public information is also supported by findings of Inget et al. [2019] which indicate that people are comfortable with positioning publicly perceivable information on higher body positions.

Several shapes are required to convey various emotions

Even though the base shape needs to be the same for all soft robots (cf. Figure 3.1a), the shape the soft robot turns into should vary across different soft robots. To convey various emotions, we need soft robots for the distinct shapes listed below.

- A single bend along its transverse axis (cf. Figure 3.1b)
- Two bends along its transverse axis (upwards and downwards, respectively; cf. Figure 3.1c)
- Elongation along its longitudinal axis (cf. Figure 3.1d)
- Twist around the longitudinal axis (cf. Figure 3.1e)

Consistent results ensure reproducibility

Furthermore, the resulting soft robots should behave consistently when actuated. If a soft robot needs to be replaced during the study, the movements of the new soft robot should be identical to those of the old one. Therefore, we prefer the process where soft robots of the same shape have the lowest variance in their actuated shape. Ensuring consistent results will enable other researchers and jewelry designers to reproduce our results.

Reliable soft robots prevent confounders

Even though the soft robots have been presented in video recordings during the user study, the same soft robot needed to be actuated multiple times to record the multiple conditions. If a soft robot's movement were to change over repeated actuation, the appearance of a condition would depend on the time of recording. Therefore, we aim to fabricate robots that can be actuated multiple times without significant changes in behavior or destruction through air leakage.

We prefer a simple process

The simplicity of the fabrication process is also a deciding factor. In addition to the apparent benefits inherent in simpler processes, such as lower susceptibility to errors and faster production, we believe that increased accessibility is crucial in supporting further research. This applies both to scientists who may conduct further studies in this field and jewelry designers who want to experiment with the new possibilities of moving parts in their adornments.

3.2 Validation of the Processes

From the various processes for manufacturing soft robots, SoRoCAD soft robots [Timchenko, 2019] and Fiber-Reinforced soft robots [Galloway et al., 2013] seem to be best suited for integration into a smart jewelry necklace and performance of the desired movements. The following section first validates the two processes in detail. The subsequent comparison of both results explains why the Fiber-Reinforced approach, as first mentioned by Suzumori et al. [1991] and later supplemented by Galloway et al. [2013], was selected as a base for our design and fabrication process.

3.2.1 SoRoCAD

SoRoCAD soft robots provide consistent surface appearance

The SoRoCAD approach, as presented by Timchenko [2019] in his bachelor's thesis, defines the shape the soft robots move into when actuated by inner air chambers and varying wall thicknesses. This approach allows the design of soft robots that do not differ externally but can take different forms when actuated due to different internal structures.

Dimensions are suitable for use in necklaces

Reducing the soft robots' size is mostly constrained by the resolution of the process for creating the molds (in our case, an 3D printing) and whether the silicone can be demolded without damaging the soft robot. We observed that the ratio of the thickness and height of the walls used in the soft robot's design limits the latter. Thin and high walls are likely to cause the robot to rip when trying to demold. The 3D printers available to us are able to print in reasonable quality, and we do not aim for extreme wall thickness to wall height ratios. This lets us conclude that the SoRoCAD approach is suitable to produce soft robots in the aimed size.

Bending along the transverse axis is possible

Simulations in the software and first experiments with the process show that bending along the transverse axis is possible if the wall in which the soft robot should bend is made

Figure 3.2: Soft robots created with the SoRoCAD approach have faced issues. Actuators could perform a bend but showed a bulge at the outer side *(left)*. At the same time, the trials of creating an elongation movement ended in banana-shaped balloons *(right)*.

thicker than the opposite wall. The same holds for the two bends around this axis. However, this design can also lead to bulges in narrow walls (cf. Figure 3.2 *(left)*). On the other hand, thicker walls generally require greater pressure, which in turn requires a system that can handle the higher pressure.

Elongation is difficult to achieve

Since air expands uniformly in all directions, it is hard to achieve an extension along a single axis (i.e., elongation of the soft robot along the longitudinal axis). Our experiments vary the thicknesses of the start and end in relation to the overall wall thickness and test fish-bone and cuboid air chamber designs. The resulting soft robots do not provide the desired elongation shape but instead create banana-shaped balloons (cf. Figure Figure 3.2 *(right)*).

Twist movement can be simulated with a vacuum

Designing a soft robot that twists along the longitudinal axis during actuation proved similarly challenging. As with the extension along a single axis, the compressed air inflates the soft robot in all directions. The *twist* movement

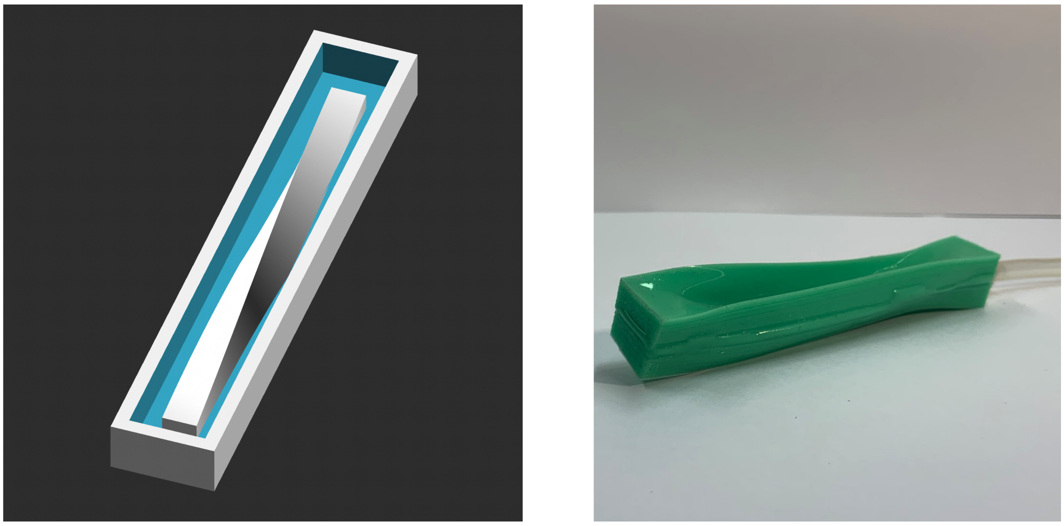

Figure 3.3: Even though the SoRoCAD approach does not provide a design that makes the actuator twist, a mold with a twisted air chamber *(left)* creates a soft robot that resembles a crushed or twisted object when vacuumed *(right)*.

in the study is reminiscent of a crushed or twisted object. It represents the consequences of an action taken due to an aroused negative emotion [Strohmeier et al., 2016]. We achieved a visually appropriate result by manually creating a soft robot mold using the same principle as the SoRoCAD software (two molds whose castings are bonded together). The air chamber of this soft robot was a cube rotated 90° along its length (cf. figure 3.3 *(left)*). A soft robot made in this way, with a vacuum created in its air chamber, shows a deformation that reaches the above target (cf. Figure 3.3 *(right)*). Even though a "real" twist is not possible with the SoRoCAD approach, we can create a suitable alternative.

Process of sealing results in a trade-off between reliability and reproducibility

The sealing process of SoRoCAD is one factor that reduces the reproducibility. The two halves are sealed together with additional silicone, which may flow into the air chamber and cause a change in the shape. On the other hand, too little silicone can lead to unstable sealing, resulting in unreliable soft robots that may have bulges or air leakage when actuated. Furthermore, the two halves can move during the sealing if, for example, the surface is not perfectly even; the top may slide away from its intended position, letting the resulting soft robots deviate from each other. To mitigate

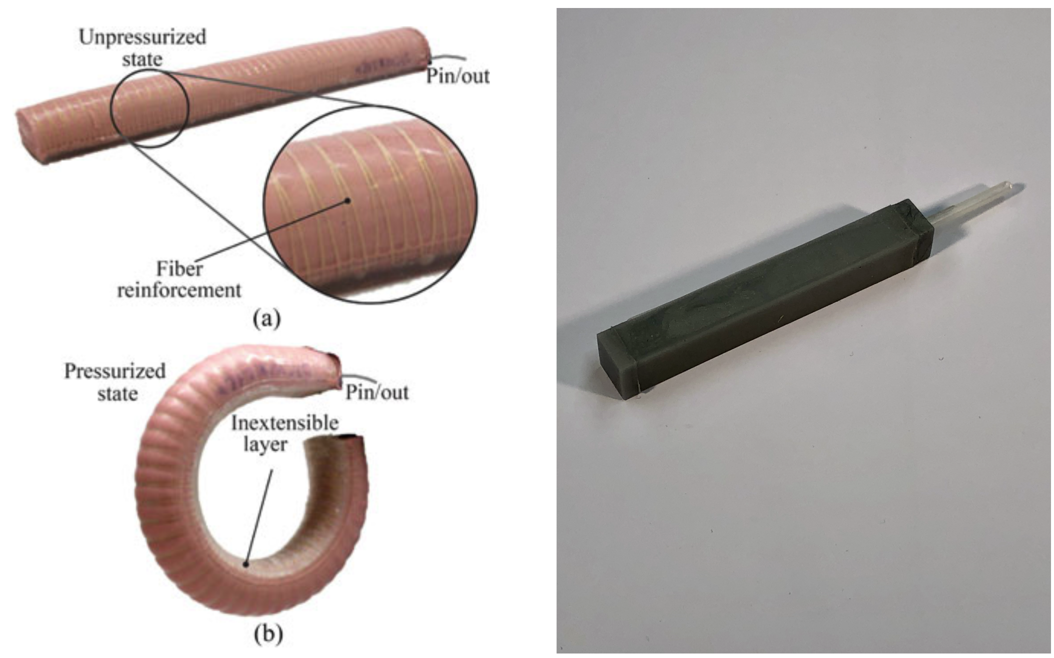

Figure 3.4: Visibility of Fiber Reinforcement as presented by Polygerinos et al. [2015] *(left)* compared to the opaque skin of our soft robots *(right)*.

the negative effect on reliability, we suggest the creation of a guidance system that prevents the halves from moving during the curing process by holding them in place.

The simple process counterbalances unreliability

A significant advantage of the SoRoCAD process is its simplicity. In advance of creating the soft robots, the molds for the two halves have to be created (e.g., by 3D printing). The actual process of molding is quick and easy, as it requires only two rounds of curing silicone: a first round to create the two halves and a second to seal them. The simplicity counterbalances deficits in the reliability since they are effortlessly reproducible.

3.2.2 Fiber-Reinforced Actuators

Opaque silicone creates a consistent appearance

In the fabrication of fiber-reinforced actuators, as shown by Polygerinos et al. [2015], the internal structure of the strain-limiting layer is visible. As a result, the external appearance depends on the soft robot's shape during actuation. Different movements require different combinations of strain-limiting layers and fiber reinforcements. Polygerinos et al. [2015] uses transparent silicone to fix these to the body (cf. Figure 3.4 *left a*), making the soft robots for the different movements visually different. To avoid this, we cast the skin (the fixing layer of silicone) from a non-transparent silicone so that all soft robots look the same regardless of their internal structure (cf. Figure 3.4 *right*).

Flexible sizes through the creation of custom molds

The 17 cm length of the fiber-reinforced actuators used by Galloway et al. [2013] is too extensive for usage in jewelry. Since the soft robots are cast in 3D printed molds, it is possible to scale down the models of the molds in advance. This allows for production of soft robots that fulfill the size requirements.

Fiber-reinforced actuators support all required shapes

In their work, Polygerinos et al. [2015] showed that this approach can produce soft robots extending or twisting along the longitudinal axis and bending once or twice along the transverse axis. This variety of shapes is made possible by combining threads wrapped around the inner part of the soft robot and optionally embedding constraint layers. This diversity of capabilities fulfills all of our soft robot shape requirements.

Achievable quality of 3D printed molds causes high variation in elongation and twist

We observed that the results varied widely during our first hands-on experience with the process, especially for the elongation and twist shape (i.e., low reproducibility). The soft robots tended to bend, which was presumably caused by small unintended differences in wall thickness. These variations likely occurred due to the varying quality and stability of the 3D-printed molds.

Reliability benefits from the way the soft robot is sealed

The resulting soft robots consisted of only two sealings (i.e., surfaces attached to another in multiple curing steps), which are responsible for the soft robot's airtightness. This increases the soft robots' reliability. The sealings are attached to the ends of the soft robot. If a sealing is defective, it can simply be removed and recast. This makes it possible to repair the soft robot in certain cases.

Constraint layers and geometry of molds increase complexity

The process of producing fiber-reinforced actuators is lengthy, requiring curing silicone four times and additionally applying the strain-limiting layer after the first time. Before casting, the silicone needs to be vacuumed since tiny bubbles cannot travel to the surface due to the more complex geometry of the molds. For example, bubbles below the rod would stay there and cause defects. Since vacuuming takes several minutes, silicone with a longer processing time (i.e., the time where it can be cast) is required. This silicone type can be processed for about 40 minutes, but also requires an additional 40 minutes until completely cured. The step mentioned above of applying the strain-limiting layer takes another 10-20 minutes per soft robot, depending on the layer's complexity. Additional time is required for the preparation and cleanup of tools and the workplace. When producing multiple soft robots simultaneously, our experience was that casting silicone one time can take 3-4 hours.

3.2.3 Comparison of the Processes

The requirement of indistinguishable outer appearance and the requirement of adequate size are fulfilled similarly by both processes.

Fiber-reinforced actuators' reproducibility is higher

Both processes presented issues in terms of reproducibility. The SoRoCAD process presented the risk of unintended flooding of the air chamber with silicone, and shifting of the halves during the sealing. In the manufacture of fiber-reinforced actuators, the inaccuracy of 3D-printed molds leads to greater variation in results as well as potential flooding of the air chamber. For fiber-reinforced actuators, we discovered that modifications (cf. Chapter 3.5.5) to the process described by Polygerinos et al. [2021] for reducing the risk of flooding the air chamber during the sealing can produce more consistent results. For SoRoCAD, we assumed that the problem of shifting halves can be remedied by fixing the halves with 3D printed guides during the curing of the silicone. On the other hand, we were unable to find a similarly simple solution to prevent flooding of the air chamber. Therefore, we assume the fiber-reinforced actuators provide better reproducibility.

Fiber-reinforced actuators' smaller sealing surface improves reliability

The reduced sealing surface also benefits the fiber-reinforced actuators' reliability compared to the SoRoCAD approach. The latter utilizes a larger sealing surface that increases air leakage probability. Furthermore, a defective sealing of a fiber-reinforced actuator is relatively easy to repair since a smaller portion of the robot needs to be cut to remove the faulty part. In comparison, a defective SoRoCAD is hard to repair since the whole sealing edge along the robot's longest side needs to be cut, which can easily cause further damage or even complete destruction. Therefore, we consider fiber-reinforced actuators to be the more reliable soft robots.

Fiber-reinforced actuators support all required shapes

Fiber-reinforced actuators can be produced for all required shapes, whereas for SoRoCAD, producing the elongation seems impossible; the twist movement is similarly not well supported. Additionally, the SoRoCAD soft robots that perform the bending movement tend to have bulges at the outer sides, which can be a confounding variable regarding the communicated emotion. These disadvantages make fiber-reinforced actuators a better choice regarding implementable shapes.

SoRoCAD's mold design is more involved, but fabrication is more straightforward

The production process of SoRoCADs, requiring the curing of silicone only twice, is faster and more straightforward than creating fiber-reinforced actuators, which involves curing four times in addition to applying the strain-limiting layers once. Therefore, the SoRoCADs can be produced much faster. However, the design process for the molds is much more involved because each shape requires a new mold. In contrast, fiber-reinforced actuators with identical base shapes and wall thicknesses only require a single set of molds to create soft robots covering all required shapes. Furthermore, the process of creating fiber-reinforced actuators already includes the mounting of a solid connection. Inserting a needle into one end of the soft robot (as shown in the bachelor's thesis by Timchenko [2019] for SoRoCAD soft robots) is likely not solid enough to withstand the pressure required to actuate the soft robot when covered with another material. Nonetheless, the fabrication of the actual soft robot is more straightforward and faster than for fiber-reinforced actuators.

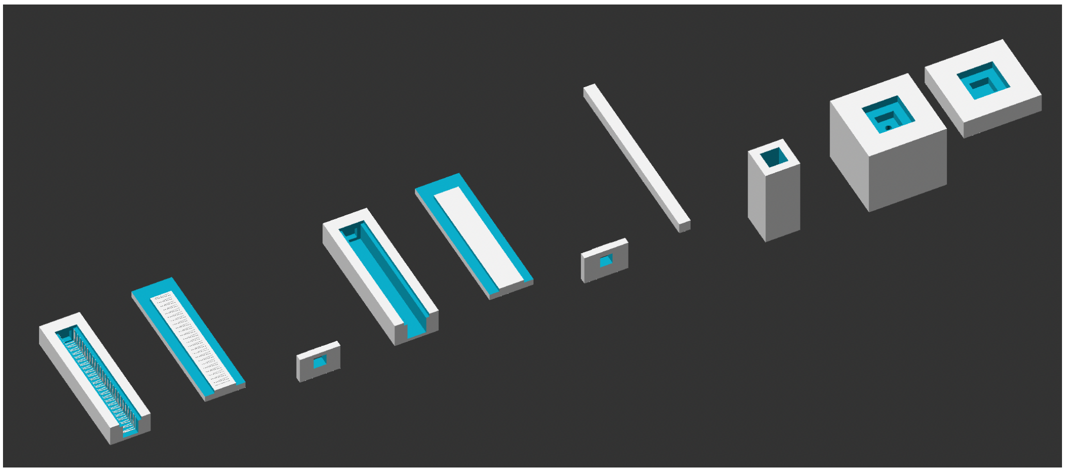

Figure 3.5: 3D models of parts provided by the tool required for fabricating fiber-reinforced soft robots. From left to right: *body-mold, body-lid, body-cap, skin-mold, skin-lid, skin-cap, rod, tower, connection-sealing, end-sealing*

Fiber-reinforced actuators are preferred

The aforementioned advantages and disadvantages led us to prefer the fiber-reinforced actuators for our study. Fiber-reinforced actuators provide more benefits even if the production process is more complex than the SoRoCAD approach. To better meet our requirements, we applied some changes to the process presented by Polygerinos et al. [2021] which we describe in Sections 3.3–3.5.

3.3 OpenSCAD Design Library for Soft Robot Molds

The production process for fiber-reinforced actuators [outlined by Suzumori et al., 1991; Galloway et al., 2013; Polygerinos et al., 2015; Connolly et al., 2017] is summarized in a tutorial by Polygerinos et al. [2021] on the Soft Robotics Toolkit[1] platform. They provide 3D models for the molds on the platform. However, they do not fit our use case since they are 17 cm long and therefore too large for our use case.

[1] softroboticstoolkit.com/book/fiber-reinforced-bending-actuators

We created a tool for parametric design of fiber-reinforced actuators

A tool created by Jørgensen [2018] which facilitates the parametric generation of molds to build PneuNet soft robots [Ilievski et al., 2011] inspired us to create a tool for the parametric creation of molds for fiber-reinforced actuators (cf. Figure 3.5). The tool is a parameterizable openSCAD[2] script[3] and is freely available. The user can adjust the script's parameters according to the requirements for the final soft robot. The following parameters are available:

- Actuator size (i.e., the outer dimensions of the final soft robot in millimeters)
- Wall thickness (i.e., the thickness of the walls along the longitudinal axis in millimeters which consist of two silicone layers containing the constraint layer)
- Seal thickness (i.e., the thickness of the sealings at both ends)
- Twist (whether the soft robot should twist around its longitudinal axis)
- Clockwise twist (whether the soft robot should twist clockwise or counterclockwise), and
- Groove spacing (the spacing between the grooves in millimeters)

Based on these parameters, the script calculates the molds' 3D models, which the user can export afterward.

Air chamber is defined by dimensions, walls, and sealings

The air chamber's size depends on the actuator's overall dimensions and the dimensions of the walls and sealings. Subtracting the wall thickness from the depth and height of the soft robot determines the air chamber's depth and height. Likewise, the seal thickness is subtracted from the air chamber's length to determine the soft robot's length.

The spacing between them determines the inclination of the grooves

The placing of the grooves (i.e., where the fiber is placed while wrapping) is calculated using the desired spacing between them, the wall's thickness, and the air chamber's

[2] openscad.org

[3] git.rwth-aachen.de/schroeder/thesis-digital-appendix/-/tree/main/soft-robots-library/fiber-reinforced

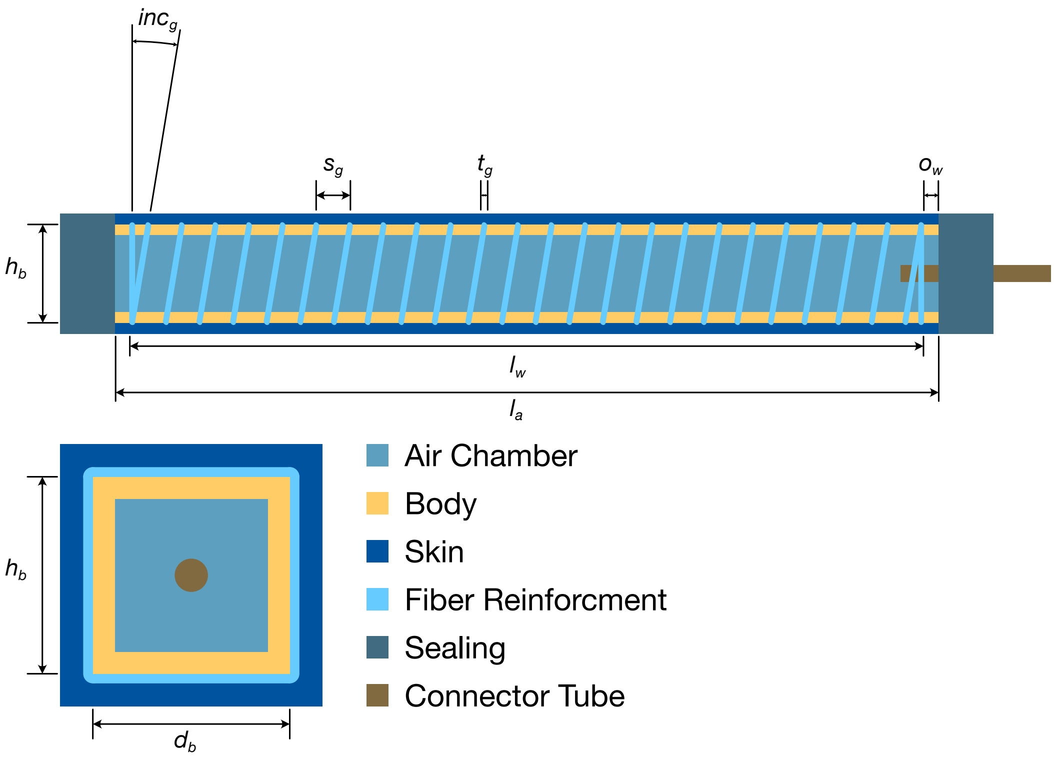

Figure 3.6: The soft robot's longitudinal section *(top graphic)* shows the silicone and fiber reinforcement layers. The cross-section *(bottom graphic)* is scaled by a factor of two with respect to the longitudinal section.

length. First, the required groove inclination inc_g is calculated using

$$inc_g = \arctan(\frac{s_g}{c_b})$$

where s_g represents the spacing between the grooves in one direction and c_b represents the body circumference (i.e. $c_b = 2h_b + 2d_b$ with h_b as the body's height and d_b as the body's depth). In Figure 3.6 inc_g and s_g are depicted in the top graphic and h_b and d_b can be seen in the bottom graphic. The dimensions of the body are defined as follows:

- Length is equal to the air chamber's length
- The height and width of the body are twice the half wall thickness, in addition to the height and width of the air chamber, respectively.

The number of grooves per side (i.e., the number of windings of the fiber) is calculated using

$$n_w = \frac{l_w - t_g}{s_g}$$

The spacing between the grooves and the soft robot's dimensions determine the number of windings

where t_g represents the groove thickness and l_w represents the length over which the winding extends (cf. Figure 3.6 *top graphic*). The latter is defined as the length of the air chamber (l_a) minus an offset (o_w) of 1 mm (cf. Figure 3.6 *top graphic*) at each end to ensure that the first and last winding do not slip off the body. Additionally, the tool informs the user in the log if the length of all windings is not l_w and suggests the closest actuator lengths where this is the case.

The tool supports different visualizations

The remaining parameters of the tool are used for controlling the rendered scene. They determine whether

- the visualization (cf. Figure 3.7) is shown or the molds are rendered.
- the mug is shown in case the visualization is rendered.
- all or only some of the molds are shown in case the molds are rendered.
- logs should be silenced.

All parameters are optional and preset with reasonable fallback values (i.e., values for molds that result in working soft robots).

The tool provides visualizations of the final soft robots

In addition to generating molds, the tool provides a preview of the final soft robot (cf. Figure 3.7). The tool provides a *full view* of the soft robot (left closed green bar in Figure 3.7). Furthermore, a cross-section is shown to visualize the internal structure of the soft robot (right green bar on Figure 3.7). This view provides the users with the following information:

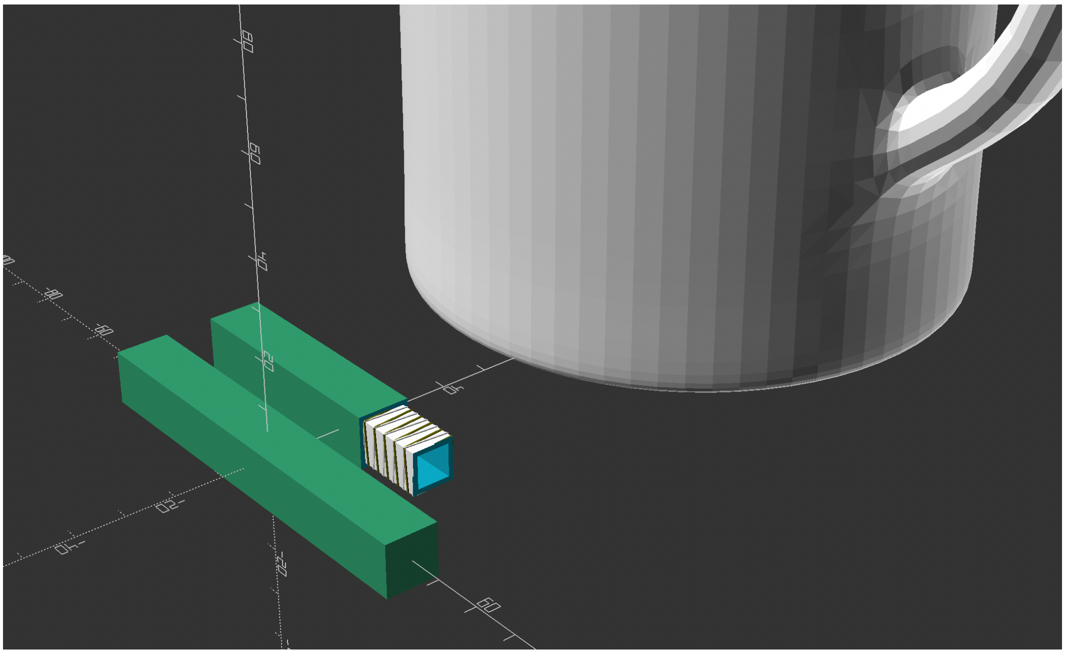

Figure 3.7: Visualization, offered by our openSCAD tool that shows the soft robot with an adjacent mug for the size ratio (cf. Baudisch et al. [2019])

1. They can see the internal air chamber's dimensions.

2. They see the soft robot's walls thickness consisting of the two layers (body and skin layer). Our experience shows that visualizing the wall thickness helps to give an idea of how much pressure is needed for actuating the soft robot and of how strong the actuation will be.

3. The visualization shows the fiber used in the constraint layer, which provides a better idea of the internal structure of the soft robot.

Furthermore, the visualization shows whether mold facilitates twisting of the soft robots (grooves only in one direction) or elongation (grooves in both directions) along the longitudinal axis. Our experience from the production process was that the *non-twisting* molds (i.e., containing grooves for wrapping back and forth) could also be used for *twisting* soft robots by only wrapping fiber in one direction.

The export script facilitates the further processing of the exported molds

To simplify the next step in the production process, we provided a script to export each of the objects seen in Figure 3.5 as a single *STL* file. This allowed for better placement in the slicing application, made printing faster and allowed us to avoid dividing the objects later.

3.4 3D Printing of Molds

Ultimaker S5 provided best results

After designing the molds as described in Chapter 3.3, we then needed to fabricate them. We decided to use 3D printers, as they were readily available and guaranteed a simple production process. We printed the molds on three different 3D printer models to determine which provided the best results. We used an Ultimaker S5[4], a Raise3D Pro 2[5], and a ProJet MJP 2500 Plus[6]. The first two were fused deposition modeling (FDM) printers, and the latter was a stereolithography (SLA) printer. Polylactide (PLA) filament from the respective manufacturer was used in the FDM printers. From our experience the Ultimaker S5 provided the best results for our use case.

Printing was performed without support material

The general procedure is similar for all three printers. The STL files are imported into the respective printer's software and printed. We used similar quality settings (layer height of 0.1 mm) for both FDM printers. Regarding support structures, it has been shown that for FDM printing, it is generally better to omit them as only small overhangs exist in the models. However, removing the support material in our study was impossible without residual unevenness that prevented parts from fitting into one another, e.g., the *rod* did not fit into *body-mold* (cf. Figure 3.5). For SLA printing, removing the support was not a problem as the wax used melted away after printing.

Size of parts that need to fit into another need to be reduced

Remaining support material is not the only variable that can prevent parts from fitting into one another. The FDM printers in particular tend to print slightly more extensively

[4] ultimaker.com/de/3d-printers/ultimaker-s5
[5] www.raise3d.com/pro2-series/
[6] www.3dsystems.com/3d-printers/projet-mjp-2500-series

than what the models specify. To mitigate this effect, our tool described in Chapter 3.3 reduces the size of parts that need to fit into each other by a small amount in each direction orthogonal to each contact surface. For the Ultimaker S5, a value of 0.15 mm proved to be reasonable. Since this value depends on the printer and its settings, printing only a single mold is advisable to determine the appropriate offset.

We observed differences between the printers in terms of how well the soft robot could be removed from its mold. Although all molds were treated with a rapeseed oil-based release agent, we observed varying degrees of difficulty in removing the soft robots from their molds. The molds from the Ultimaker S5 offered the most uncomplicated removal of the soft robots. Removing the soft robots from both the ProJet and Raise3D molds was problematic because they adhered firmly to the surfaces of the molds. The adhesion caused silicone to remain in the molds and even destroyed some soft robots during removal. This effect was noticeable during the first use of a mold. After several uses, the removal became easier, but not as easy as with the molds printed by the Ultimaker S5. Since all three printers used different materials, we cannot state whether the printer or the material caused this behavior. For all three printers, the silicone adhesion to the mold decreased when the mold was cleaned with water and detergent prior to its first use.

Silicone was most easily removed from molds printed with the Ultimaker S5

During the use of different molds, we also observed that the ones made of resin (i.e., the molds printed with the SLA printer) broke faster. In contrast, the PLA molds did not break at all.

Resin molds tend to break after some time

During our work we used molds made by all three of the presented printers. Because of the aforementioned issues with the ProJet and Raise3D, we recommend the Ultimaker S5 for printing the molds as shown in Figure 3.8. We tested only three printers in a non-systematic way. We suggest that future work should investigate the crucial aspects influencing the quality of 3D-printed silicone molds.

We suggest performing a systematic investigation of 3D-printed molds for casting silicone

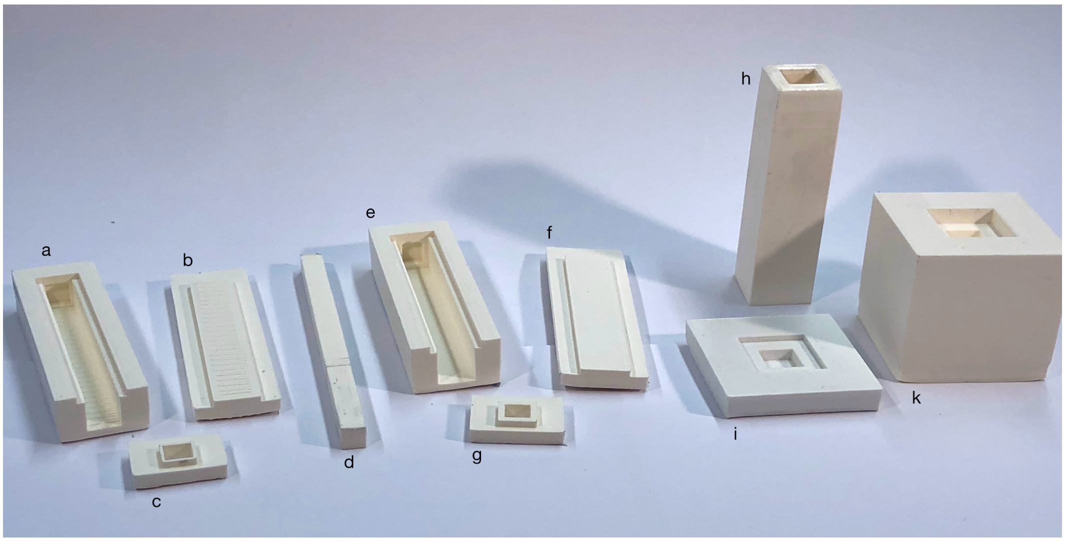

Figure 3.8: The mold parts shown in Figure 3.5 printed with the Ultimaker S5.

3.5 Fabrication of Fiber-Reinforced Actuators

The soft robots used for creating the necklace which was presented in the user study are based on the fiber-reinforced approach by Galloway et al. [2013]. A five-step process is required to create these soft robots that are capable of changing into different shapes.

3.5.1 Silicone Processing

Over the course of the fabrication process, multiple layers of silicone are connected to each other by placing the already cured parts in the newly added fluid silicone. Therefore, silicone must be prepared multiple times during the fabrication process before it is cast into the molds. Since this procedure is the same every time, it is described only once in this section.

We used liquid silicone with a shore value of 22 to cast the soft robots

For all soft robots presented in the user study, we used a white 2-component silicone rubber[7] with a shore value of

[7] trollfactory.de/produkte/silikon-kautschuk/haertegrad-

Figure 3.9: To degas the mixed silicone, it was vacuumed with −1 Bar *(left)* until it boiled *(right)* and left for one minute until almost no more bubbles popped on the surface.

22 from Trollfactory. As specified by the manufacturer, the two components were mixed in a 1:1 weight ratio. Since our soft robots were relatively small (∼80 x 11 x 11 mm), only a small amount of silicone was needed per casting step. Therefore, we weighed the silicone and the paint for colorizing it using a Newton meter.

We selected gray as the soft robot's color

In order to ensure consistent colors across the different materials in the user study, we decided to use a gray silicone. We achieved this by adding Trollfactory's gray aluminum silicone paint paste[8] during the mixing process. We used a mixing ratio of about 1:16.

Vacuuming the silicone prevents defects

The silicone is vacuumed with −1 Bar (relative to ambient

shore/weich-shore-a25/7037/tfc-silikon-kautschuk-typ-11-weisslich-neutral-shore-22-lange-topfzeit

[8] trollfactory.de/produkte/farbenfarbpigmente/tfc-silikonfarben/8501/tfc-silikonfarbe-farbpaste-silikon-kautschuk-ral9007-graualuminium-grey-aluminium?number=TFC48870015

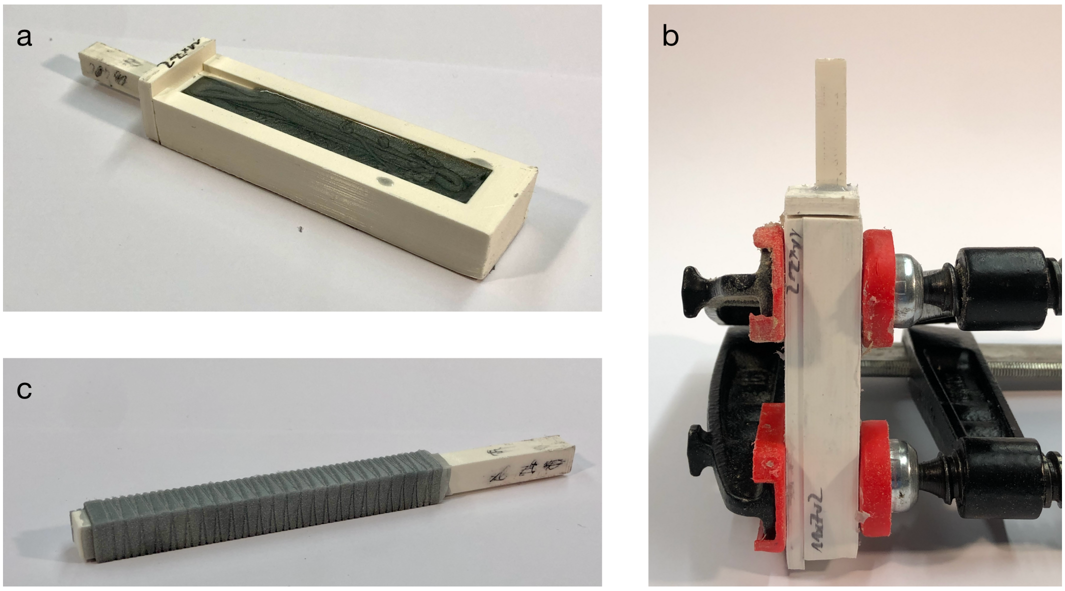

Figure 3.10: The silicone is filled into the *body-mold* which is closed by the *body-lid* and contains the *rod (a)*. To prevent the silicone from leaking before it is cured, screw clamps are applied *(b)* after the *body-lid* is closed. After curing and demolding the body, the groves can be seen on its surface *(c)*.

pressure, cf. Figure 3.9 *(left)*) until it boils as shown in Figure 3.9 *(right)*. It remains for another 60 seconds before the chamber pressure is slowly normalized [Inc., 2021]. Afterward, the silicone is ready to be used in the casting step. Vacuuming is crucial to remove the air added when mixing the components and the paint. Otherwise, the air might cause leakage and defects in the soft robot.

3.5.2 Body

First the soft robots body is casted

After printing, the molds must be treated with a release agent to facilitate demolding in the subsequent steps and, therefore, reduce the stress applied to the silicone during fabrication. The release agent needs to be applied before each use of the mold. The soft robot's body is cast by pouring the prepared silicone into the *body-mold* (cf. Figure 3.8a), and the *rod* is put through the *body-cap* (cf. Figure 3.8d and c) and inserted into the pocket at the end of the *body-mold* as depicted in Figure 3.10a [Galloway et al., 2013].

At this point, it is essential to ensure that enough silicone is added to the mold. We found it effective to overfill the mold because the excess silicone spills out when the mold is closed with the *body-lid*. If done carefully and slowly, this results in fewer defects in the soft robot's body.

Preventing gaps by overfilling molds

The lid is fixated with screw clamps (cf. Figure 3.10b) to prevent silicon from leaking form the mold [Polygerinos et al., 2021]. Furthermore, this prevents the lid from displacing, which could cause non-fitting groves on the soft robot's top. The soft robot is cured in an upright position. If air bubbles have formed despite the vacuuming of the silicone, they travel to the top. Causing a gap at this position is less problematic than if they occurred in the middle of the soft robot. A hole in the middle would cause the body not to be airtight, and when actuated, the air can extend into the strain-limiting layer. This would cause the body and the skin layer to separate from each other, which would destroy the soft robot. Whereas, at the soft robot's end, the gap can easily be filled with silicone either in the skin or sealing steps (cf. Chapters 3.5.4 and 3.5.5).

Curing with clamps in an upright position to mitigate problems due to trapped air

When the silicone is fully cured, the lid is opened to pull out out the rod with the silicone. Applying some compressed air between the silicone and rod is recommended to separate them from each other. This procedure facilitates the removal of the rod later in the process. Easier removal of the rod reduces the risk of damaging the strain-limiting layer (cf. Chapters 3.5.3 and 3.5.5). This also causes the silicone to move back to its original position in case removal from the mold has led to deformation. Otherwise, this could lead to undesirable tensions inside the soft robot and thus cause unintentional bending.

Application of compressed air between silicone and rod for easier removal

The mold and lid of the body have narrow elevations on the contact surface with the silicone. These form the grooves in the cured silicone as seen in Figure 3.10c. The fiber is placed in these grooves during the next step [Galloway et al., 2013].

Elevations in the mold provide fiber placement grooves

3.5.3 Strain-Limiting Layer

Apply strain-limiting layer to the side in which the soft robot should bend

After demolding the soft robot's body attached to the rod, the strain-limiting layer is attached to the body as described by Galloway et al. [2013]. The layer consists of a non-stretch but pliable material placed on the body's side to which it should bend and secured by wrapping a fiber along the body's grooves for a uniform distance between the windings [Galloway et al., 2013]. In contrast to Galloway et al. [2013], we used a simple non-stretch polyester sewing yarn (No. 100 by Goldmann). We decided to use a gray yarn to prevent it from being visible through the *skin*.

Parameter	**Value**
Build Plate Adhesion Type	Raft
Raft Extra Margin	40.0 mm
Raft Smoothing	5.0 mm
Raft Air Gap	0.25 mm
Raft Top Layers	0
Raft Middle Thickness	0.09 mm
Raft Middle Line Width	0.7 mm
Raft Middle Spacing	1.3 mm
Raft Base Thickness	0.24 mm
Raft Base Line Width	0.8 mm
Raft Base Line Spacing	2.3 mm

Table 3.1: Raft settings in Cura to create material for the strain-limiting layer. Since *Raft Top Layers* is set to 0, other top layer parameters are omitted in this table. Emphasized parameters deviate from Cura's default values for rafts.

Modified 3D printed raft as an alternative to woven fiberglass

As a strain-limiting layer, Galloway et al. [2013] used woven fiberglass due to its porosity [Polygerinos et al., 2015]. Due to the unavailability of this material, we tested several substitute materials which were easier for other researchers and designers to acquire as well. We tested Rigips® glass

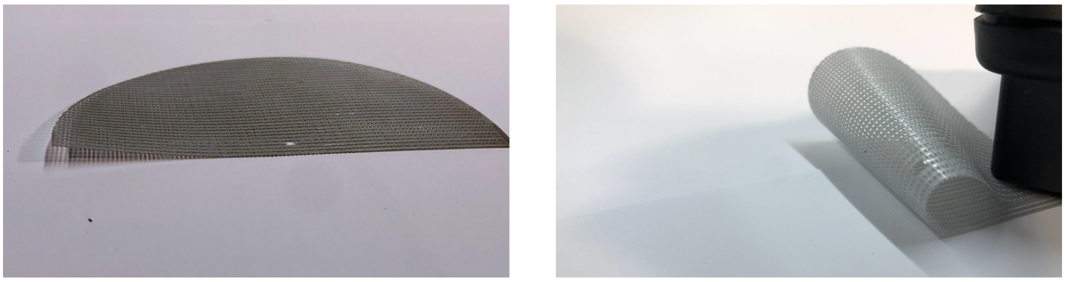

Figure 3.11: We used a strain-limiting material that was printed by manipulating the raft settings of the 3D printer's slicing software to create a mesh *(left)* that is bendable but does not stretch *(right)*.

fiber reinforcement strips, paper [Polygerinos et al., 2021], reinforcement mesh, fabric, and a 3D printed mesh. The glass fiber reinforcement strips and paper tended to rip, either when the soft robot was pulled from the rod or during later actuation. The use of the reinforcement mesh resulted in bumps on the surface of the soft robot after several actuations. Therefore, the soft robot's surface could have become a confounding variable since it differed depending on its shape. Soft robots with fabric tended to bend less under the same pressure compared to other materials. We suspect that the fabric's increased stretchiness occurred due to the liquid silicone causing the fabric fibers to swell. The 3D-printed mesh turned out to be the best replacement for our soft robots. It is easy to produce with FDM 3D printers and provides flexibility due to its inelastic nature.

We used a modified raft for the strain-limiting layer

The material used as a strain-limiting layer was created by modifying the raft settings[9] in Cura[10] (cf. Table 3.1). The raft consists of two layers of parallel separated filament lines. The layers are to each other, creating a pliable, non-stretchable, and tear-resistant mesh (cf. Figure 3.11)

Creating distinct movements by combining strain-limiting material with fiber reinforcement

Four different strain-limiting layers were needed for the soft robots of our user study. The strain-limiting fiber (i.e., non-stretch sewing yarn) was wrapped around the body along the grooves for the elongation movement [Polygeri-

[9] A technique used in FDM printers by printing multiple filament layers on the print bed before starting with the actual 3D printed object to prevent it from losing adhesion during the printing process

[10] ultimaker.com/software/ultimaker-cura

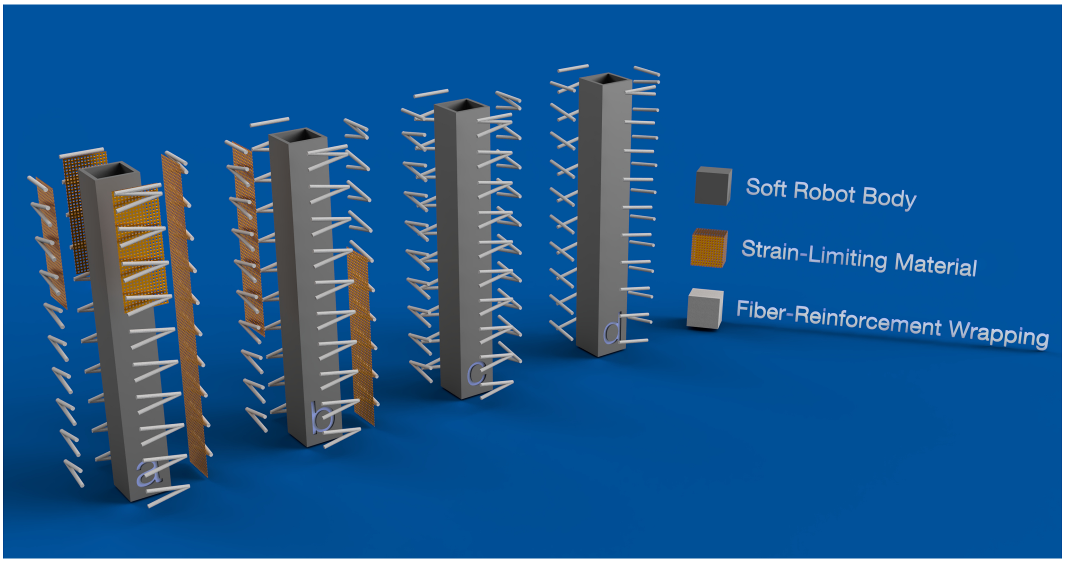

Figure 3.12: Different strain-limiting layer designs are needed to create the desired movements. The *bend* (a), *wave* (b), and *elongate* (c) layer designs use the same bi-directional fiber-reinforcement wrapping, whereas the *twist* (d) layer design uses only uni-directional wrapping. For *bend* and *wave*, strain-limiting materials are secured between the body and the wrapping. The strain-limiting material and the fiber-reinforced wrapping are displayed in an exploded-view style.

nos et al., 2021]. The wrapping was done in both directions from the beginning to the end and back (cf. Figure 3.12c). Wrapping the fiber only in one direction results in an extending *twist* movement along the longitudinal axis of the soft robot [Polygerinos et al., 2021] (cf. Figure 3.12d). The *bending* soft robot was created by applying short mesh strips to three sides and one long mesh strips to the fourth side of the body, secured by wrapping as done for the *elongation* movement. The long strip is applied over the entire length and determines the side to which the soft robot bends. The short ones are applied to the remaining three sides of the soft robot, all on the same end, covering about 1/3 of the entire length (cf. Figure 3.12a). When actuating the soft robot, this design creates a bend in the part of the soft robot where the mesh is only applied on one side. Furthermore, the section of the soft robot with a strain-limiting layer on all four sides does not change and prevents any expansion. Two mesh strips were applied on opposite sides of the body for the *wave* movement. The strips were slightly

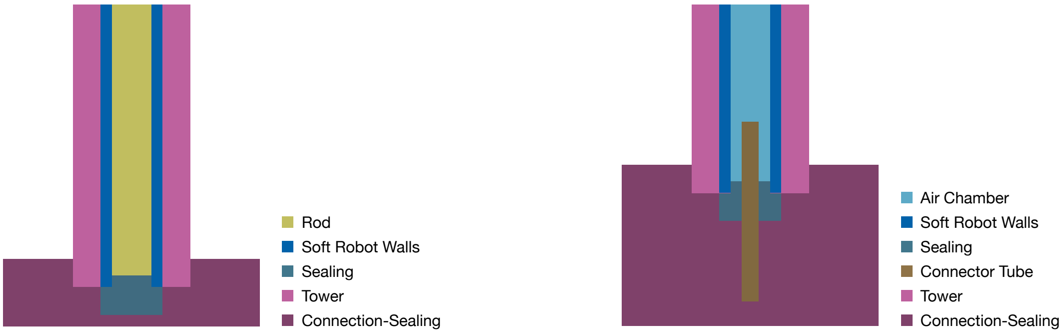

Figure 3.13: The soft robot's end is sealed by placing it inside the tower, then inserting it into the silicone filled *end-sealing* mold *(left)* or into the *connection-sealing* mold *(right)*.

longer than half of the body's total length and were aligned, respectively, at the beginning and end of the soft robot (cf. Figure 3.12d).

3.5.4 Skin

Skin covers and secures the strain-limiting layer

The skin layer is cast around the body to fix the strain-limiting layer using the mold parts depicted in Figure 3.8e-g. The silicone is poured into the mold. Afterward, the *rod*, with the body strain-limiting layer attached to it, is placed into the mold [Polygerinos et al., 2015]. After curing, the soft robot is removed from the mold and has a smooth surface which gives no indication of which strain-limiting design was used. Due to the holes in the 3D printed mesh, the silicone can flow through it and provide a stable connection between the body and the skin that holds the strain-limiting layer in its place.

Removing rod as preparation for next step

The rod needs to be removed before sealing the soft robot's end. To achieve this, the rod is fixed to the workbench with a screw clamp [Polygerinos et al., 2021], and the soft robot is separated from the rod with compressed air. While one hand is applying compressed air, the other hand carefully removes the soft robot. A release agent is again applied to the rod, facilitating the final removal without damaging the strain-limiting layer. Afterward, the rod is placed back inside the soft robot's air chamber to prevent flooding in the next step. The rod is placed so that about 2 mm of the air chamber remains open at the end of the soft robot to be sealed (cf. Figure 3.13 *left*). This ensures that silicone can reach the inside of the soft robot, but only in the first 2 mm, which ensures reliable sealing without flooding the whole air chamber.

3.5.5 Sealing and Connector

Sealing the end of the soft robot

To close the soft robot's end, the molds from Figure 3.8h-i are used. The soft robot is inserted into the *tower* lining up with its edge. The silicone is poured into the *end-sealing* mold and applied to the soft robot's contact surface to prevent tiny air bubbles from being formed between the two parts and weakening the sealing. The *tower* is then inserted into the *end-sealing* mold. The design of the 3D printed molds and the placing of the soft robot in the tower ensures that the sealing is adequately placed (cf. Figure 3.13 *left*). After curing the silicone, the soft robot is pulled out of the mold, and the rod is removed carefully.

Silicone tube is used as connector

The final step in producing the soft robot is to seal the remaining end. During this step, a silicone tube is embedded into the sealing as the soft robot's connection to the pressure control system. The soft robot is inserted into the tower and aligned with the tower's edge. A silicone tube (inner diameter of 2 mm, outer diameter of 3 mm) is cut to a length of about 40 mm. A slightly longer (about 45 mm) piece of 3D printer filament is inserted into the tube such that it sticks out at both ends. This prevents the tube from getting clogged during casting. The tube is inserted into the cylinder-shaped hole at the bottom of the *connector-sealing* mold (cf. Figure 3.8h and k). It is crucial to ensure that the end of the tube is higher than the first edge of the mold to ensure that the tube is not sealed by silicone (cf. Figure 3.13 *right*).

Embedding the tube into the second sealing

Afterward, silicone is poured into the mold up to the first edge and applied to the contact surface. As in the last step, the tower is again inserted into the mold, and the design ensures the correct alignment of the sealing, tube, and soft robot. After curing the silicone, the tower is removed, and the soft robot is gently pulled out of the mold. The soft robot should be grabbed as low as possible to prevent the connection tube from ripping off. Turning the soft robot while pulling can help. As the last step, the filament piece is pulled out of the tube with pliers. The finished soft robot can now be connected to a syringe to be actuated and tested.

Chapter 4

User Study on Conveyed Emotions

We conducted a user study to investigate whether smart jewelry with moving parts (i.e., shape-changing smart jewelry) can convey moods and emotions to a viewer and whether the material of the moving parts affects the conveyed information. We want to explore the parameters that enable shape-changing jewelry to convey the desired emotions. Furthermore, we want to explore whether the material used for the external appearance of the jewelry influences certain emotions and consequently needs to be taken into account in the design process. The answers to these questions will provide insights for researchers and designers of smart jewelry.

We conducted a user study to answer our research questions

In the user study, we showed study participants videos of different shape-changing necklaces and asked them to rate the emotion they perceived when observing the necklaces. The necklaces shown differed in the outer materials used for the movable parts and in their movement. The movement was achieved by actuating a fiber-reinforced soft robot embedded in the necklace. The soft robots were created with the process described in Chapter 3.

Participants answered questions regarding a shape-changing necklace

4.1 Aim of the Controlled Experiment

We stated hypotheses to answer the investigated research questions

In Chapter 1 "Introduction" we presented the research questions that we aim to answer with this work. The answers to these questions will contribute to the current state of research. For each research question, we stated several hypotheses. We expected to obtain evidence from the experiment's results supporting the hypotheses. As far as possible, the hypotheses were based on prior research presented in 2 "Related work".

To answer the first research question, "Can the emotions communicated by a shape-changing soft robot used in smart jewelry be controlled by manipulating the properties of the movement?" *(RQ 1)*, we stated the following four hypotheses:

- In line with the findings of Hu and Hoffman [2019], Strohmeier et al. [2016], and Davis [2015b], we expect the shape a soft robot's turns into to influence the valence of the perceived emotion *(H 1)*.
- In line with the findings of Strohmeier et al. [2016] and Hu and Hoffman [2019], we expect the presence or absence of repetition in a soft robot's movement to influence the perceived valence *(H 2)*
- In line with the findings of Strohmeier et al. [2016] and Hu and Hoffman [2019], we expect the frequency of a soft robot's movement to influence the perceived arousal *(H 3)*.
- In line with the findings of Strohmeier et al. [2016] and Hu and Hoffman [2019], we expect the amplitude of a soft robot's movement to influence the perceived arousal *(H 4)*.

According to van Waveren et al. [2019], the outer material of a robot can influence the emotions conveyed. Since the choice of material is an essential part of creating smart jewelry [Miner et al., 2001], we want to determine whether the effect is transferable to soft robots in the context of smart jewelry. In the event that we confirm the influence of outer material, jewelers would have to consider it during the design of emotion-conveying smart jewelry.

To answer our second research question, "Does the surface material of a soft robot used in smart jewelry influence the emotions conveyed by its shape change?" *(RQ 2)*, we stated the following three hypotheses:

- The soft robot's material influences arousal of the perceived emotion *(H 5)*.
- The soft robot's material influences valence of the perceived emotion *(H 6)*.
- The emotions conveyed by a leather or textile soft robot are perceived more positively than emotions conveyed by a metal or silicone soft robot *(H 7)*.

4.2 Independent Variables

One goal of the study was to determine parameters that can be manipulated to convey different emotions. Therefore, we designed movements that we expected to cover a variety of emotions. From prior work (cf. Chapter 2), we knew several factors that influence the perception of a shape-changing object in terms of conveyed emotions. We decided to manipulate the *shape*, *frequency*, and *amplitude* to create movements conveying different emotions. Furthermore, we used different *materials* for the surface of the movable part to determine their influence on the conveyed emotions.

We used three factors to create different movements and material as a fourth factor

4.2.1 Material

To investigate the influence of the material on the emotions conveyed, we covered the movable parts of the necklace with different *materials* intended to make the soft robots visually appear made of *metal*, *fabric*, and *leather*, in addition

Silicone, *metal*, *fabric*, and *leather* were tested in the study

Figure 4.1: The surface material of the soft robots used in the necklace was either *silicone*, *leather*, *metal*, or *fabric* (from left to right). Each participant in the user study was assigned one of the four materials.

to their original *silicone* surface (cf. Figure 4.1). These materials were chosen because they are common in the jewelry industry and because stretchable fabrics resembling them were available. The covers needed to be fabricated from a stretchable material in order to allow the soft robot to move. They were sewn with a specially designed cutting pattern[1] and were closed with snaps for easy and quick attachment to the soft robot. All the materials used were chosen in a similar color (gray, since it was the closest to the metallic condition) to prevent the color from affecting the perceived emotion [Song and Yamada, 2017].

4.2.2 Shape

We included bend movements to reassemble smile and frown

According to Strohmeier et al. [2016], the shape of a movement is primarily responsible for the valence rating of the perceived emotion. Furthermore, they discover that shapes which resemble symbols are suitable for influencing valence in a targeted way. For example, a shape reminiscent of corners of the mouth drawn upward or downward can convey a correspondingly positive or negative emotion. [Strohmeier et al., 2016]. Borrowing from the mouth angle example, we added a 90° bend *up*ward and *down*ward to

[1]git.rwth-aachen.de/schroeder/thesis-digital-appendix/-/tree/main/cutting-pattern

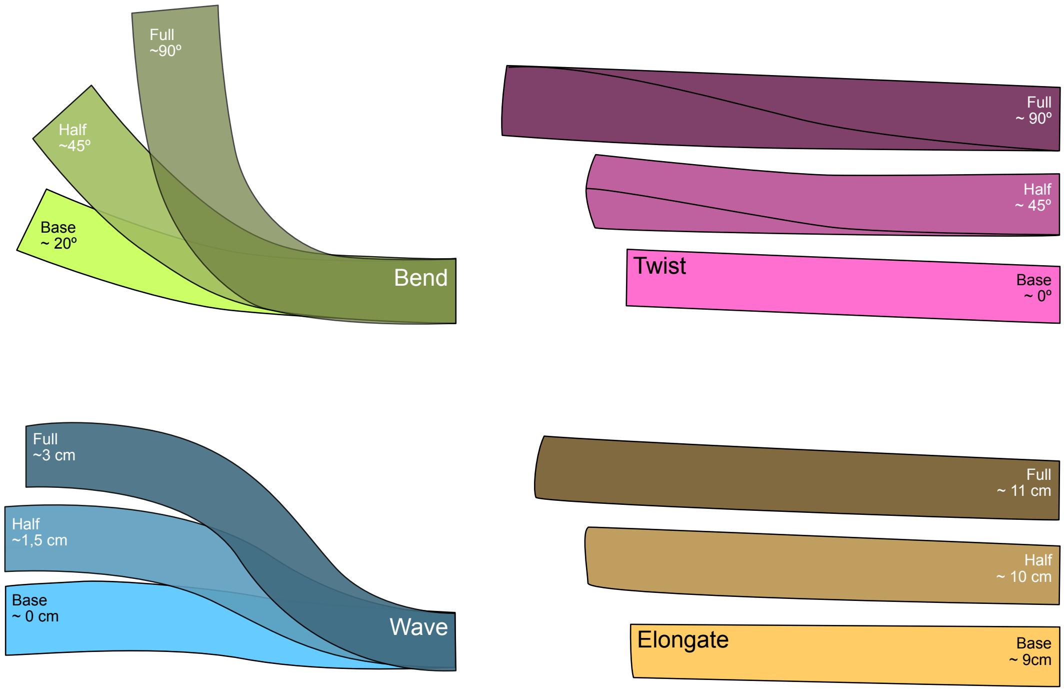

Figure 4.2: We defined the full and half amplitude for each of the four shapes (up and down combined) as shown in the figure. In addition, the graphic illustrates the shape of the soft robots with base pressure applied. We used these sketches as a reference when empirically determining the required pressures for the various combinations of material, shape, and amplitude (cf. Section 4.2.3).

each of our shapes. The curve started around the second third of the soft robot and extended to just before its end (cf. Figure 4.2 *Bend*).

Wave as a complex shape

Combining multiple bends in a single soft robot creates a more complex shape which, according to Strohmeier et al. [2016], is connected to emotions with higher arousal and lower valence. For our study, we created a soft robot with two bends in opposite directions, which shaped an "S"- or *wave*-form. In the same way as the single 90° bend, each of the two bends reached a maximum of 90° (cf. Figure 4.2 *Wave*). This shape was of interest because it could resemble an animal (e.g., a snake) to some participants. According to Davis [2015b], such associations can lead to different interpretations of the communicated emotion.

Twist as an imitation of the result of an action

The next shape resembled an object which is *twisted* due to a negative emotion (e.g., anger) (cf. Strohmeier et al. [2016]). When turned into the *twist*, the soft robot rotated its end to a maximum of 90° around its longitudinal axis to its beginning. The body was then linearly twisted between the two ends (cf. Figure 4.2 *Twist*).

Flat shape for less extreme valence values

Adding a flat shape to the user study covered the less extreme center of the valence axis [Strohmeier et al., 2016]. Therefore, we created a shape that *elongates* along its longitudinal axis (cf. Figure 4.2 *Elongate*). The soft robot used was able to extend from about 90 mm (due to base pressure larger than length of base shape, cf. Section 4.2.3) to a maximum of about 110 mm which corresponds to an extension of about 22%.

4.2.3 Repetition and Frequencies

Repetitive movements are expected to be perceived more positive

The way a movement is perceived depends not only on the form it takes, but also on whether it is repeated or not. A repetitive movement is expected to be perceived more positively [Strohmeier et al., 2016]. Furthermore, the *frequency* of a repetitive movement is expected to influence the arousal level [Hu and Hoffman, 2019].

We investigated two repetitive and one non-repetitive condition

We decided to include three levels of frequency in our study: *none* (movement is performed only once), *low* (movement repeats at $1/6$ Hz), and *high* (movement repeats at $1/3$ Hz). The *none* condition is implemented by actuating the soft robot from the start until maximum pressure is reached. Afterward, the pressure is kept constant until it is released at the end. Each condition lasts for 12 seconds. This duration was chosen because it is brief enough to keep the participant attentive, and a multiple of the two repetitive frequencies ($1/3$ Hz and $1/6$ Hz).

Utilizing a slight overpressure as base pressure increased the available frequency

The high frequency was limited by the controller's abilities (cf. Section 4.5.2). The frequencies were made possible by not deflating the soft robot completely during each period. We observed that the soft robots barely changed shape during the first part of the piston movement. This effect increased further when the material covers were applied. In addition to the lower possible frequencies, this also resulted in erratic movements since the robot would not move for a long time at the beginning and end of each period. To achieve more continuous movements and higher frequencies, we empirically determined a *base pressure* for every *combination of shape* x *material*. The base pressure is defined as a pressure where the soft robot moves only minimally, and only insignificant differences between the *shapes* occur. Furthermore, the soft robot must have the same shape for every material and respective shape (cf. Figure 4.2). This approach allowed us to keep the conditions comparable by having visually similar starting points.

4.2.4 Amplitude

The final factor of interest was the effect of differences in the *amplitude* of the movement on the perceived emotion. Strohmeier et al. [2016] and Hu and Hoffman [2019] provided evidence that changes in the *full* amplitude would change the perceived level of arousal. We defined the movements the soft robots could perform (cf. Section 4.2.2) as the *amplitude* level. As the second level, we defined the *half* amplitude condition for all shapes as depicted in Figure 4.2.

We expected amplitude also to have an effect on valence

4.3 Experimental Design

Combining the four factors, we have a 4 *material* x 5 *shape* x 3 *frequency* x 2 *amplitude* design, resulting in 120 conditions. During the pilot study, we found a single session requiring 2 hours for all trials to be too long. Therefore, we decided to make the *material* a between-subjects factor, while the remaining stayed within-subjects factors.

We investigated 120 conditions

The mixed factorial design reduced the number of trials to 30 per participant, allowing us to conduct a session in 60 to 90 minutes. Reducing the required time allowed us to mitigate fatigue effects that were likely to occur otherwise.

A mixed factorial design resulted in 30 trials per participant

Conditions were counterbalanced with a Latin square

Davis [2015b] reported that participants tend to compare the presented stimulus among trials for a similar study setup. Therefore, the order in which the necklaces are presented influences the participants' interpretation of what is communicated. We counterbalanced the conditions per group to mitigate these carryover effects with a Latin square (cf. Appendix B). Furthermore, this reduced the influence of novelty effects. The assignment to one of the four material groups was done by block randomization[2] in advance of the study.

4.4 Participants

The convenience sample for the study consists of 24 participants

A pilot study was performed with one participant. For the final study, we retrieved a convenience sample of 24 participants. One participant was excluded since we failed to preset the training videos. When we noticed the error, we decided to redo the excluded session to fill the Latin square of the corresponding group. We used a random process to decide whether the next participant should redo the condition of the excluded one or continue with the block randomization. This was performed until a participant replaced the excluded one. Our 24 final participants (0 non-binary, 10 female, 14 male) spanned a wide age range from 14 to 59 years (M = 29.21 years, SD = 10.13 years). In the case of minors, the informed consent was also signed by a person with parental authority.

Most of the participants had not heard about soft robots or smart jewelry prior to the study

Across the selected sample, experience with soft robots and smart jewelry was relatively low. More than half (13) stated that they had never heard of soft robots before the study. One participant had heard of soft robots but never seen one, and six had already seen a soft robot but not interacted with it. The remaining four had already interacted with soft robots. Participants were even less familiar with the concept of smart jewelry. Fifteen of them had never heard of smart jewelry. Five had some experience (2 heard of; 3 saw), and four had already interacted with smart jewelry.

[2] www.randomizer.org

Figure 4.3: The necklace shown to the participants consists of a golden chain that holds a pendant. Two soft robots fit into the sides of the 3D-printed pendant *(left)*. The left soft robot could change its shape by being actuated with compressed air. By changing the soft robots and their covers, diverse shape changes can be realized *(center & right)*

The user study was conducted both in the lab and in several remote locations. For participants who could not visit the lab, we offered to bring the experimental setup to a location in their vicinity to conduct the study there. With this offer, we were able to conduct the experiment with 9 participants at remote locations. The remaining 15 participants came to participate in the lab.

The study took place at the lab and at remote locations

4.5 Apparatus

The apparatus for the user study mainly consisted of two parts. The first was the apparatus used to record the videos presented in the user study. It contains the necklace with the shape-changing soft robots and the controller, which actuated them as defined by us. During the user study, the apparatus consisted mainly of the notebook used to play the videos. Additionally, a necklace and pendants of each material were presented for better comprehensibility.

4.5.1 The Shape-Changing Necklace

To provide the participants a better understanding of the appearance of a piece of smart jewelry with movable parts, we designed a prototypical shape-changing necklace that embedded our fiber-reinforced soft robots in the context of

We built a shape-changing necklace to present in the user study

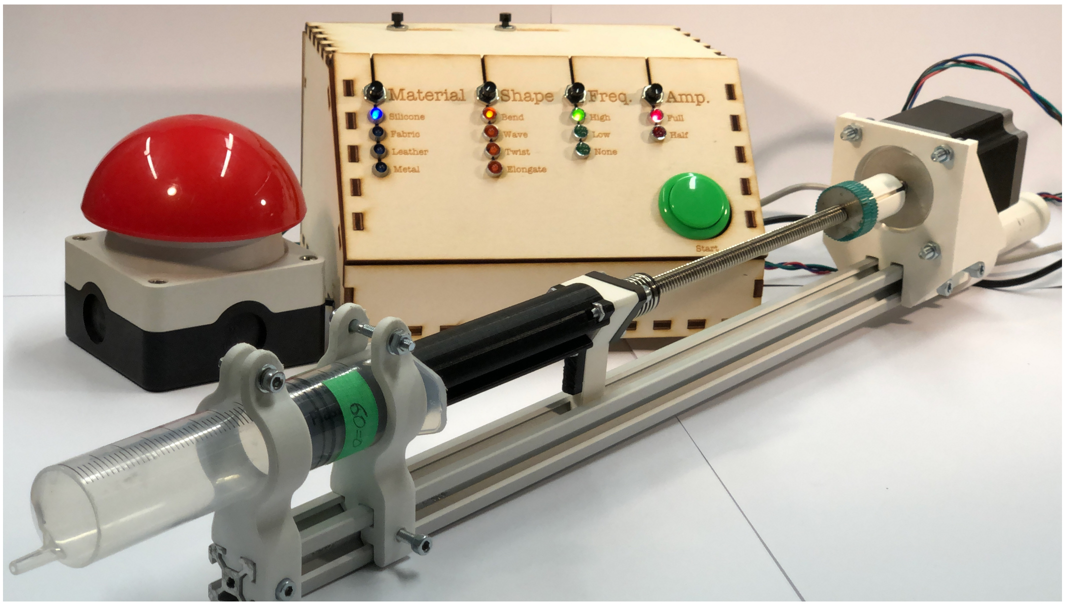

Figure 4.4: The controller consists of multiple components. A syringe and a stepper motor actuating it are attached to an aluminum profile *(foreground)* and console for configuring the controller. A red buzzer is attached to the console, which acts as an emergency stop to prevent damage and injuries.

smart jewelry. The necklace's pendant[3], as shown in Figure 4.3 *(left)*, was modeled in CAD software and printed with a 3D printer. The golden chain is connected to the eyelets on the pendant. The pendant was designed so that two soft robots with the same material can be inserted into each side. One of the soft robots (in the study, the one on the observer's left) can be actuated with compressed air via the tube that runs up the chain. By exchanging the soft robots we were able to present the necklace with different shape changes and materials as exemplified by Figure 4.3 *(center)* and *(right)*.

4.5.2 Controller

We built a controller to precisely actuate the soft robots

To actuate the soft robots with high precision, we built a hardware controller (cf. Figure 4.4) similar to the one pre-

[3] git.rwth-aachen.de/schroeder/thesis-digital-appendix/-/tree/main/pendants

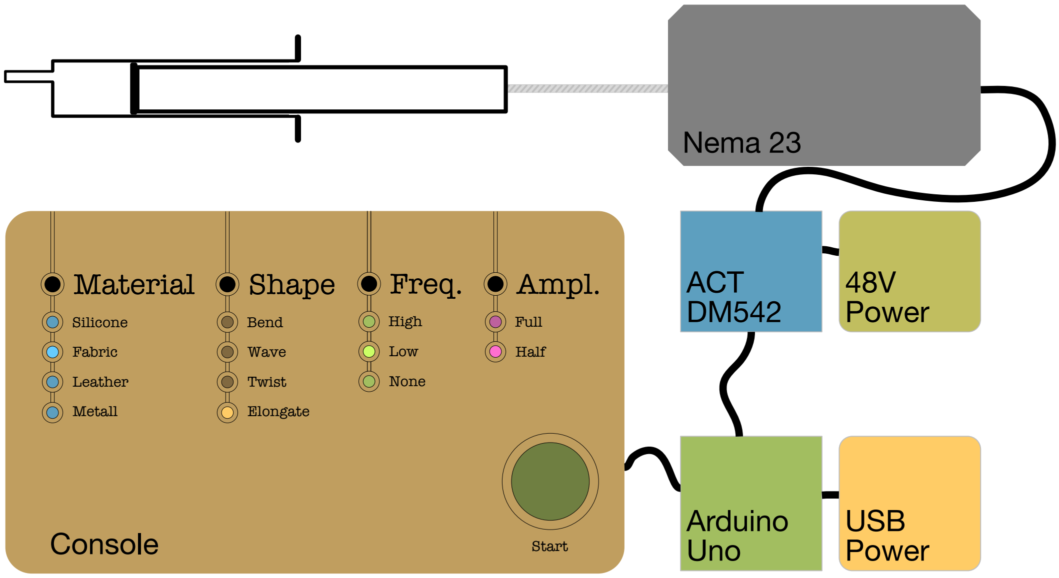

Figure 4.5: The console is connected to the Arduino Uno, which is powered by 5V USB. The Arduino controls the ACT DM526 stepper motor driver, powered by 48V DC. The driver translates the Arduino's commands into control sequences sent to the Nema 23 stepper motor, operating the syringe.

sented by Hu et al. [2018]. The controller consists of an actuation unit and a computing unit. The actuation unit provides the pressure to actuate the soft robot by moving a custom-designed 3D-printed piston[4] inside a syringe. The piston is moved by a 2-phase NEMA 23 stepper motor (Voltage: 3.0 V, Current: 3.0 A/Phase) with a holding torque of 190 Ncm. The motor is connected to the piston by a lead screw and a nut. The nut is bolted to the piston, and the lead screw is attached to the motor by a 3D printed coupling generated with the *Customizable Stepper Motor Mount for OpenBeam* by Cox [2017]. All parts are attached to an aluminum profile by additional 3D-printed mounts[5]. The adapter for the stepper motor was created with the *Customizable axis coupler* from toxnico [2014].

The controller's actuation unit operates a syringe

The computing unit is connected to the stepper motor via an ACT DM542 driver, which is controlled by an Arduino

The computing unit controls the actuation unit's stepper motor through a driver

[4] git.rwth-aachen.de/schroeder/thesis-digital-appendix/-/blob/main/controller/3D%20models/Syringe%20Connector.stl

[5] git.rwth-aachen.de/schroeder/thesis-digital-appendix/-/tree/main/controller/3D%20models

Uno. In addition to the driver, a control panel consisting of several LEDs and push buttons is connected to the Arduino (cf. Figure 4.5). The components are housed in an enclosure[6] assembled from plywood panels. The panels were cut to size using a laser cutter and were based on a template[7] created using an online generator for laser cutter templates. Pushing the green *start* button sends a command sequence to the driver to move the motor, which actuates the soft robot attached to the syringe.

Driver is controlled by raising and lowering pin voltage

The Arduino communicates with the stepper motor driver by raising and lowering the voltage on the connected pins. In doing so, the speed of the stepper motor is controlled by the time between the voltage changes. Since a step consists of raising and lowering, two intervals are required per step. Shorter intervals result in faster rotation.

Speed of syringe piston was determined by base and maximum pressure

The different *material* conditions influenced the shape and amplitude of a soft robot for a certain pressure. By using different maximum pressures for certain combinations of *material*, *shape*, and *amplitude* we were able to partially mitigate the effect, although minor differences between the materials remained. The different maximum pressures for the conditions were determined empirically, similar to the process for the base pressures described in Section 4.2.2. The required pressure can be represented by the displaced piston volume stated in ml. In addition, the constant s_p given in $steps/ml$ indicates how many steps the stepper must take to change the volume in the piston by one milliliter. The required time interval d in seconds between raising and lowering the stress for a given combination of *material*, *shape* and *amplitude* can be calculated using the piston position for base (p_{min}), maximum pressure (p_{max}) and frequency f_m by means of:

$$d = \frac{f_m \times s_p \times (p_{max} - p_{min})}{4}$$

Since the drivers API operates with microseconds represented by integer values, fractions of a microsecond were omitted by the code. Depending on the condition, this resulted in the entire movement being shorter than expected,

[6]git.rwth-aachen.de/schroeder/thesis-digital-appendix/-/tree/main/controller/lasercutter%20templates
[7]www.festi.info/boxes.py/Console2

Figure 4.6: The distance from the camera to the necklace was similar to the participants' distance to the display on which the videos were shown during the study. We used an LED ring to provide sufficient lighting.

and thus the frequency being somewhat higher than defined. We added additional delays at the pistons turning points to result in equally long animations and the required frequencies for mitigation.

4.5.3 Video Recording

Magnets were used to keep the necklace in place

For the recordings of the stimulus material[8], we placed the necklace on a mannequin. To prevent any change of the pendant's position between the recordings of the different conditions, we attached two magnets to the mannequin and another two with flipped polarity to the back of the necklace's pendant.

[8]git.rwth-aachen.de/schroeder/thesis-digital-appendix/-/tree/main/stimulus%20material/emotion

Necklace was filmed from about 75 cm distance with a 50 mm small-format equivalent focal length

In order to hide the actuation unit of the controller during the recordings, the unit was placed behind the mannequin. The necklace was filmed with a camera from a distance of about 75 cm (cf. Figure 4.6). To provide proper lighting, we used an LED ring, which was placed around the lens. Images taken with a 50 mm focal length on a small-format film provide natural-looking results [Martin et al., 2014]. Therefore, we decided to record the videos with the small-format equivalent of a 50 mm focal length. For the ASP-C sensor in the camera used, this corresponds to a focal length of 30 mm.

Camera was slightly below eye level

Due to the limitations of the mannequin stand used and the tripod used, the camera was placed 10 cm above the necklace. This resulted in a viewing angle slightly below the eye level of the mannequin. Since the point of view was only slightly below the mannequin's eyes, we believe that this factor did not affect the results.

Video of each condition lasted for 13 seconds

After the videos were recorded, they were edited into 13-second clips for each condition. The beginning of each clip faded in from black over 0.5 seconds. Likewise, the last 0.5 seconds were used for a fade-out. The total duration of 1 second for fading and the 12 seconds for a condition resulted in 13 seconds per video. To ensure playback of the videos in the correct order (i.e., as defined by the Latin square), we wrote a script[9] that creates the Latin squares (cf. Appendix B) and corresponding playlists of each group's videos [10].

4.5.4 Study

Conditions for the lab and remote situations were kept as consistent as possible,

The setup for the study was the same for both the lab (cf. Figure 4.7 *left*) and remote locations (cf. Figure 4.7 *right*). While conducting the study, we ensured in both situations

[9] git.rwth-aachen.de/schroeder/thesis-digital-appendix/-/tree/main/latin-square-playlist-generator

[10] Due to a bug in the script that occurred when creating the Latin squares, the one we used in the study repeated itself after 15 rows. This bug did not affect our study because all rows that appeared in our square were also present in the fixed version and we only used the first six rows of each square.

Figure 4.7: The user study was conducted either in the lab *(left)* or in one of several remote locations *(right)*.

that the room was well lit and no disturbances occurred. Furthermore, the layout of objects on the table was the same for all sessions. As depicted in Figure 4.7, the participants were seated in a chair at a table. In front of them, the informed consent (cf. Appendix A) and questionnaire (cf. Appendix C for the version without repetitive questions for each condition) were placed together with a pen.

To avoid bias due to changes in presentation conditions, the stimulus was always shown on the same device (MacBook Air (M1, 2020)) with the same settings (screen brightness set to maximum) at the same position. Therefore, the MacBook was placed behind the documents at about 1 m distance from the participant. The experiment conductor controlled the laptop using an external wireless keyboard.

Distance was kept constant to avoid bias

The experiment conductor was positioned on the participant's right side. This position has multiple advantages. First, the position on the participant's side is less confronting than a face-to-face situation, which we assume contributes to making the participants feel more comfortable during the study. Furthermore, the position created a distance of about 1.5–2 m between the participant and the conductor. We suspect that participants answer more freely, primarily when freely associating, if they do not feel that the experiment conductor is reading their answers. Furthermore, the experiment conductor was able to see the MacBook display during the study and was able verify that the videos were played in the correct order.

Experiment conductor was positioned right of the participant to increase their comfort

Pendants were placed on the table for comparison

The recorded videos did not accurately reflect the materials as they appeared in real life. To mitigate this disadvantage of the presentation style, we placed a pendant next to the MacBook for each material. This allowed participants to match the soft robot's material seen in the videos with their real-life appearance. A Latin square counterbalanced the order of the pendants' placement.bl

The necklace was shown on the mannequin from the videos to give an idea of dimensions

The size of the necklace on display was about 80% of its actual dimensions. To allow the participants to compare the actual dimensions of the necklace on the mannequin, we placed the setup behind the table. In the remote situation, we placed a wig head wearing the necklace on the table to keep the setup portable (cf. Figure 4.7 *left* for lab and *right* for remote).

4.6 Study Procedure

Compensations have been offered to the participants

After being greeted, the participant was seated as described in the previous section. The experiment conductor offered them snacks and drinks. In remote situations where offering drinks was not possible, this was communicated in advance, and additional snacks were offered as compensation.

Participants received an introduction after stating prior knowledge

After giving informed consent, the participants started by stating their prior knowledge of soft robots and smart jewelry. Afterward, they received a brief introduction to the topic, and the necklace was introduced and actuated on the mannequin or wig head. A necklace with a silicone soft robot was presented and manually actuated.

Participants performed two training trials

Prior to the 30 trials, the participants performed two training conditions. They were shown *elongation* x *high* x *full* and *bend upwards* x *none* x *half* (shape x frequency x amplitude) of their assigned material group to provide an overview of possible movements (cf. [Hu and Hoffman, 2019]). If the participants had no questions about the procedure, the experiment conductor continued presenting the remaining trials. Each video could be viewed a second time if desired by the participant.

As performed in the study by Davis [2015b], we asked participants after each video: "What does the necklace convey to you?" This question was asked directly after the video ended to get the very first impression. For each dimension of the Circumplex Model by Russell [1980], the participants could select one of five checkboxes. The checkboxes were printed from left to right with labeled extremes (cf. Appendix C). For the dimension of valence, the lowest (i.e., the leftmost item) was labeled with "Negative Mood" and the highest (i.e., the rightmost item) with "Postive [sic] Mood" (cf. Appendix C). The spelling mistake in labeling was noticed after conducting the study. Since none of the participants mentioned the mistake, we assume that it is negligible for the evaluation. The second dimension (arousal) of the Circumplex model was labeled with "Relaxed Mood" (lowest) and "Stimulated Mood" (highest). With the pilot study participant, we encountered that "Stimulated Mood" was hard to grasp. We decided to explain the axis of arousal more comprehensively for the remaining sessions. We emphasized that the arousal dimension does not have any positive or negative meaning since it is intended to be orthogonal to and therefore independent of the dimension of valence [Ekkekakis, 2013]. To give participants a better sense of dimension, we used the term pairs "excited-calm" and "aroused-unaroused" [Gorn et al., 2001] as alternatives for the extreme values in our oral explanation of the arousal dimension.

Measurement of the valence and arousal of the conveyed emotion

We use the terms mood and emotion interchangeably. Both terms describe the concept of a core affect and are primarily distinguished by their duration [Ekkekakis, 2013]. A mood tends to last longer than an emotion[Ekkekakis, 2013], but in our case, both describe the core affect the observer perceives when looking at the shape-changing necklace. Due to the artificial setting of our user study, the participants (i.e., the observers of the necklace) weren't able to distinguish whether the movement was shown over a longer period, which would suggest that the expression is rather a mood, or only for a short period, which would suggest that the expression is rather an emotion. The focus of this study was whether the effect could be communicated. Since a distinction between the terms would not have benefited our research, we decided to use them synonymously. The term

Since they mean the same in our context, the terms mood and emotion are used interchangeably in this work "mood" was selected for the labels of the axes as done by Davis [2015b] because we expected it to be easier to understand for the participants.

Participants should state what they associate with the necklace

Like Davis [2015b] and Bucci et al. [2018], we asked the participants to state what the necklace and its movement reminded them of (cf. Appendix C). We asked this question to help us better understand the mental model and to explain the prior answers given on the circumplex model [Davis, 2015b]. This question was asked second because the association task required reflective thinking. We encouraged the participants to state everything that came to their minds and not limit themselves to emotions.

We asked the participants to rate the outer material of the soft robots

After the trials, we offered the participants a break before we continued the study. Next, participants were shown four images of the necklace in turn, with the soft robots in each image having different shell materials. For each of the four materials *metal*, *fabric*, *silicone*, and *leather*), the participants were asked to rate whether the outer material of the moving part resembled the respective material on a 5-point Likert scale from "strongly agree" to "strongly disagree" (cf. Appendix C). The images could be viewed as long as desired. The order of the materials was counterbalanced by the Latin square of the pendants placement on the table.

We asked the participants to list all shapes they remembered

To check whether the participants were able to distinguish the different shapes, we asked them to list all the shapes they could remember (cf. Appendix C). To elaborate on the definition of "shape" without naming a specific shape from the study, we compared the movements of the soft robots to sports exercises like push-ups and crunches, which can be performed either repetitively in high or low frequency, or without repetition. Moreover, the execution of a sports exercise can be complete or incomplete. With this analogy, all participants stated that they understood the task. The questionnaire was concluded by asking for the participant's age and gender. Afterward, the participants were allowed to touch the soft robot and hold it in their hands.

We concluded the study with a semi-structured interview

We concluded the study with a semi-structured interview (cf. Appendix D). The goal of the interview was to gain a better understanding of the participants' perception of the necklace, since it was a novel kind of jewelry. We also asked for their opinions on how people express their emotions with what they wear. Finally, we were interested in the participant's jewelry wearing habits. We expected this question to give us information about the kind of jewelry they wore, and help us draw conclusions on which type of jewelry is best suited for communicating moods and emotions. Furthermore, this question enabled us to investigate reasons for wearing jewelry (e.g., for adornment or for emotional reasons). Because of the semi-structured format of the interview, we asked relevant follow-up questions whenever a topic came up that was worth exploring further.

4.7 Results

We interpreted Likert scales as interval data

In our study, we used Likert scales to let participants assess *valence* and *arousal*. In the scientific community, there is a controversy regarding the interpretation of data from Likert scales. It mainly concerns whether data from Likert scales should be handled as interval or ordinal. We are aware of this discourse and are making the data[11] resulting from the user study available for alternative evaluations. To ensure anonymity, we stored the demographic data (age, gender) with randomized participant IDs. The purpose of this is to prevent conclusions from being drawn about the answers of specific persons on the basis of this information. However, for this work, we decided to interpret Likert scales as interval data as done in most prior work in the field of smart jewelry [Davis, 2015b; Strohmeier et al., 2016; Bucci et al., 2018; Hu and Hoffman, 2019].

Effect sizes and confidence intervals are reported

Even though we collected quantitative data by asking participants to rate valence and arousal, the nature of this data is highly subjective. In order to analyze the obtained data in a more sophisticated way than null-hypothesis significance testing (NHST), we decided to report effect sizes (ES) and confidence intervals (CI) based on the *estimation* approach

[11] git.rwth-aachen.de/schroeder/thesis-digital-appendix/-/tree/main/data

described by Cumming [2013] and Dragicevic [2016]. This approach enables us to not only make dichotomous decisions about whether the null hypothesis can be rejected, but also allows us to offer a differentiated interpretation of the results. Especially in combination with the qualitative results, this appears to be a more feasible way of reporting the outcomes.

Bootstrapping was performed to obtain CIs

We averaged measurements for each participant to calculate CIs with a single measurement per participant [Dragicevic, 2016]. Calculating the mean for each condition provided us with the corresponding point estimate. For retrieving 95% CIs, we used the BCa bootstrapping [Carpenter and Bithell, 2000]. The bootstrapping method was performed with 1000 replications and used a random but fixed seed to provide reproducible results. Dragicevic [2016] and Cumming [2013] emphasize in their work that it is essential to convey the uncertainty inherent in the data and avoid reporting exact values of the estimates (point estimate and CIs) as we do in this section. However, to perform comparative work with our data, we provide the exact estimate values in Appendix E. Furthermore, we published our analysis script[12] to make our process transparent and verifiable.

Pairwise comparison was performed for within-subjects factors

We performed a pairwise comparison for each within-subjects factor to gain further insight into the data. To investigate changes in the conveyed emotion when switching from one level to another, we calculated the difference of means for two levels (e.g., *high* and *low* frequency) per participant. We then calculated point estimates and 95% confidence intervals as described before for the differences between the two levels.

4.7.1 Manipulation Checks

Most materials were perceived as intended

The results of the manipulation checks showed that for most conditions, they worked as intended. The participant rated each presented material on a 5-point Likert scale according to how strongly they agreed that it looked like

[12] git.rwth-aachen.de/schroeder/thesis-digital-appendix/-/tree/main/analysis%20script

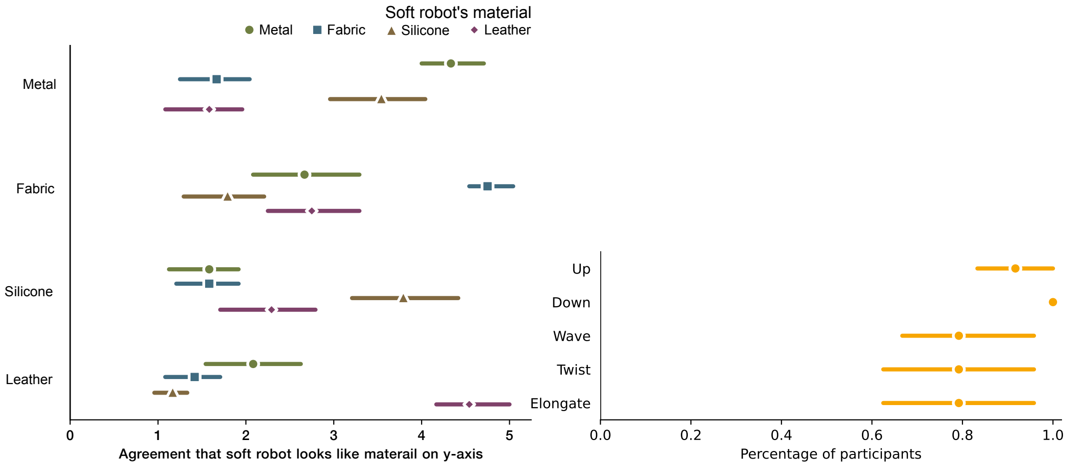

Figure 4.8: The results of the material manipulation check *left* show that participants rated the matching material significantly higher for all conditions. Since all participants remembered the soft robot turning into *down* shape, we could not used the BCa method but had to use basic bootstrapping. Furthermore, CIs had to be clipped since their values exceed 100%. The other forms were also frequently remembered. Bars are 95% CIs. and $n = 24$

metal, *fabric*, *silicone*, and *leather* (cf. Figure 4.8 *left*. Estimates of the same color belong to one presented material. Grouped estimates belong to the same material we asked for in the questionnaire). In general, most materials were perceived as intended. However, for silicone soft robots, participants agreed similarly strong that they look like *metal* and *silicone*. Some participants also inquired about the meaning of *silicone*. This suggested that not all participants had a clear image of the appearance of silicone, which may explain the material's ambiguity.

Participants remembered shapes equally well

To check whether they were able to distinguish the different shapes, the participants were asked to list all the shapes they could remember (cf. Figure 4.8 *right*). Most notably, every participant remembered the *down* shape. The other shapes were remembered similarly often. *Down* was the only shape moving downwards, which could be its reason for being remembered more often than the others. In contrast, two shapes were moving horizontally *(twist, elongate)* and two were moving upward *(up, wave)*, which the participants might have mixed up.

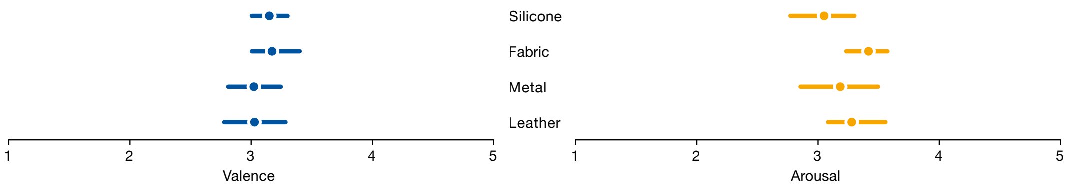

Figure 4.9: Results of *valence* and *arousal* for Material conditions with mean as the point estimate, 95% CIs, and $n = 6$.

4.7.2 Material

Low participant count for material requires the results to be interpreted carefully

The results regarding the *material* are shown in Figure 4.9. Since the material was used as a between-subjects factor, we must emphasize that we had only six participants per material condition. Even though multiple measurements were made per participant, we aggregated them as described in the above section.

Valence

No support for material influencing valence

The average valence reported by the participants (cf. Figure 4.9 *left*) shows no considerable difference based on what material the movable part of the necklace is made of. *Silicone* and *fabric* seem to be rated slightly more positively than *metal* and *leather*. However, the differences are minimal and may be the result of sampling errors. Therefore, we found no evidence that the material influences the conveyed valence *(H 6)* or that soft robots made from leather and textile are perceived more positively than metal or silicone robots *(H 7)*. It is noteworthy that the CI for *silicone* is narrower than for the other conditions, which might indicate that silicone soft robots have a lower variance in the valence they are able to convey.

Arousal

Material seems to have no significant effect on arousal

All materials rate slightly above 3 on the 5-point Likert scale (cf. Figure 4.9 *right*). The most considerable difference exists between *silicone* and *fabric*. Between all other

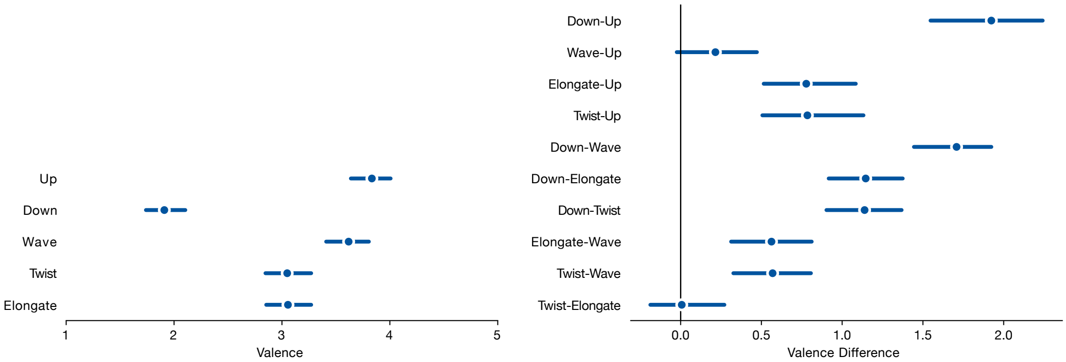

Figure 4.10: The overall *valence* rating for the different shapes is shown on the left. The change in valence in the emotion conveyed by the necklace when changing form A to B (labeled A-B) is shown on the right. Pairs were formed, and the point estimate is ≥ 0. Both diagrams show means with 95% CIs and $n = 24$.

materials, no clear difference can be reported. *Fabric* has the tightest CI, just about half the CI of metal. This may indicate that soft robots from fabric convey a smaller variety of arousal states. All findings regarding the conveyed arousal of different materials do not provide us with any insight that would support the hypothesis that the material influences the intensity (i.e., the arousal) of a conveyed emotion *(H 8)*.

4.7.3 Shape

For the five different shapes (*Up*, *Down*, *Wave*, *Twist*, and *Elongate*) the average valence level, pairwise differences, and association are reported below.

Particular shapes are most likely perceived differently in terms of valence

Up and *Wave* are the shapes with the highest *valence* rating, both with a little less than four on the 5-point Likert scale (cf. Figure 4.10 *left*). It is unlikely that a significant difference exists between these two shapes, as their difference estimate (cf. Figure 4.10 *right*) shows. Nevertheless, with high probability, both conditions result in a significantly higher valence rating than the remaining three shapes (*Down*, *Twist*, and *Elongate*). *Elongate* and *Twist* are also estimated to have little difference in their valence rating. Both have an estimate of about three, and the pairwise

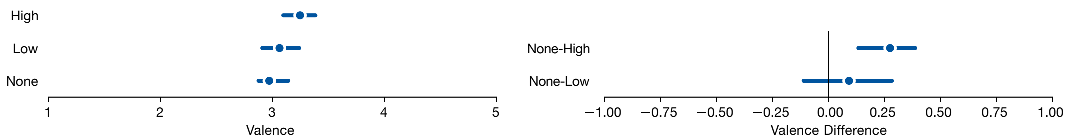

Figure 4.11: The overall *valence* rating for the different frequency levels is shown on the left. On the right, the estimated change of *valence* when switching from frequency A to frequency B is shown and labeled with *A–B*. Both diagrams show means with 95% CIs and $n = 24$.

comparison suggests no apparent difference between them. However, they seem to be most likely rated higher on the Likert scale than *Down*. *Down* is the most negatively perceived form, with an estimated rating of two. Moreover, it can be stated with a high probability that a change from *Down* to *Elongate* or *Twist* will result in a more considerable increase in valence than a change from *Elongate* or *Twist* to *Wave* (cf. Figure 4.10 *right*).

We found support for different forms conveying emotions with different valence

These findings provide some support for the hypothesis that the shape influences the conveyed emotion's valence *(H 1)*. However, not all of the five shapes resulted in significantly different valence ratings. It seems that shapes which share some similarities like *twist* and *elongate* (both stay horizontal in their movement) or *up* and *wave* (both move upwards) are more likely to convey emotions with similar valence.

4.7.4 Frequency

To verify the hypotheses regarding the effect of changes in the movement's frequency, we evaluated the results regarding valence and arousal for all three levels.

Valence

Levels of frequency result in minor differences in valance rating

In the overall valence rating for all three levels in Figure 4.11 *(left)*, we see only minor differences between the three levels. However, there is some indication of a significant difference in how positively movements without

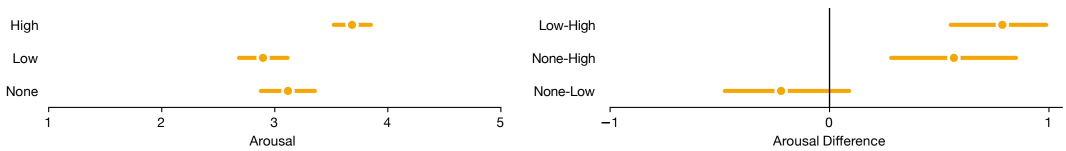

Figure 4.12: The overall *arousal* rating for the different frequency levels is shown on the left. On the right, the estimated change of *arousal* when switching from frequency A to frequency B is shown and labeled with *A–B*. Both diagrams show means with 95% CIs and $n = 24$.

repetition (*none*) and movements with high-frequency repetitions are perceived. However, the difference of about 1/4 of a level on the 5-point Likert scale is relatively small compared to the observed effect of shape changes (cf. Chapter 4.7.3). Furthermore, perceiving a significant difference between singular movements (*none*) and *low*-frequency movements is quite unlikely.

Therefore, we gained minimal support for the hypothesis that valence conveyed by non-repetitive movements differs from what is conveyed by repetitive movements *(H 2)*. Even though there seems to a different between *(none)* and *high*, the effect size is low. Thus, the statistically significant effect may not be relevant for the design of smart jewelry, since it is particularly small and possibly even nonexistent between *(none)* and *low*.

Effect size for the influence of frequency on valence may be too small to be relevant

Arousal

Analyzing the effect of repetitive movement and frequency on arousal (cf. Figure 4.12 *left*) shows non-repeating movements *(none)* and *low*-frequency movements were both rated with an arousal level of approximately three, whereas the rating for *(high)* frequency movements is estimated to be somewhat higher, with an average rating slightly below four. Investigating the differences in Figure 4.12 *(right)* also shows that *high*-frequency movements are more likely to be rated as more aroused than both non-repetitive movements (*none*) and slower repeating movements (*low*). These results provide some support for the hypothesis that frequency affects the perceived arousal *(H 3)*.

High frequency movements convey more aroused emotions than low frequency and non-repetitive movements

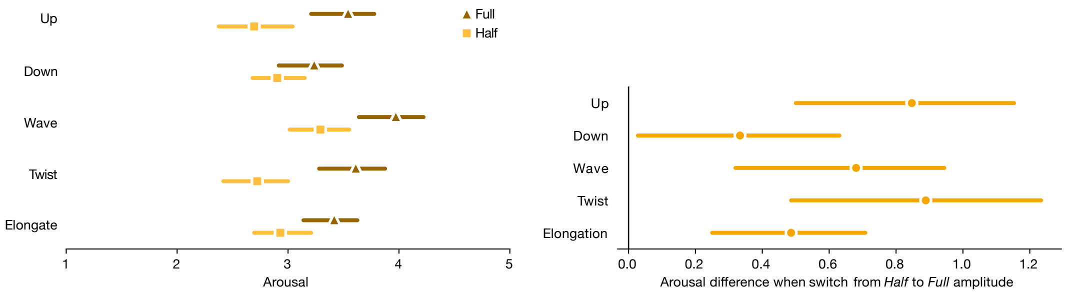

Figure 4.13: The *arousal* for *full* and *half* amplitude is shown per shape *(left)*. The arousal differences are shown on the right when switching from *half* to *full* for each shape. Both diagrams show means with 95% CIs, and $n = 24$.

4.7.5 Amplitude

Greater amplitude most likely conveys more aroused emotion

The last factor we evaluated is the level of amplitude. Since amplitude is defined independently for each shape (cf. Figure 4.2), we analyzed the interaction between each shape and each level of amplitude (*half* and *full*). Figure 4.13 *(right)* shows the arousal ratings for each amplitude level per shape. The *full* amplitude is likely perceived as more aroused for all shapes. Even though the differences between the two levels are not remarkably different among all shapes, their CIs are relatively wide. Possible differences between the amplitudes can reach from close to zero up to around one step (cf. Figure 4.13 *(right)*).

Partial support for amplitude influencing arousal

The high variance hinders a clear statement regarding the effect of different amplitude levels, which provides us only with some support for the hypothesis that the amplitude of a movement influences the arousal level *(H 4)*. However, due to the high variance, it is difficult to determine what the expected effect size is, and whether it is relevant for the design of smart jewelry.

4.7.6 Associations

We oriented our coding on the model by Mayring [2015]

The participant's answers to what the necklace reminded them of were analyzed by assigning each a code, then building up categories from these codes. We oriented our

Associations	Count
human	**434**
fictional characters	2
characteristics	11
social interactions	54
attitudes	16
(mental) conditions	120
judgements	32
facial expressions	68
gestures	65
body movements	63
body parts	3
nature	**81**
liveliness	32
animals	39
environment	10
objects	**85**
stationary objects	37
moving or movable objects	48
mobility	**34**
directions	13
movements	21
actions	**32**
results from actions	7
actions / activities	25
sports	**38**
Sum	**704**

Frequency of Occurrence
higher
lower

Table 4.1: Subcategories were created to show which general topics the participants associated with the necklace. Most associations were grouped in the *human* category, followed by the categories *nature* and *objects*. *Mobility*, *actions*, and *sports* form the smallest categories.

approach around the model for the *inductive development of categories* by Mayring [2015, p. 86]. We reviewed our categories and subcategories after about 25% of the answers. During the review, we also merged similar codes and categories. Afterward, we only created new categories if codes did not fit into one of the existing subcategories and at least two codes existed, forming a new (sub)category.

Participants often associated human-related terms

The unequivocally most extensive category is *human*. One reason for the many *human*-related associations (cf. Table 4.1) is the subcategory *(mental) conditions*, which contain a reasonable amount of emotional associations. This accumulation might be due to the rating of emotions in advance of the association question. However, even if we exclude this subsection, *human* still contains substantially more occurrences than the other categories.

The remaining medium-sized categories are *nature* and *objects*. Additionally, there are three smaller categories with *mobility*, *actions*, and *sports*, the last of which is the only top-level category containing no further subcategory.

Hereinafter we will refer to the top-level categories from Table 4.1 as *categories*. Categories on the second level in Table 4.1 are referred to as *subcategories*. They contain at least two codes that were grouped inside this subcategory. The only exception is the top-level category *sport*, which does not have any subcategories and only contains codes. For simplicity, we will also refer to *sport* as a subcategory.

Each code could be used only once per answer

Since participants were allowed to specify as many associations as they wished (even none), we coded every concepts the participants provided. If two codes in one answer belonged to the same subcategory (i.e., every non-top-level category and the *sport*s category), we only kept the first code. We assume that the first answer written down by the participant was likely also the first that came to mind. By removing these duplicates, we avoided biased results produced by naming similar things multiple times.

Material

Fewer codes for *leather* were caused by outlier

When splitting up associations by material conditions, the overall lower number of codes for *leather* is noticeable (cf. Table 4.2). This difference can be at least partially explained by an outlier in this group who provided associations that resulted in only seven codes, compared to the remaining participants with an average of about 30 codes. The distribution was relatively even for the categories *human*, *mo-*

Associations	*silicone*	*fabric*	*metal*	*leather*	Sum
human	105	118	110	101	434
nature	19	36	20	6	81
objects	31	18	19	17	85
mobility	7	10	10	7	34
actions	9	8	6	9	32
sports	16	0	19	3	38
Σ Sum	187	190	184	143	**704**

Frequency of Occurrences per Category
higher
lower

Table 4.2: Splitting up the associations with a particular top-level category by materials shows that categories other than *objects*, *nature*, and *sports* are used evenly across materials. Participants who viewed *leather* answered with fewer associations than other participants, which may be due to an outlier with only seven distinct associations. The color-coding shows the relative frequency of occurrences of a category in the named condition (i.e., color coding per row). $n = 6$.

bility, and *actions*. For *leather*, the categories *nature* and *sports* were used less frequently than for other conditions. The high amount of *object*-related connections participants made with the silicone condition is worth pointing out. Lastly, *fabric* was the only condition where no *sports* association was given.

The materials differ in terms of the subcategories used

Looking into the subcategories (cf. Table F.1) provides some additional insights. Necklaces with moving *fabric* were associated far more strongly with animals than the other materials. Therefore, terms for *movable and moving objects* were named more often in the *silicone* group. The number of terms connected to *facial expressions* was noteworthy for fabric regarding the human section. In contrast, *metal* has been more often connected to *body movements* than any other material.

Extremes might be due to few participants and habituation effects

For all these results, it is important to keep in mind that we had only six participants per condition. Furthermore, some participants reported that if they answered the association question in a particular direction (e.g., comparing the shapes with emojis), they continued with associations from this category (cf. Figure F.1). Therefore, the more extreme results in this breakdown have to be interpreted with particular caution.

Associations	*up*	*down*	*wave*	*twist*	*elongate*	Sum
human	103	112	80	75	64	434
nature	8	5	21	13	34	81
objects	14	11	16	26	18	85
mobility	2	7	2	14	9	34
actions	7	6	5	10	4	32
sports	9	0	19	5	5	38
Σ Sum	143	141	143	143	134	**704**

Frequency of Occurrences per Category: *higher* (red) – *lower* (blue)

Table 4.3: The occurrences of terms per top-level category were split by the different shapes the soft robots turned into during the study. Overall there were no noteworthy differences in the distribution of associations over the levels. The color-coding shows the relative frequency of occurrences of a category in the named condition (i.e., color coding per row). $n = 20$.

Shape

The *up* and *down* shape were often connected with facial expressions

The overall distribution is mostly even across all five shapes (cf. Table 4.3). The shapes *up* and *down* seem to evoke more *human*-related associations than the other shapes, which is especially interesting since both shapes are the same but rotated by 180°. One cause for this accumulation is that these two shapes are more often associated with the subcategory *facial expressions* (up 23, down: 26) than the others (wave: 14, twist: 1, elongation: 4). Additionally, *up* was often connected with *gestures* and *(down)* with *(mental) conditions* (cf. Table F.2).

Wave and *elongation* shapes were associated more often with nature than other shapes. *Twist* shapes were associated more often than other shapes with terms of *object*, *mobility*, and *actions*. Most of the *sport*-related terms were used for *wave* movements.

Frequency

Division of codes across frequency differed in details

The overall number of codes was divided evenly across all three levels of *frequency* (cf. Table 4.4), with the exception of the necklaces with non-repeating movements, which were more often associated with *human*-related terms than the

Associations	*high*	*low*	*none*	Sum
human	144	128	162	434
nature	31	36	14	81
objects	25	30	30	85
mobility	15	10	9	34
actions	8	10	14	32
sports	16	14	8	38
Σ Sum	239	228	237	**704**

Frequency of Occurrence per Category
higher
lower

Table 4.4: The three frequency levels evenly divided the occurrences of terms per top-level category. All three levels had a similar number of associations. The color-coding shows the relative frequency of occurrences of a category in the named condition (i.e., color coding per row). $n = 20$

low-frequency condition. Particularly *facial expressions* and *body movements* were associated with non-repeating movements, which was somewhat unexpected for *body movements* (cf. Table F.2). Another noteworthy observation inside the *human* category is that *high*-frequency movements were more often connected to *gestures* than the other frequency levels.

Furthermore, movements without repetition (*none*) were seldom associated with terms from *nature* or *sport*. Movements with a *low* frequency were more often associated with *characteristics*, *moving or movable objects*, *animals* (cf. Table F.2). The distribution was mainly even across all three frequencies for the remaining categories.

Amplitude

Only little differences between categories regarding the amplitude

The distributions are similarly even for the number of codes for each amplitude level. The distribution across all categories is also relatively even. Looking into the subcategories (cf. Table F.2) reveals some differences between the levels. It shows that *full* movements are more connected to *social interaction*, *stationary objects*, and *directions*. On the other hand, *half* amplitude movements are associated more often with *(mental) conditions*, *liveliness*, and *environment*. However, the subcategory *environment* numbered only ten

Associations	*full*	*half*	Sum
human	214	220	434
nature	36	45	81
objects	48	37	85
mobility	20	14	34
actions	18	14	32
sports	21	17	38
Σ Sum	357	347	**704**

Frequency of Occurrences per Category: *higher* … *lower*

Table 4.5: The occurrences of terms per top-level category were divided according to whether the movement had *full* or *half* amplitude. The distribution of occurring terms across the two levels is even. The color-coding shows the relative frequency of occurrences of a category in the named condition (i.e., color coding per row). $n = 20$.

terms in total, so the results must be interpreted with caution.

4.8 Evaluation

We evaluate the results presented in Section 4.7 "Results" with respect to the research questions stated in Section 4.1 "Aim of the Controlled Experiment" by combining the results from the measurements of the conveyed emotions with the answers to the open questions of what participants associated with a certain movement.

4.8.1 The Effects of Movements

Clear symbols can be used to convey a negative or positive emotion

Considering the findings regarding a soft robot's shape, we suggest creating shapes that resemble or mimic gestures when aiming to convey an emotion with a particular valence. The most clear effect on the conveyed *valence* was caused by the different shape changes of the necklace's soft robot. We can roughly divide the forms used into the three groups "positive forms", "negative forms", and "neutral forms".

The *down* bending soft robot was negatively perceived. One reason for this result may be the symbolism reported by Strohmeier et al. [2016], since participants often associated the down bend with sad faces or emojis which is confirmed by our results. Another very common association was not based explicitly on symbolism, but also on the negative judgment of downward-pointing shapes. Thus, the *down*ward bend seems to be particularly suitable for expressing more negative emotions.

Negative perception of *down* shape movements may be due to symbolism and bilogical mapping

A similar observation was made for shapes that were perceived more positively (*wave* and *up*). Both were also frequently associated with facial expressions and also with gestures. In both categories we can find examples for clearly positive associations what explains the rather high frequency of codes.

The third group was formed by shapes that were perceived as neutral with *twist* and *elongate* shapes. They were perceived as more positive than the first group, but not as positive as the third group of shapes. In terms of associations, they were more often connected with terms that may not have clear negative or positive connotations, but rather depend on the participant's prior experience similar as for the (sub)categories *animals*, *objects*, and *movements*.The lack of clear positive or negative connotations may influence people to try to make connections with familiar shapes instead [Krueger, 1975]. This high variety of associations can cause higher variance in the conveyed emotions, depending on their prior experiences. Further research might be of interest to investigate whether these more neutrally interpreted shapes tend to have higher variance in their valence rating.

Experience might be a more important factor for neutral shapes

Frequency seems to be less important when it comes to the valence of a conveyed emotion. However, it is noteworthy that the qualitative data suggests this evaluation is due to different associations (i.e., associations from different categories). We suggest further investigation on whether the interpretation of repetitive and non-repeating movements is based on different associations.

To gain a more in-depth understanding of how frequency affects the conveyed valence, we suggest investigating the

Effect of frequency on valence might be shape dependent effect of shape and frequency on valence to see if conditions mutually counteract each other. An analysis of this detail was not within this work's scope.

Non-repeating movements were experienced as tense

An explanation for non-repetitive movement having been perceived with a higher level of arousal than low-frequency levels may be that their holding of a certain shape was perceived by several participants as tense. This was also reflected in some reported associations. We assume that this is related to our definition of the non-repetitive condition. It would be worth investigating whether the non-repetitive movements would still be experienced as tense if the observer did not observe the robot's shape change, but only its still posture.

High frequency, gesture resembling movements might be well suited to convey higher arousal

Gestures were often associated with high-frequency movements. However, gestures may not necessarily convey high arousal in general. Nonetheless, it seems to be a feasible approach to convey higher arousal by using high-frequency movements which resemble gestures that also communicate a high arousal value. We suggest further investigation on high-frequency movements that resemble gestures.

Interaction between amplitude and direction of movement is possible

From our data, it is hard to determine the magnitude of the effect caused by the change in amplitude. This becomes particularly clear when comparing the differences between the amplitude levels for the shapes *up* and *down*. Their only difference is their respective upward or downward bending direction. However, estimates of the size of the change between the low amplitude levels differs across the two shapes. This suggests that the direction in which a movement is performed may also change how it is perceived.

Movements are capable of conveying different emotions

All three factors have some degree of control over which emotion is conveyed by a soft robot to an observer. Shape is especially useful in influencing the conveyed valence, even though the difference between the shapes needs to be great enough and the direction of movement may also affect the perception. We observed that the level of arousal can be controlled by frequency and amplitude, although for amplitude, the anticipated effect depends at least partially on the shape. This is to be expected, as the definition of the amplitude already depends on the shape.

4.8.2 The Effects of Material

Material may have interaction effects with other factors

Our estimates for the effect of the chosen material on valence and arousal are relatively similar across materials. However, the participants themselves provided a large number of different associations for each material. This could be indicative of interactions that were not investigated in our work. Even though there are differences in the reported occurrences of associations, we must again point out the small number of subjects in the material conditions.

Effect of material seems to be negligible

According to our data, movement factors seem to have a greater effect on the conveyed valence as well as on the the conveyed arousal. Therefore, we can state that the chosen material of the soft robot surface likely has a negligible influence on the conveyed emotion. This does not necessarily mean that designers of smart jewelry do not have to take it into account. The chosen material may interact with other factors which did not consider. Furthermore, we only provided necklaces with soft robots in motion. The results may be different if only static shapes are presented to participants.

Chapter 5

Discussion

The user study results partially confirmed our hypotheses. We showed that some findings from other application areas could be transferred into the field of smart jewelry.

Both our results concerning the influence of the shape into which the soft robot deforms on the perceived valence and the influence of the frequency and amplitude of the movement on the perceived arousal are in agreement with the results of Davis [2015b], Strohmeier et al. [2016], and Hu and Hoffman [2019]. We also partially confirmed the findings of Strohmeier et al. [2016] regarding the difference in valence between repetitive and non-repetitive movements. However, the effect does not seem to be strong enough to influence the design of a soft robot's movement. That movements with lower frequency convey lower arousal values could be confirmed for the two levels used in work by Hu and Hoffman [2019]. According to our results, this is only partially applicable to non-repeating movements that remain in full amplitude posture when reached. Finally, we were able to observe the effect of change in amplitude on the arousal level of the perceived emotion [Strohmeier et al., 2016] in our data. However, the high variance made it challenging to quantify the influence's strength on a perceived emotion.

Our results regarding the movements confirm our expectations to a large extent

For all findings regarding the soft robot's movements, it should be taken into account that participants only ob-

Observation via video may have weakened the effects served the movements via video. According to [Hu and Hoffman, 2019], the strength of the communicated emotions is expected to be weaker when presented via video as opposed to in-person observation. This may be one reason why some of our measurements resulted in comparatively small effect sizes.

The associations named were manifold

Furthermore, the variety of stated associations shows the diversity of the process of interpreting smart jewelry and the number of factors to consider. This aligns with the various different factors Strohmeier et al. [2016] reported in their work (e.g., symbolism, similarity, and consequences).

Direction of shape might be a factor

Regarding shape, we would like to raise a discussion of whether the direction of a movement could be a factor that influences valence. The results regarding the different shapes suggest that it may be not only the shape itself that determines what is conveyed, but also the direction in which it moves. This would fit the basic biological mapping stating that higher spatial placements are often associated with *more*, and lower spatial placements are often associated with *less* [Norman, 2013]. Nevertheless, further research is needed to investigate this hypothesis.

The lack of evidence for the effect of the material could be due to differences between previous research and our design

The differences in valence caused by different materials as reported by van Waveren et al. [2019] could not be confirmed by our results. However, there are several differences to consider when comparing their study with this work. One crucial factor is that the robot's movements changed throughout our experiments. Therefore, participants may have focused more on the differences between the movements. Furthermore, the material in our study was a between-subjects factor while the it was a within-subjects factor in their study. Furthermore, it was the only changing factor in their study. As a result, our participants may not have paid particular attention to the material used. We assume that our setup provides greater external reliability since, in a real-world scenario, a sudden change of the soft robots' surface material, as in the study of van Waveren et al. [2019], is unlikely. In conclusion, we expect that the material choice of a smart jewelry piece will remain a primarily aesthetic choice, even for emotion-conveying, shape-changing smart jewelry.

Chapter 6

Summary and Future Work

Finally, we would like to summarize the contributions presented in this paper and point out the limitations of the chosen approach. Building on these, we want to identify potential future research questions and fields. We also make some suggestions on how to improve the tools we developed for making soft robots.

6.1 Summary and Contributions

User study results provide insights for the design of shape-changing emotion-conveying smart jewelry.

In this work, we investigated the factors that play a role when emotions are conveyed by an intelligent piece of jewelry that contains a moving soft robot. To this end, we conducted a user study in which participants were shown videos of a shape-changing necklace. We recorded which emotions the participants perceived and which associations they made. Our results show that it is possible to use the shape-changing abilities of smart robots to convey different emotions. We found that the resulting shape of the soft robot as well as the frequency and amplitude of its movements are important factors in conveying a certain emotion. Furthermore, the results from the user study offer insight on what the participants associate with certain movements. These associations provide information about the observer's mental models, which may have influenced which emotions they perceived. This data not only provides an overview of the association's categories but also provides information about how the frequency changes across the different levels of the conditions. This information can help designers to establish new methods of communication through shape-changing smart jewelry.

The parametric mold generation tool allows customized fiber-reinforced soft robots

In addition to this main contribution, we made several minor contributions in the field of soft robotics and smart jewelry. First, we created a parametric tool for the generation of soft robot molds. The molds are used to fabricate fiber-reinforced soft robots as described by Galloway et al. [2013]. The presented tool allows various parameters to be changed, such as the dimensions and wall thickness of the soft robot. This enables users to design fiber-reinforced actuators according to their specific needs.

Simplified fabrication process of fiber-reinforced actuators

We additionally contributed by adjusting the process of creating fiber-reinforced soft robots [Polygerinos et al., 2021] in various ways. First, we improved the sealing process to use less material by creating extra molds suitable for this step. Furthermore, we presented a simpler and quicker way of embedding connectors into soft robots. Finally, we provided an alternative material for the strain-limiting layer which can be easily created by a 3D-printer. With all these improvements, we reduce the requirements that must be met in order to carry out the fabrication process.

Publication of all parts needed for the construction of the presented soft robotic controller

Lastly, we published[1] all schematics, 3D models, laser cutting templates, software and other resources required to build the controller that actuates the soft robot. Even though the display was designed for the conditions in the user study, the models can be changed and adapted for other use cases as well. With this controller we provide a working solution that supports users in precisely controlling the movements of a soft robotic actuator.

[1] git.rwth-aachen.de/schroeder/thesis-digital-appendix

6.2 Limitations and Future Work

During the course of the study we had to make several compromises and limit our research on certain factors. However, we want to provide some ideas for further improvements for both the created artifacts and the design of the user study.

6.2.1 Artifacts

We suggest further improvement of the soft robot's connection

We introduced some improvements to the fabrication process of fiber-reinforced soft robots as presented by Polygerinos et al. [2021] especially for smaller actuators. Nevertheless, there were some disadvantages and necessary compromises for which solutions could be sought in the future. We simplified the connection of the soft robots by embedding a silicone tube into the soft robot. However, this connection did not always hold during removal from the mold or during actuation, which caused the tube to detach from the soft robot. We could reduce the occurrence of the problem by cleaning the tube, mold and soft robot in advance in order to remove any residual release agent. Nevertheless, the problem still occurred on occasion, so we propose looking for a more reliable and yet similarly simple solution.

Ensure all covers influence shape in a similar way

During the study we observed that the covers slightly influenced the shape of the soft robot. Therefore, the material might be a confounding variable for the presented shapes. For future studies, we suggest using covers that uniformly constrain the movement of the soft robots to mitigate the aforementioned effect.

Soft robots need to be more reliable and reproducible for in-person studies

Additional improvements to the soft robot's reliability and reproducibility would allow for in-person studies. For such a study, it would be necessary to ensure that the soft robots did not change over the course of the study. This could be achieved by optimizing the process such that the soft robots did not break or move differently throughout the study. Alternatively, it would also be possible to improve the process so that the soft robots with the same shape did not differ from each other (i.e., to reduce their variability). Furthermore, a mechanism would be needed to enable quick switching between the different conditions. An in-person study employing the method we used to change the shape and material conditions, with the same number of conditions we had, could not feasibly be executed in a reasonable amount of time.

To allow higher frequencies, another type of actuation system would be required. Even though the stepper motor enabled us to define particularly precise movements, its movement speed would be inadequate. One option would be using a thread with a higher ratio, but this could exceed the torque of the motor. An alternative controller system that may enable higher frequencies would be FlowIO presented by Shtarbanov [2021]. However, it would be necessary to determine whether the pumps supplied met the pressure requirements of the soft robot.

The tool for creating fiber-reinforced soft robot molds enables the generation of a variety of soft robots. To increase the usability of the tool, we suggest allowing the researcher to define the resulting soft robot in a more flexible manner. Since only two of the three parameters – "overall dimension" "air chamber size" and "wall thickness" – are needed, we suggest allowing the user to choose freely which of them they want to use to define their soft robot. To increase the variety of possible soft robots, we propose adding base shapes such as cylinders, half cylinders and prisms. Finally, to reduce the number of trials, we suggest enhancing the tool with a simulation of the resulting soft robot, as done in the tool SoRoCAD described in Section 2.1.1 "SoRoCAD".

6.2.2 Additional Factors

Variation in video length may be better than delays

In section 4.5 "Apparatus" we describe how short delays were added to keep the duration consistent across all conditions. Since one participant explicitly mentioned these short breaks, we suspect they may have been a confounding variable. In retrospect, videos with minimal differences in their lengths may have been less conspicuous.

For the non-repetitive condition, we chose to create a movement that could be approximated with a square function, where the maximum was reached as quickly as possible and held over a longer period before finally returning to the starting position. Two other ways of designing a non-repetitive movement would be either using a continuous and therefore slower change of shape that is similar to a sine function, or by simply showing the maximum amplitude without movement at all. Each way has its own aesthetic advantages and should be investigated in subsequent studies.

Other implementations for non-repeating movements are possible

In our study we tested only a limited selection of shapes. Our selection may have been too small to make a general claim about certain types of shapes. However, we saw indications that particularly the direction in which a shape moves has an influence on the mediated valence. We suggest closer examination of these characteristics of shape-changing objects in the context of conveyed emotions.

Further investigation on shapes direction is required

Another factor not included in our study is the color of smart jewelry. Color, similar to material, is an especially important factor in the design of jewelry. As shown by Löffler et al. [2018] colors are able to convey certain emotions and therefore should be investigated in the context of emotion-conveying soft robots and smart jewelry.

Color should be investigated as an important factor in future studies

6.2.3 Study Design

Our user study was based on a somewhat artificial approach. We showed the participants a number of different movements over a short period of time. We assumed that this would not correspond to everyday use. Therefore, we suggest that further studies confirm the results we have shown by means of in-situ studies. This could involve simulating different everyday situations in which one or more people wear a piece of smart jewelry similar to the necklace used in this work.

In-situ studies might complement our findings

To investigate the topic of conveying emotions from another direction, we suggest performing a study were the

Conduct studies where users can define movements participants can freely design their own movements for a given emotion. Similar approaches have been performed by Wobbrock et al. [2009] for identifying natural touch screen gestures and by Strohmeier et al. [2016] for identifying shapes to communicate emotions.

We suggest to use the presented necklace as device to convey emotions to the wearer

In our study, we focused on emotions conveyed through observation of a necklace. However, the findings of Hu and Hoffman [2019] showed that emotions are communicated more confidently and more intensely (in terms of valence) through touch. Therefore, reversing the direction of communication by letting a necklace express emotions through movement which are targeted at the wearer may be a worthy approach for future research. This also enables many-to-one communication, whereas our approach provides one-to-many communication.

6.3 Conclusion

The further development of small electrical components, their affordability and availability, and information about their potential use cases have recently led to the exploration of various new concepts in the field of smart jewelry. This new development is expected to continue and ultimately attract greater public attention beyond academic and artistic circles. With our work, we hope to make a small contribution to support designers of smart jewelry in their development and discovery of new possibilities for interaction and communication.

Appendix A

Informed Consent

In this section the informed consent is provided as hand to the participants in the user study described in Chapter 4. The participants could choose to either sign the English (cf. Figure A.1) or German (cf. Figure A.2) version.

Informed Consent

Experimental study on the conveyance of emotions through a necklace containing movable parts

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Study goal: The goal of this study is to understand how a piece of jewelry with moving parts can be used by the person wearing it to communicate certain emotions to their environment. Furthermore, the study aims to create an understanding of which factors are involved in this process and how manipulation of them can be used to communicate desired emotions. In the study, participants are asked to rate which emotion a piece of jewelry shown communicates. Furthermore, the participants are asked to answer related questions. The data listed in the following item will be included in the analysis.

Recorded Data: The following data is recorded during the interview and stored anonymously by using identification numbers:

- Information, which the participant enters into the questionnaire
- Notes were taken by the principal investigator (You are welcome to review the notes at the end of the study to ensure that they do not reveal any information about the participant)
- Audio recording during the interview

Procedure: Participation in this study will involve four phases:

- The participants receive a brief introduction to the topic and asked about prior experiences.
- Afterward, pre-recorded videos and pictures of a piece of jewelry with moveable parts are presented. After each video/picture, the participants are asked to answer questions.
- In the third phase, the participants are asked to answer a demographics questionnaire.
- Finally, the subjects are asked some questions about jewelry and emotions in an interview.

Risks: You may become fatigued during the course of your participation in the study. You will be given opportunities to rest, and additional breaks are also possible. During the introduction, a necklace is actuated. In rare cases, a connection of the air system might lose and the compressed air can cause a loud noise. They are not expected to harm you but if you tend to be jumpy it might be that you get frightened. If you experience any kind of discomfort it is totally fine to pause or cancel the study at any point. Should completion of either the task or the questionnaire become distressing to you, it will be terminated immediately.

Benefit: The results of the study can contribute to the understanding of how novel types of jewelry can be used by their wearer to communicate to the surrounding.

Alternatives to Participation: Participation in this study is voluntary. You are free to withdraw or discontinue the participation.

Cost and Compensation: Participation in this study will involve no cost to you. There will be snacks and drinks for you during and after the participation.

Confidentiality: All information collected during the study period will be kept strictly confidential. You will be identified through identification numbers. The data is going to be used for publications or reports (e.g., master thesis or conference paper). Thereby it is ensured that no identifying information about a participant is contained in them. If you agree to join this study, please sign your name below.

□ I have read and understood the information on this form.
□ I have had the information on this form explained to me.

Participant's Name Participant's Signature Date

Principal Investigator Date

Upon request, it is possible to receive a copy of this document. If you have any questions regarding this study, please contact Sören Schröder at soeren.schroeder@rwth-aachen.de

Figure A.1: Informed consent in English as presented in the user study.

Informierte Zustimmung (Informed Consent)

Experimentelle Studie über die Vermittlung von Emotionen durch eine Halskette mit beweglichen Teilen

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Studienziel: Ziel dieser Studie ist es, zu verstehen, wie ein Schmuckstück mit beweglichen Teilen von der tragenden Person genutzt werden kann, um ihrer Umgebung bestimmte Emotionen zu kommunizieren. Darüber hinaus soll ein Verständnis dafür geschaffen werden, welche Faktoren an diesem Prozess beteiligt sind und wie diese manipuliert werden können, um gewünschte Emotionen zu vermitteln. In der Studie werden die Teilnehmer:innen gebeten zu bewerten welche Emotion ein gezeigtes Schmuckstück kommuniziert. Darüber hinaus werden die Teilnehmer:innen gebeten, damit verbundene Fragen zu beantworten. Die im folgenden Punkt aufgelisteten Daten werden in die Analyse einfließen.

Aufgezeichnete Daten: Die folgenden Daten werden während des Interviews aufgezeichnet und unter Verwendung von Identifikationsnummern anonymisiert gespeichert:

- Informationen, welche die Teilnehmer:innen in den Fragebogen einträgt
- Notizen, die von der Versuchsleitung angefertigt wurden (Sie können die Notizen am Ende der Studie gerne einsehen, um sicherzustellen, dass diese keine Rückschlüsse auf die Teilnehmer:innen zulassen)
- Audioaufzeichnung während des Interviews

Verfahren: Die Teilnahme an dieser Studie erfolgt in vier Phasen:

- Die Teilnehmer:innen erhalten eine kurze Einführung in das Thema und werden nach ihren bisherigen Erfahrungen befragt.
- Danach werden voraufgezeichnete Videos und Bilder eines Schmuckstücks mit beweglichen Teilen gezeigt. Nach jedem Video/Bild werden die Teilnehmer:innen gebeten, Fragen zu beantworten.
- In der dritten Phase werden die Teilnehmer:innen gebeten, einen demographischen Fragebogen zu beantworten.
- Schließlich werden den Teilnehmer:innen in einem Interview einige Fragen zu Schmuck und Emotionen gestellt.

Risiken: Im Laufe Ihrer Teilnahme ist das Auftreten von Ermüdungserscheinungen bei den Teilnehmer:innen möglich. Es wird die Gelegenheit zur Pause geben und auch weitere Pausen sind möglich. Während der Einführung wird eine Halskette betätigt. In seltenen Fällen kann sich ein Anschluss des Luftsystems lösen und die entweichende Druckluft kann ein lautes Geräusch verursachen. Es ist nicht zu erwarten, dass Ihnen dies schadet. Wenn Sie aber zur Schreckhaftigkeit neigen, kann es sein, dass Sie sich erschrecken. Wenn Sie sich in irgendeiner Form unwohl fühlen, ist es völlig in Ordnung, die Studie zu unterbrechen oder abzubrechen. Sollte die Bearbeitung der Aufgabe oder des Fragebogens für Sie zu einer Belastung werden, wird die Studie sofort abgebrochen.

Nutzen: Die Ergebnisse der Studie können dazu beitragen, zu verstehen, wie neuartige Schmuckstücke von ihren Trägern zur Kommunikation mit der Umgebung genutzt werden können.

Alternativen zur Teilnahme: Die Teilnahme an dieser Studie ist freiwillig. Es steht Ihnen frei, die Teilnahme zurückzuziehen oder abzubrechen.

Kosten und Entschädigung: Die Teilnahme an dieser Studie ist für Sie kostenlos. Während und nach der Teilnahme gibt es Snacks und Getränke für Sie.

Vertraulichkeit: Alle während des Studienzeitraums erhobenen Informationen werden streng vertraulich behandelt. Sie werden durch Identifikationsnummern identifiziert. Die Daten werden für Veröffentlichungen oder Berichte (z. B. Masterarbeiten oder Konferenzbeiträge) verwendet. Dabei wird sichergestellt, dass diese keine identifizierenden Informationen über die Teilnehmer:innen enthalten. Wenn Sie sich mit der Teilnahme an dieser Studie einverstanden erklären, unterschreiben Sie bitte unten Ihren Namen.

□ Ich habe die Informationen auf diesem Formular gelesen und verstanden.
□ Ich habe mir die Informationen auf diesem Formular erklären lassen.

Name der teilnehmenden Person	Unterschrift der teilnehmenden Person	Datum
	Unterschrift des Versuchsleiters	Datum

Auf Wunsch ist die Aushändigung einer Kopie dieses Dokuments möglich. Wenn Sie Fragen zu dieser Studie haben, wenden Sie sich bitte an Sören Schröder unter soeren.schroeder@rwth-aachen.de.

Figure A.2: Informed consent in German as presented in the user study.

Appendix B

Latin Square

This section provides the Latin square as it was used by the experiment conductor during the user study.

Trial (column) x Participant (row)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	UHF	UHH	ENH	ULF	ENF	ULH	ELH	UNF	ELF	UNH	EHH	DHF	EHF	DHH	TNH	DLF	TNF	DLH	TLH	DNF	TLF	DNH	THH	WHF	THF	WHH	WNH	WLF	WNF	WLH
2	WNF	WNH	WLH	THF	WLF	THH	WHH	TLF	WHF	TLH	DNH	TNF	DNF	TNH	DLH	EHF	DLF	EHH	DHH	ELF	DHF	ELH	UNH	ENF	UNF	ENH	ULH	UHF	ULF	UHH
3	ULF	ULH	UHH	UNF	UHF	UNH	ENH	DHF	ENF	DHH	ELH	DLF	ELF	DLH	EHH	DNF	EHF	DNH	TNH	WHF	TNF	WHH	TLH	WLF	TLF	WLH	THH	WNF	THF	WNH
4	THF	THH	WNH	TLF	WNF	TLH	WLH	TNF	WLF	TNH	WHH	EHF	WHF	EHH	DNH	ELF	DNF	ELH	DLH	ENF	DLF	ENH	DHH	UHF	DHF	UHH	UNH	ULF	UNF	ULH
5	UNF	UNH	ULH	DHF	ULF	DHH	UHH	DLF	UHF	DLH	ENH	DNF	ENF	DNH	ELH	WHF	ELF	WHH	EHH	WLF	EHF	WLH	TNH	WNF	TNF	WNH	TLH	THF	TLF	THH
6	TLF	TLH	THH	TNF	THF	TNH	WNH	EHF	WNF	EHH	WLH	ELF	WLF	ELH	WHH	ENF	WHF	ENH	DNH	UHF	DNF	UHH	DLH	ULF	DLF	ULH	DHH	UNF	DHF	UNH
7	DHF	DHH	UNH	DLF	UNF	DLH	ULH	DNF	ULF	DNH	UHH	WHF	UHF	WHH	ENH	WLF	ENF	WLH	ELH	WNF	ELF	WNH	EHH	THF	EHF	THH	TNH	TLF	TNF	TLH
8	TNF	TNH	TLH	EHF	TLF	EHH	THH	ELF	THF	ELH	WNH	ENF	WNF	ENH	WLH	UHF	WLF	UHH	WHH	ULF	WHF	ULH	DNH	UNF	DNF	UNH	DLH	DHF	DLF	DHH
9	DLF	DLH	DHH	DNF	DHF	DNH	UNH	WHF	UNF	WHH	ULH	WLF	ULF	WLH	UHH	WNF	UHF	WNH	ENH	THF	ENF	THH	ELH	TLF	ELF	TLH	EHH	TNF	EHF	TNH
10	EHF	EHH	TNH	ELF	TNF	ELH	TLH	ENF	TLF	ENH	THH	UHF	THF	UHH	WNH	ULF	WNF	ULH	WLH	UNF	WLF	UNH	WHH	DHF	WHF	DHH	DNH	DLF	DNF	DLH
11	DNF	DNH	DLH	WHF	DLF	WHH	DHH	WLF	DHF	WLH	UNH	WNF	UNF	WNH	ULH	THF	ULF	THH	UHH	TLF	UHF	TLH	ENH	TNF	ENF	TNH	ELH	EHF	ELF	EHH
12	ELF	ELH	EHH	ENF	EHF	ENH	TNH	UHF	TNF	UHH	TLH	ULF	TLF	ULH	THH	UNF	THF	UNH	WNH	DHF	WNF	DHH	WLH	DLF	WLF	DLH	WHH	DNF	WHF	DNH
13	WHF	WHH	DNH	WLF	DNF	WLH	DLH	WNF	DLF	WNH	DHH	THF	DHF	THH	UNH	TLF	UNF	TLH	ULH	TNF	ULF	TNH	UHH	EHF	UHF	EHH	ENH	ELF	ENF	ELH
14	ENF	ENH	ELH	UHF	ELF	UHH	EHH	ULF	EHF	ULH	TNH	UNF	TNF	UNH	TLH	DHF	TLF	DHH	THH	DLF	THF	DLH	WNH	DNF	WNF	DNH	WLH	WHF	WLF	WHH
15	WLF	WLH	WHH	WNF	WHF	WNH	DNH	THF	DNF	THH	DLH	TLF	DLF	TLH	DHH	TNF	DHF	TNH	UNH	EHF	UNF	EHH	ULH	ELF	ULF	ELH	UHH	ENF	UHF	ENH
16	UHF	UHH	ENH	ULF	ENF	ULH	ELH	UNF	ELF	UNH	EHH	DHF	EHF	DHH	TNH	DLF	TNF	DLH	TLH	DNF	TLF	DNH	THH	WHF	THF	WHH	WNH	WLF	WNF	WLH
17	WNF	WNH	WLH	THF	WLF	THH	WHH	TLF	WHF	TLH	DNH	TNF	DNF	TNH	DLH	EHF	DLF	EHH	DHH	ELF	DHF	ELH	UNH	ENF	UNF	ENH	ULH	UHF	ULF	UHH
18	ULF	ULH	UHH	UNF	UHF	UNH	ENH	DHF	ENF	DHH	ELH	DLF	ELF	DLH	EHH	DNF	EHF	DNH	TNH	WHF	TNF	WHH	TLH	WLF	TLF	WLH	THH	WNF	THF	WNH
19	THF	THH	WNH	TLF	WNF	TLH	WLH	TNF	WLF	TNH	WHH	EHF	WHF	EHH	DNH	ELF	DNF	ELH	DLH	ENF	DLF	ENH	DHH	UHF	DHF	UHH	UNH	ULF	UNF	ULH
20	UNF	UNH	ULH	DHF	ULF	DHH	UHH	DLF	UHF	DLH	ENH	DNF	ENF	DNH	ELH	WHF	ELF	WHH	EHH	WLF	EHF	WLH	TNH	WNF	TNF	WNH	TLH	THF	TLF	THH
21	TLF	TLH	THH	TNF	THF	TNH	WNH	EHF	WNF	EHH	WLH	ELF	WLF	ELH	WHH	ENF	WHF	ENH	DNH	UHF	DNF	UHH	DLH	ULF	DLF	ULH	DHH	UNF	DHF	UNH
22	DHF	DHH	UNH	DLF	UNF	DLH	ULH	DNF	ULF	DNH	UHH	WHF	UHF	WHH	ENH	WLF	ENF	WLH	ELH	WNF	ELF	WNH	EHH	THF	EHF	THH	TNH	TLF	TNF	TLH
23	TNF	TNH	TLH	EHF	TLF	EHH	THH	ELF	THF	ELH	WNH	ENF	WNF	ENH	WLH	UHF	WLF	UHH	WHH	ULF	WHF	ULH	DNH	UNF	DNF	UNH	DLH	DHF	DLF	DHH
24	DLF	DLH	DHH	DNF	DHF	DNH	UNH	WHF	UNF	WHH	ULH	WLF	ULF	WLH	UHH	WNF	UHF	WNH	ENH	THF	ENF	THH	ELH	TLF	ELF	TLH	EHH	TNF	EHF	TNH
25	EHF	EHH	TNH	ELF	TNF	ELH	TLH	ENF	TLF	ENH	THH	UHF	THF	UHH	WNH	ULF	WNF	ULH	WLH	UNF	WLF	UNH	WHH	DHF	WHF	DHH	DNH	DLF	DNF	DLH
26	DNF	DNH	DLH	WHF	DLF	WHH	DHH	WLF	DHF	WLH	UNH	WNF	UNF	WNH	ULH	THF	ULF	THH	UHH	TLF	UHF	TLH	ENH	TNF	ENF	TNH	ELH	EHF	ELF	EHH
27	ELF	ELH	EHH	ENF	EHF	ENH	TNH	UHF	TNF	UHH	TLH	ULF	TLF	ULH	THH	UNF	THF	UNH	WNH	DHF	WNF	DHH	WLH	DLF	WLF	DLH	WHH	DNF	WHF	DNH
28	WHF	WHH	DNH	WLF	DNF	WLH	DLH	WNF	DLF	WNH	DHH	THF	DHF	THH	UNH	TLF	UNF	TLH	ULH	TNF	ULF	TNH	UHH	EHF	UHF	EHH	ENH	ELF	ENF	ELH
29	ENF	ENH	ELH	UHF	ELF	UHH	EHH	ULF	EHF	ULH	TNH	UNF	TNF	UNH	TLH	DHF	TLF	DHH	THH	DLF	THF	DLH	WNH	DNF	WNF	DNH	WLH	WHF	WLF	WHH
30	WLF	WLH	WHH	WNF	WHF	WNH	DNH	THF	DNF	THH	DLH	TLF	DLF	TLH	DHH	TNF	DHF	TNH	UNH	EHF	UNF	EHH	ULH	ELF	ULF	ELH	UHH	ENF	UHF	ENH

Table B.1: The Latin square as it was used to counterbalance order effects among participants in the user study.

Appendix C

Questionnaire

This section provides the questionnaire as it was handed to the participants to answer the questions during the user study. Pages 2–17 are omitted since they are identically to page 1

Prior Knowledge 1 ID:__________

How much experience do you have with “soft-robots”?
Wie viel Erfahrung haben sie mit “Soft-Robotern” (engl. Soft-robots)?

Never seen or heard about in advance of this study *Vor der Studie noch nie gesehen oder davon gehört*	☐
Heard about in advance of this study but never seen or interacted with *Vor der Studie schon von gehört aber noch nicht gesehen oder mit interagiert*	☐
Seen in advance of this study but not interacted with *Vor der Studie schon gesehen aber noch nicht mit interagiert*	☐
Interacted with in advance to this study *Vor der Studie bereits mit interagiert*	☐

If you did select one of the three last options please give an example of a “soft-robot” or explain briefly what this means to you:
Wenn Sie eine der drei letzten Optionen gewählt haben, nennen Sie bitte ein Beispiel für einen "Soft-Roboter" oder erklären Sie kurz, was Sie darunter verstehen:

How much experience do you have with “smart jewelry”?
Wie viel Erfahrung haben sie mit “intelligenter Schmuck” (engl. “smart jewelry”)?

Never seen or heard about in advance of this study *Vor der Studie noch nie gesehen oder davon gehört*	☐
Heard about in advance of this study but never seen or interacted with *Vor der Studie schon von gehört aber noch nicht gesehen oder mit interagiert*	☐
Seen in advance of this study but not interacted with *Vor der Studie schon gesehen aber noch nicht mit interagiert*	☐
Interacted with in advance to this study *Vor der Studie bereits mit interagiert*	☐

If you did select one of the three last options please give an example of a “smart jewelry or explain briefly what this means to you:
Wenn Sie eine der drei letzten Optionen gewählt haben, nennen Sie bitte ein Beispiel für einen “intelligentes Schmuckstück” (engl. “smart jewelry) oder erklären Sie kurz, was Sie darunter verstehen:

Pictures 18 ID:__________

Condition: **1**

The outer material of the necklets moving part looks like:
Das Außenmaterial des beweglichen Teils der Halskette sieht aus wie:

	Totally agree *Stimme voll und ganz zu*		**Neither nor** Weder noch		**Totally Disagree** *Stimme überhaupt nicht zu*
Metal *Metall*	☐	☐	☐	☐	☐
Fabric *Stoff*	☐	☐	☐	☐	☐
Silicone *Silikon*	☐	☐	☐	☐	☐
Leather *Leder*	☐	☐	☐	☐	☐

Condition: ***2***

The outer material of the necklets moving part looks like:
Das Außenmaterial des beweglichen Teils der Halskette sieht aus wie:

	Totally agree *Stimme voll und ganz zu*		**Neither nor** Weder noch		**Totally Disagree** *Stimme überhaupt nicht zu*
Metal *Metall*	☐	☐	☐	☐	☐
Fabric *Stoff*	☐	☐	☐	☐	☐
Silicone *Silikon*	☐	☐	☐	☐	☐
Leather *Leder*	☐	☐	☐	☐	☐

Pictures 19 ID:__________

Condition: **3**

The outer material of the necklets moving part looks like:
Das Außenmaterial des beweglichen Teils der Halskette sieht aus wie:

	Totally agree *Stimme voll und ganz zu*		**Neither nor** Weder noch		**Totally Disagree** *Stimme überhaupt nicht zu*
Metal *Metall*	☐	☐	☐	☐	☐
Fabric *Stoff*	☐	☐	☐	☐	☐
Silicone *Silikon*	☐	☐	☐	☐	☐
Leather *Leder*	☐	☐	☐	☐	☐

Condition: **4**

The outer material of the necklets moving part looks like:
Was hat die Halskette kommuniziert?

	Totally agree *Stimme voll und ganz zu*		**Neither nor** Weder noch		**Totally Disagree** *Stimme überhaupt nicht zu*
Metal *Metall*	☐	☐	☐	☐	☐
Fabric *Stoff*	☐	☐	☐	☐	☐
Silicone *Silikon*	☐	☐	☐	☐	☐
Leather *Leder*	☐	☐	☐	☐	☐

The necklace movements, shown previously in the videos, consist of different underlying base movements. These base movements were performed at different frequencies (how fast the movement was) and amplitudes (how large the movement was). Please list all of these base movements that you can remember. Feel free to give the base movement a name that you feel is appropriate. You are also welcome to describe or sketch the basic movement. If you are not sure what is meant by "base movement", feel free to ask the experimenter.
Die zuvor in den Videos gezeigten Bewegungen der Halskette bestehen aus verschiedenen zugrunde liegenden Basisbewegungen. Diese Basisbewegungen wurden in unterschiedlichen Frequenzen (wie schnell die Bewegung war) und Amplituden (wie groß die Bewegung war) ausgeführt. Zählen Sie bitte alle dieser Grundformen auf, an die Sie sich erinnern können. Sie können der jeweiligen Basisbewegung dazu gerne einen Namen geben, den Sie für passend empfinden. Sie können die Basisbewegung aber auch gerne beschreiben oder skizzieren. Wenn Sie sich nicht sicher sind, was mit "Basisbewegung" gemeint ist, fragen Sie gerne den Versuchsleiter.

Please state the following information. All your data is handled anonymously.
Bitte geben Sie die folgenden Informationen an. Alle Ihre Daten werden anonym behandelt.

Age:________

Gender:______________________

Appendix D

Interview

This section provides the interview questions as they were used by the experiment conductor during the user study.

ID:__________

Anfassen erlauben.

How would you describe the necklet to someone who doesn't know about it (e.g., friends or relatives of you)?
Wie würdest du die Halskette einer Person beschreiben, die diese nicht kennt (bspw. Deinen Freunden oder Verwandten)?

What do you think how people express their emotions by what they wear (cloth, jewellery, accessories, etc.)?
Was denkst du, wie Menschen ihre Emotionen mit dem was sie tragen (Kleidung, Schmuck, Accessoires, etc.) zum Ausdruck bringen?

ID:__________

Do you usually wear jewelry? If yes, which jewelry and of which kind (e.g., Costume jewelry, pieces of emotional value, valuable jewelry
Tragen Sie Schmuck? Wenn ja, welchen Schmuck und welche Art von Schmuck (bspw. Modeschmuck, Stücke von emotionalem Wert, wertvoller Schmuck)

What do you like about the shown necklet?
Was gefällt Ihnen an der gezeigten Halskette?

What do you dislike about the shown necklet?
Was gefällt Ihnen nicht an der gezeigten Halskette?

Appendix E

Estimates

In this section we provide the data that was used to plot the point estimates and 95% Confidence Intervals in the section 4.7 "Results". All presented numbers are given to three decimal places and dot as decimal separator.

Shape	**Mean**	**Lower**	**Upper**
Up	0.917	0.833	1.0
Down	1.0	1.0	1.0
Wave	0.792	0.667	0.958
Twist	0.792	0.625	0.958
Elongate	0.792	0.625	0.958

Table E.1: Point estimates and 95% CIs for the proportion of participants who remembered the shape.

Shape	Mean	Lower	Upper
M-M	4.333	4.0	4.708
F-M	1.667	1.25	2.043
S-M	3.542	2.958	4.042
L-M	1.583	1.083	1.959
M-F	2.667	2.082	3.292
F-F	4.75	4.542	5.042
S-F	1.792	1.292	2.208
L-F	2.75	2.25	3.292
M-S	1.583	1.125	1.917
F-S	1.583	1.208	1.917
S-S	3.792	3.208	4.417
L-S	2.292	1.708	2.792
M-L	2.083	1.542	2.625
F-L	1.417	1.082	1.708
S-L	1.167	0.958	1.333
L-L	4.542	4.167	5.0

Table E.2: Point estimates and 95% CIs for how strongly participants agreed that a presented soft robots material (first character) looks like a certain material (second character). With M = Metal, F = Fabric, S = Silicone, and L = Leather.

Material	Mean	Lower	Upper
Silicone	3.150	3.006	3.294
Fabric	3.172	3.017	3.889
Metal	3.022	2.828	3.245
Leather	3.028	2.778	3.283

Table E.3: Point estimates and 95% CIs for conveyed valence by material conditions.

Material	Mean	Lower	Upper
Silicone	3.05	2.75	3.333
Fabric	3.417	3.228	3.572
Metal	3.183	2.878	3.494
Leather	3.278	3.078	3.55

Table E.4: Point estimates and 95% CIs for conveyed arousal by material conditions.

Shape	Mean	Lower	Upper
Up	3.833	3.639	4.007
Down	1.91	1.739	2.104
Wave	3.618	3.41	3.806
Twist	3.049	2.847	3.271
Elongate	3.056	2.854	3.271

Table E.5: Point estimates and 95% CIs for conveyed valence by shape conditions.

Compared Shapes	Mean	Lower	Upper
Down-Up	1.924	1.547	2.242
Wave-Up	0.215	-0.024	0.472
Elongate-Up	0.778	0.514	1.084
Twist-Up	0.785	0.506	1.132
Down-Wave	1.708	1.444	1.924
Down-Elongate	1.146	0.917	1.375
Down-Twist	1.139	0.903	1.368
Elongate-Wave	0.562	0.312	0.811
Twist-Wave	0.569	0.326	0.807
Twist-Elongate	0.007	-0.188	0.271

Table E.6: Point estimate and 95% CIs for differences in conveyed valence between shape conditions.

Frequency	Mean	Lower	Upper
High	3.246	3.096	3.383
Low	3.063	2.908	3.239
None	2.971	2.875	3.141

Table E.7: Point estimates and 95% CIs for conveyed valence by frequency conditions.

Compared Frequencies	Mean	Lower	Upper
None-High	0.275	0.133	0.388
None-Low	0.092	-0.111	0.283

Table E.8: Point estimate and 95% CIs for differences in conveyed valence between frequency conditions. The comparison between *Low* and *High* was omitted, since it wasn't of interest to verify our hypotheses.

Frequency	Mean	Lower	Upper
High	3.683	3.521	3.85
Low	2.896	2.683	3.112
None	3.117	2.876	3.354

Table E.9: Point estimates and 95% CIs for conveyed arousal by frequency conditions.

Compared Frequencies	Mean	Lower	Upper
Low-High	0.788	0.552	0.987
None-High	0.567	0.281	0.85
None-Low	-0.221	-0.477	0.089

Table E.10: Point estimate and 95% CIs for differences in conveyed arousal between frequency conditions.

Frequency	Mean	Lower	Upper
Up-Full	3.542	3.208	3.778
Up-Half	2.694	2.375	3.042
Down-Full	3.236	2.917	3.486
Down-Half	2.903	2.681	3.151
Wave-Full	3.972	3.639	4.222
Wave-Half	3.292	3.014	3.552
Twist-Full	3.611	3.28	3.875
Twist-Half	2.722	2.417	3.0
Elongate-Full	3.417	3.139	3.625
Elongate-Half	2.931	2.694	3.208

Table E.11: Point estimates and 95% CIs for conveyed arousal by interaction of shape and amplitude conditions.

Compared Frequencies	Mean	Lower	Upper
Up	0.847	0.5	1.153
Down	0.333	0.028	0.631
Wave	0.681	0.319	0.944
Twist	0.889	0.486	1.234
Elongation	0.486	0.25	0.708

Table E.12: Point estimate and 95% CIs for differences in conveyed arousal when switching from *half* amplitude to *full* amplitude per shape.

Appendix F

Qualitative Analysis

In this section additional, more detailed visualizations of the qualitative data from the association question are provided. First, we provide a more detailed breakdown on both, between-subjects factor material (cf. Table F.1) and the within-subjects factors (cf. Table F.2). Last, we provide a comparison of the codings among all participants in Figure F.1.

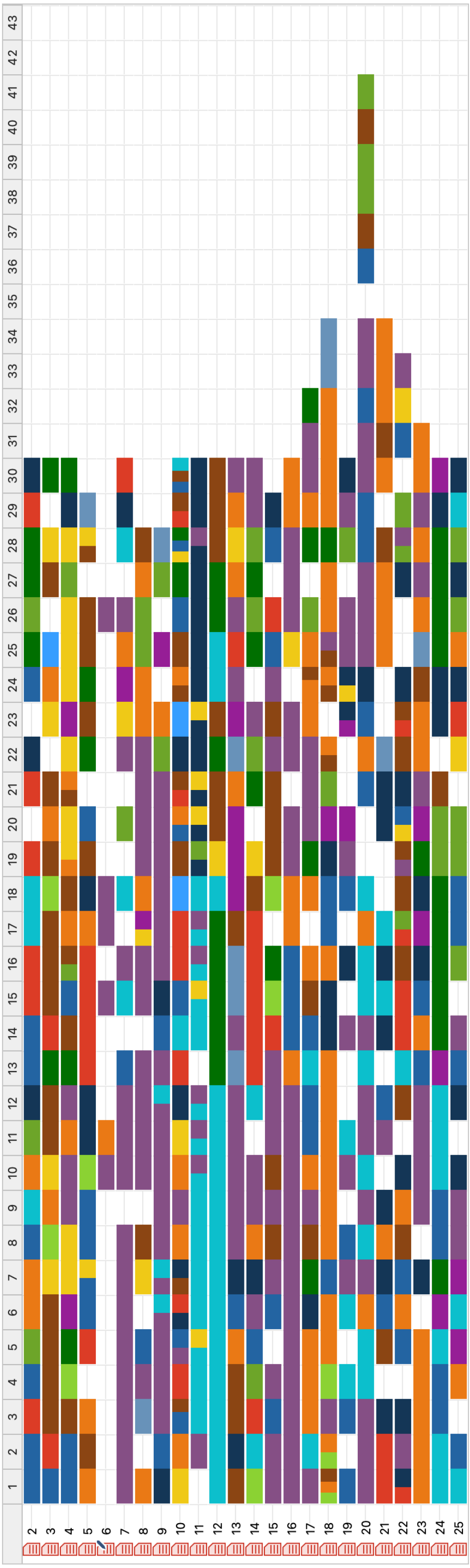

Figure F.1: Comparison between participants show, that a habituation effect was present due to longer parts of same or similar color. The numbers in the header denote the paragraph of the participant's documents.

Code System	silicone	fabric	leather	metal	SUM
human					0
fictional characters	2				2
characteristics	3	1	5	2	11
social interactions	15	10	16	13	54
attitudes	3	5	8		16
(mental) conditions	29	33	28	30	120
judgements	3	9	20		32
facial expressions	8	34	3	23	68
gestures	23	18	11	13	65
body movements	17	8	9	29	63
body parts	2		1		3
nature					0
liveliness	7	11	1	13	32
animals	6	24	3	6	39
environment	6	1	2	1	10
objects					0
stationary objects	7	12	10	8	37
moving or movable objects	24	6	7	11	48
mobility					0
directions	2	6	2	3	13
movements	5	4	5	7	21
actions					0
results from actions	2	3	1	1	7
actions / activities	7	5	8	5	25
sports	16		3	19	38
SUM	187	190	143	184	704

Table F.1: Breakdown of between-subjects factor and subcategories.

Code System	amp...	full	half	freq...	high	low	none	shape	up	down	wave	twist	elon...
human													
fictional characters		1	1		1	1							2
characteristics		5	6		1	7	3		1		3	3	4
social interactions		35	19		17	16	21		14	10	5	9	16
attitudes		9	7		6		10		3	1	4	7	1
(mental) conditions		53	67		38	39	43		22	39	21	26	12
judgements		14	18		13	12	7		9	13	1	3	6
facial expressions		30	38		19	18	31		23	26	14	1	4
gestures		34	31		29	19	17		23	11	20	8	3
body movements		31	32		19	16	28		8	12	11	17	15
body parts		2	1		1		2				1	1	1
nature													
liveliness		11	21		15	15	2		2	1	3	10	16
animals		22	17		12	17	10		1	2	15	3	18
environment		3	7		4	4	2		5	2	3		
objects													
stationary objects		24	13		13	9	15		7	4	7	7	12
moving or movable objects		24	24		12	21	15		7	7	9	19	6
mobility													
directions		8	5		6	3	4			6	1	4	2
movements		12	9		9	7	5		2	1	1	10	7
actions													
results from actions		4	3		1	3	3		3	3	1		
actions / activities		14	11		7	7	11		4	3	4	10	4
sports		21	17		16	14	8		9		19	5	5
SUM	0	357	347	0	239	228	237	0	143	141	143	143	134

Table F.2: Breakdown of within-subject factors and subcategories.

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