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RWTH AACHEN UNIVERSITY

Evaluation of Shapes and Movement Mechanism Designs of Silicone Actuators

Master's Thesis
submitted to the
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Abstract

Soft robotics is a research field of robotics. It gained its popularity due to soft robots' flexible structure and natural way of movement in comparison to the former rigid robots, providing soft robots with the opportunity to handle tasks rigid robots cannot. This would not be possible without a deformable part of a soft robot called soft actuator. However, its design variety is limited and usually represented by different kinds of crawlers, tentacles and gripper-based mechanisms. Consequently, the application range of soft robots is limited as well. In this study, we design new shapes of soft actuators. We focus on silicone material and air supply as the mechanisms generating a soft robot's movement. Designs associated with real world objects help to assign intuitive movement to the soft robot and form correct affordances that help users during the interaction process. The contribution of this thesis is to answer questions on how silicone actuator shapes with intuitive movement mechanisms are able to expand areas in which soft robots can be helpful. We conducted the experimental study with participants in order to investigate how familiar our newly designed shapes were to them and what application they would assign to the shapes. Based on their ideas we identified common areas of application. Based on the experiments' results, we investigate several important characteristics of our silicone actuator designs such as shape trainability (the ability of the shape to do different kinds of movement), how intuitive the proposed movement for a certain design shape would be, how comfortable the movement appeared to be for participants and whether the soft actuator would be able to deliver the desired speed and dynamics needed for the movement it is supposed to assist.

Überblick

Das Feld der Soft-Robotik ist ein Forschungsfeld der Robotik. Es erlangt seine Beliebtheit aufgrund der flexiblen Struktur und den natürlich anmutenden Bewegungen der Soft-Roboter im Vergleich zu den bisher verbreiteten rigiden Robotern. Dies wäre nicht möglich ohne den verformbaren Teil eines jeden SoftRoboters: Dem Soft Actuator. Allerdings sind die Designmöglichkeiten limitiert und normalerweise repräsentiert durch verschiedene Arten von Raupen, Tentakeln und greiferbasierten Mechanismen. Dementsprechend sind die Anwendungsmöglichkeiten von Soft-Robotern ebenfalls limitiert. In dieser Studie haben wir neue Formen für Soft Actuators konzipiert. Wir fokussieren uns auf Silikonmaterialien und Luftversorgung als Mechanismen die die Bewegung des Soft-Roboters generieren. Designs, die mit Objekten aus der echten Welt assoziiert werden, helfen dem Soft-Roboter eine intuitive Bewegung zu verleihen und formen korrekte Affordanz die dem Nutzer während des Nutzungsprozesses hilft. Der Beitrag dieser Arbeit ist es, Fragen darüber zu beantworten wie Actuator-Formen aus Silikon mit intuitiv zubedienenden Bewegungsmechanismen in der Lage sind die Felder zu erweitern in denen SoftRoboter hilfreich sind. Wir haben die experimentalen Studien mit Teilnehmern gemacht um herauszufinden wie vertraut die neu entwickelten Formen für sie sind und welche Nutzungsmöglichkeit sie ihnen geben würden. Basierend auf ihren Ideen haben wir übliche Felder für ihre Nutzbarkeit identifiziert. Basierend auf den Ergebnissen der Experimente haben wir einige wichtige Charakteristika unserer Soft-Acuator-Formen erforscht wie etwa Form-Trainierbarkeit (die Fähigkeit der Form unterschiedliche Arten von Bewegung durchzuführen), wie intuitiv die vorgeschlagene Bewegung für die spezifische Designform wäre, wie komfortabel die Bewegung für die Teilnehmer zu sein schien und ob der Soft Actuator in der Lage wäre die gewünschte Geschwindigkeit und Dynamik zu liefern die für die Bewegung, die unterstützt werden soll, erforderlich wäre.

Acknowledgements

First of all, I would like to thank all people who participated in user study experiment for your interest in contributing to the research on soft robotics, for the time you spent and for your helpful feedback.

I want to express my sincere gratitude to my thesis supervisor Anke Brocker. Thank you especially for letting me write my thesis in the incredibly interesting field, your assistance and reasonable feedback throughout all stages of the thesis.

I would like to thank Prof. Dr. Jan Borchers and Prof. Dr. Ulrik Schroeder for being the first and the second examiners.

Last but not least, I am grateful to my family for always believing in me and supporting me in all undertakings, in distance and in any life circumstances.

Conventions

We refers to the main study researches of the study Ekaterina Nedorubkova and Anke Brocker, her supervisor.

They is used instead of he/she and refers to a participant in order to obtain the anonymity.

All numbers are accurate to three decimal points. This does not included Nemenyi test calculations of pairwise comparisons of the shapes of silicone actuators presented in the plot.

The whole thesis is written in British English.

Chapter 1

Introduction

1.1 Soft Robotics

Soft robotics is a quickly broadening field focused on designing and manufacturing flexible, highly adaptive mechanisms. These are aimed to provide forceful, but at the same time compliant interaction with other objects.

Soft robots provide natural flexibility.

Usually, a soft robot consists of the following parts [Chen et al., 2017]. An essential part of a soft robot is the *soft actuator*. It is based on compliant material that evolves the movement, transferring received power. In the area of different soft actuators the following types are commonly distinguished: shape memory alloys, fluidic elastomers, shape morphing polymers, electroactive polymers and electro-magnetic actuators [Boyraz et al., 2018]. The most common materials used to obtain flexibility are silicone, hydrogels and braided fabrics. Next, there is a *mechanism* inside of a soft actuator or inside many soft actuators joined together that aimed to provide the movement. Microfluidic chips, water supply, air supply, magnetic stimulation can be considered as mechanisms of soft robots. In order to activate the mechanism a *power generator* is used. There are also *sensors* attached to the soft robot shape, which collect the information during the process of interaction of a soft robot with the environment. Last but not least, there is a *controller* which is in charge of logic operations.

Soft robots usually consist of a stretchable silicone actuator and mechanisms generating and controlling the movement.

1.2 Soft Robotics Actuator's Design

The design of silicone actuators is usually inspired by nature or everyday objects.

In our study, we focused on soft actuator's designs. The majority of the designs are inspired by the human body, animals and other living organisms, their appearance and behaviors [Schmitt et al., 2018]. This enables them to provide complex, but at the same time soft and natural movement. Other soft robotic actuator's designs are inspired by the origami paper folding technique constitutive to the origami exoskeleton of a silicone actuators [Zhang et al., 2019]. Since it is a paper based idea, silicone actuator designs usually consist of relatively thin layers of silicone, imitating the paper, with several connections in between. The most popular design of soft robots is usually based on tentacle morphology [Jan et al., 2018], [Paek et al., 2015]. Various types of crawling robots [Zhou et al., 2019], [Yu et al., 2020], [Gamus et al., 2020] are also highly popular.

1.3 Outline

The study includes the experiment to evaluate how familiar designed shapes are to users and how clear the future application of shapes is to them.

The introductory chapter is represented by the description of soft robots and its soft actuator part that we focused on. Chapter 2 concentrates only on papers and research that are closely related to the study, in particular, application aspect of soft robotics, challenges of soft robotics actuators' designs and research methodologies that could be sufficient for experimental study in this thesis. Chapter 3 describes the development process of 3D modeling. Next, in Chapter 4 we present an experiment with 18 participants: we investigated how intuitive shapes and movement mechanism designs can enrich the application field of soft robotics. Chapter 5 presents the results of quantitative and qualitative analysis. We conclude the study with Chapter 6 by discussing the study's limitations and ideas for future research.

Chapter 2

Related Work

In the following chapter, we give an overview on the main application areas of soft robotics. As well as we observe major problems in the field, particularly the lack of soft actuator's designs. This is an important motivation for our study. The second section focuses on executing experimental studies in the field of shape-changing interfaces: the design of experiments in soft robotics could be based on it.

It is hard to divide applications into categories.

2.1 Application of Soft Robots

The fields soft robotics are used in are growing rapidly. Among many areas where soft robots are more powerful than the rigid ones, it is hard to categorize applications into certain fields. Nevertheless, medicine, wearable devices, smart textures and smart jewellery can be distinguished as main domains of application.

Soft robots are commonly used in medicine, wearable devices and fashion.

2.1.1 Wearable Devices

Due to the delicacy of the materials soft robots are capable to interact cautiously with a human body [Alexander et al., 2018]. The majority of wearable devices has assistance

Usually wearable devices are made for assistance of human body parts.

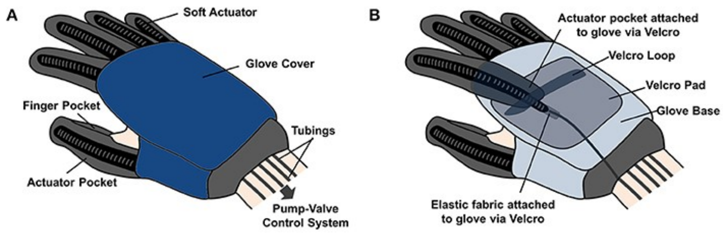

Figure 2.1: Soft robotics glove design, Yap et al., [2017].

purposes. Therefore, these can be considered as medical devices as well. One example is a soft robotic assistance glove for people with hand functioning problems. It enhances the fingers' ability to grasp objects [Yap et al., 2017]. Another example is an exosuit to assist users in walking [Awad et al., 2017].

2.1.2 Medical Devices

Medical capabilities include the use of soft robots inside the human body.

Since the materials and components of soft robots can be organic, making them safe for human beings and animals, they are also applicable inside the body in case of surgeries [Banerjee et al.] and for endoscopic screening [Yanagida et al., 2012]. The attachment of soft robots to the internal organs, including the testing phase of these devices, still have many drawbacks and limitations. Nevertheless, the abilities of soft robots in this field are very promising. One example of this application is implantable soft robotics system for maintaining heart activity is proposed by Payne, et al. [2017]. Placed around the heart it provides assistance via contracting and relaxing movements in order to normalize blood inflow.

Soft robots are empowering people to maintain their normal routine.

Nowadays, considerable attention is paid to the research and design of tools helping human beings go through their bodies physical processes such as women menstruation [Søndergaard et al., 2020]. The possibility to attach soft robotics devices such as *Menarche Bits* to different parts of the human body, makes it useful for many applications.

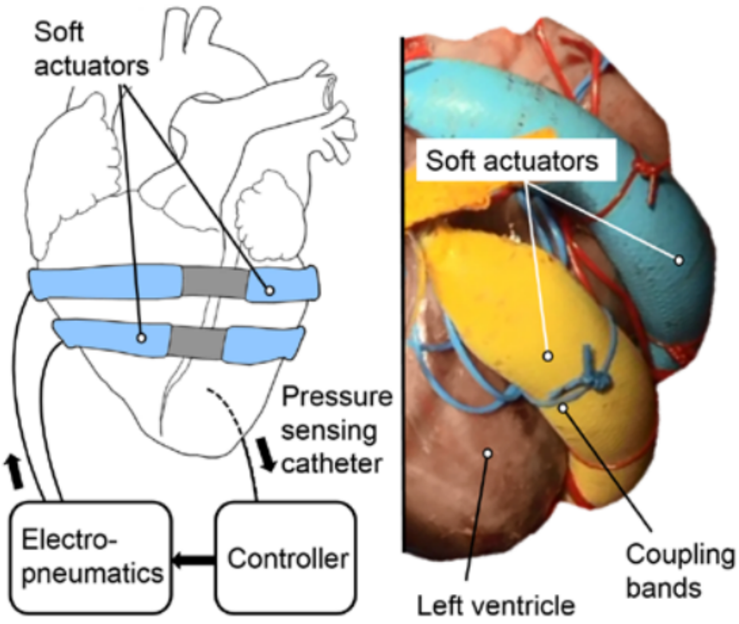

Figure 2.2: Implantable device supplementing the contracting and relaxing actions of the heart system, Payne, et al. [2017].

Figure 2.3: "Menarche Bits" are inflating on a human body, Sondergaard et al. [2020].

Figure 2.4: Electroactive polymers integrated inside the fabrics, Maziz et al. [2017].

2.1.3 Fashion, Smart Fabrics and Smart Jewellery

Soft robots are able to combine functionality and decorating purposes.

There are also many decorative capabilities that soft robots can be used for in fashion. One example are smart fabrics that let the clothes do the elongation and shrinking movements. At the same time they allow clothes to be adapted to a body shape [Perovich et al., 2013]. The ability to change the appearance of clothes dynamically is not the only way fashion can profit from the use of soft robots. There are functional capabilities as well. Clothes with soft robotic actuators inserted into its fabric are able to work as artificial muscles [Maziz et al., 2017]. At the same time, great attention is paid to adhesive backing of smart fabrics aiming to enhance fabrication reliability and simplify the whole process of fabrication [Miller-Jackson et al., 2019].

Rigid subsystems reinforce soft robots.

Soft robots can be equipped with rigid subsystems in order to provide additional features. One example is embedding sound system into soft robotic designs [Bering Christiansen and Jørgensen, 2020]. A sound feature is also applicable to the smart jewellery design, for example, to provide audio feedback to users as part of a notification system.

2.2 Soft Robotics Challenges

Design challenges of soft robots are closely related to the challenges of shape-changing interfaces in general.

Despite the fact that application areas of soft robots are continuously growing, there are undoubtedly some limitations and challenges, hindering further development

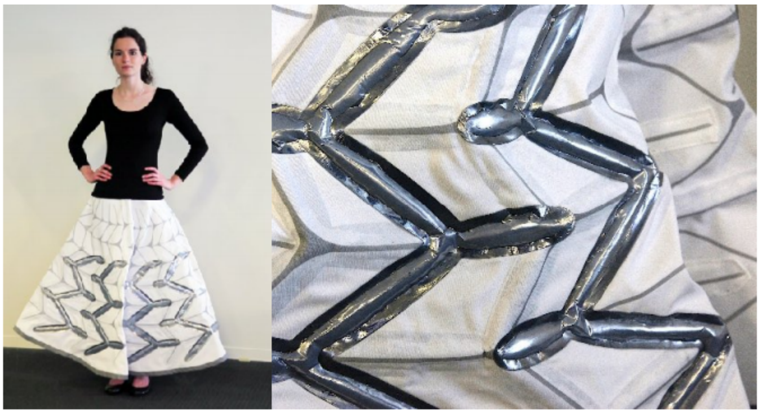

Figure 2.5: Prototyped version of a skirt with an inserted origami pattern of pneumatic actuators, Perovich et al. [2013].

in the field. Design challenges of shape-changing interfaces are in general distinguished as a separate group [Alexander et al., 2018]. Design ideas can tackle a functionality problem of soft actuators that usually operate with and are able to effectively apply their force to quite low masses [Banerjee et al.]. At the same time, the weight and dimensions of soft robots themselves could be minimized. There are two challenges of shape-changing interfaces that are relevant in particular to soft robotics actuator's designs. Firstly, movement design ideas are limited. One particular example is the field of electroactive polymers' designs that is quite poor in terms of predesigned shapes for prototyping and research. Therefore, any study conducted in this field usually includes a designing phase of electroactive polymers, too [Franinovic and Franzke, 2019]. Soft robotics devices can be categorized in more than one field at a time. This fact makes the whole field of shape changing interfaces very vague and sometimes not focused on specific challenges [Alexander et al., 2018]. In addition, researchers highlight the desired ability of silicone actuators to act correctly even in the situation of damaging materials they are made of [Marchese and Rus, 2016].

2.3 Experimental Studies of Shape-Changing Interfaces

Experimental design is popular in shape-changing interface research.

To brainstorm design ideas, test new features and the functionality of shape-changing interfaces an experimental study is usually conducted. The following papers deal with organizing and conducting experimental studies with participants, applying different study techniques to evaluate various aspects of shape-changing interfaces domain.

2.3.1 Conveying Emotions via Shape-Changing Interfaces

Two experimental studies: expression and perception of emotions via shape-changing interface.

In this paper Strohmeier et al. [2016], two complementary studies were conducted that aimed to examine firstly, whether participants are able to express proposed emotions, using shape-changing interface. Secondly, whether emotions explained in this way will be correctly perceived by other participants. In the first experiment, all emotions were rated by participants in advance in terms of valence and arousal factors, using 5-point scale. Next, participants expressed these emotions by deforming a flexible 2D sensor. As a result, emotions of contentment, delight, happiness, sadness and love were expressed in relatively the same manner. For the second experiment these shapes were designed as animated 3D models. Videos of shapes with questionnaires were given to another group of participants. Emotions were identified correctly 33,8% of the time.

2.3.2 Morphees+: Taxonomy for the Shape-Changing Interfaces Design

The experiment is based on brainstorming session of shape-changing everyday objects.

In this paper Kim et al. [2018] built shape-changing interfaces design taxonomies based on 82 reconfigurable ordinary objects that participants use daily. The study was conducted in two sessions. During the first session,

Figure 2.6: Flexible 2D sensor, Strohmeier et al. [Strohmeier et al., 2016].

Figure 2.7: Examples of shape-changing objects collected for the analysis, Kim et al. [2018].

investigators explained to nine participants what they might consider as a reconfigurable object. During the next seven days, participants had to collect 15 ideas each. Afterwards, they conducted a brainstorming session with the same participants in order to accumulate deformation ideas. Among 149 ideas, 82 already existing objects were analysed with two taxonomies in order to reveal missing features and form a new taxonomy.

2.3.3 Sketching Shape-Changing Interfaces

A brainstorming session is aimed to change radio or mobile phone interfaces according to a certain task.

Rassmussen et al. [2016] conducted the study as a brainstorming session for 21 participants from shape-changing interfaces field. The task for participants was

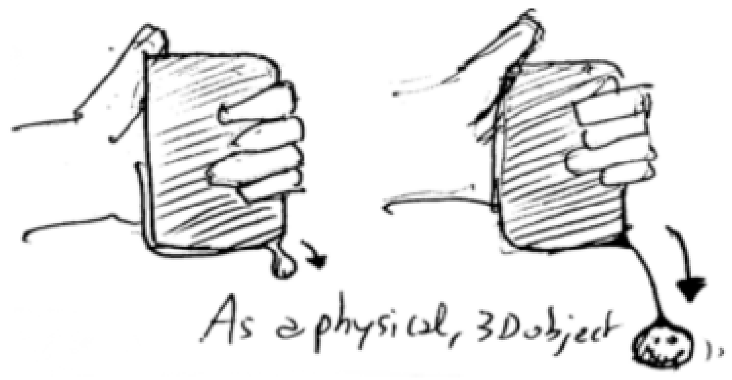

Figure 2.8: An example of sketch modification of a shape-changing interface, Rassmussen et al. [2016].

to sketch their ideas related to two tasks. Sketches were supposed to either relate to the radio to specify the genre of music and sound volume or to a mobile phone, showing the phone mode and representing the emotion received in a message. The whole session was focused more on producing creative ideas, rather than technical specification of sketched features. Results of the session were analysed using thematic analysis in terms of vocabulary (types of the object modification), metaphor and analysis of different types of affordances, that help users to recognize interaction ways with an object.

2.3.4 A Repertory Grid Interviews Study

The study is based on continuous differentiating of shape-changing interfaces.

Kwak et al. [2014] conducted a study that was aimed to gather the 18 participants' descriptions of six shape-changing interfaces (constructs) that they saw and interacted with. In the study, constructs and labeled shape-changing interfaces are elements of the repertory grid. The first task was to differentiate two shape-changing interfaces in groups of three using constructs. Next, participants ranked artifacts on the 7-point scale starting from the construct pole (1) and ending at the contrast pole (7). The procedure was repeated with another group of three shape-changing interfaces till the moment the participant cannot

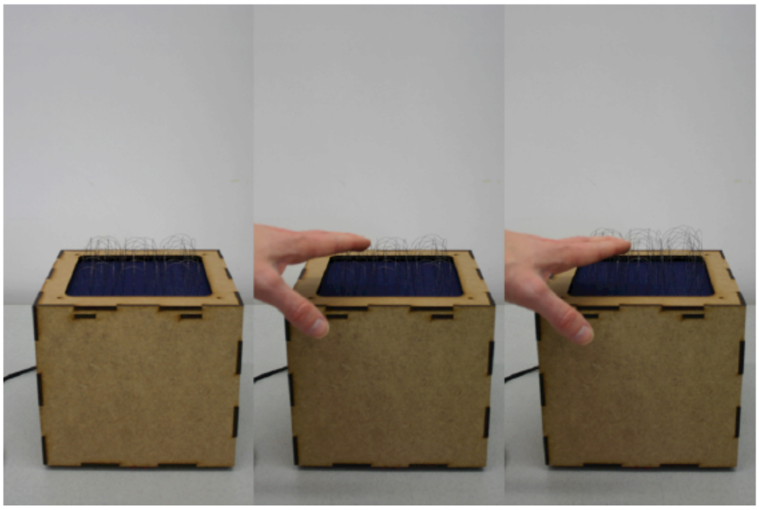

Figure 2.9: Interaction with one of six shape-changing interfaces, Kwak et al. [2014].

come up with any more constructs. Both quantitative and qualitative analysis were done.

2.3.5 A Workshop with Electroactive Polymers

Participants are asked to find videos that would be associated with the movement.

In this study [Franinovic and Franzke, 2019], researchers executed several workshops. The workshop most relevant for this study is called *Alive Spaces*. During the session eleven participants tested a new tool for designing electroactive polymers. The whole workshop took three weeks. The first week was based on lectures and exercises, including the phase where participants were asked to find videos of movements, which create an association with, for example, human, animal and mechanic movement and split them into the corresponding categories. Next, there was several sessions in order to develop mockups and prototypes. Finally, participants exchanged their design prototypes with others. The variety of designs were then categorized into several groups, from natural movements to abstract ones.

Chapter 3

Design of Silicone Actuators

3.1 Motivation

The aim of enhancing application area of soft robots is highly depends on the the variety of designs of silicone actuators that the field of soft robotics can offer. A certain application might be limited by the soft actuator shape design that does not fit to the use case. One example of this is a wrong perception of the shape design by users and, therefore, not intuitive interaction. However, the shape design of silicone actuators do not only affect the appearance of the shape, but also set the movement character. Therefore, endowing soft actuator shape design with the ability to provide intuitive movement makes the whole interaction process easier. Soft robots are aimed to provide complex, natural movement. Due to this fact soft robots quite often perceived as artificial analogies of human, animals and other living organisms.

A variety of shapes with familiar to users design and intuitive movement is able to enhance an application field.

In order to first evaluate the design of shapes a good approach is a 3D models of the shapes endowed with simulation of its movement. In the current situation of COVID-19 pandemic, we decided to substitute phases of molding and casting of obtained shapes by creating a 3D

Design and experiments took place online.

simulation of the their movement. And further conduct a pre-study phase of brainstorming silicone actuators shapes' ideas and experiment study itself online.

3.2 Brainstorming Sessions

3.2.1 Initial Brainstorming Session

Passive brainstorming of sketches ideas for three weeks.

The brainstorming session was the starting point of the design of silicone actuators on this thesis. During the period of three weeks, we were sketching silicone actuators designs, including the rough ones via pen and pencil anytime when a new idea came to our mind. Since the time of session were not an issue, our main purpose was to collect as many ideas as possible, even ones that look almost alike to further group them and choose the most interesting and relevant for the filed.

26 shapes as a result of the first brainstorming session.

After the first brainstorming session, grouping of looking alike ideas and excluding not related ones (for example, the ideas that are more suitable for rigid robots), we had 26 shape sketches. Not surprisingly for soft robotics actuators design, the majority of the sketches were inspired by the nature 1.2 "Soft Robotics Actuator's Design". A possible reason behind this is that we know their appearance quite well, therefore, besides simple geometric forms, usually it comes to our mind first. We also associate the movement to it and usually it's hard to imagine the alternative way of the movement to well-known shapes.

3.2.2 Brainstorming Session With Participants

Brainstorming more ideas with participants.

In order to enrich the variety of shape designs and take into consideration different view points, we conduct the second brainstorming session with four participants of different study and (or) work fields, including Human-Computer Interaction (HCI), Virtual Reality (VR) development and Computational Biomedicine. Two participants had no previous knowledge of silicone actuators. The session was conducted online via video conferencing service Zoom[1], using any preferable option to sketch (digitally or using pen and pencil) and took one hour and 30 minutes, including the time allotted to ask questions related to the topic of soft robotics from the participants' side.

We started the procedure with a presentation of soft robotics actuators to give participants an overview of the field, limit the design perspectives with silicone material for the actuators and air supply as a movement generator. Next, they had a first 15-minutes slot to sketch their ideas. The task was to sketch the shape of silicone actuator, that supposed to evolve a certain movement in reality. Subsequently, participants shared their results with others and explain their ideas. Thus, the first brainstorming part of the session was aimed to minimize the biasing of participants on existing ideas of silicone actuators shapes and their movement. However, there was a chance that any part of introduction remained unclear for participants and therefore limited their imagination. To deal with this, we presented sketches from 3.2.1 "Initial Brainstorming Session" as examples of how the sketch could look like and explanation of how in the reality the movement of this shape might be evolved. In order to give participants the opportunity to reconsider their ideas or to come up with new ones there was another 15-minutes brainstorming part, finished with participants' explanation of their shape and associated movement ideas. As a result, 30 shapes of silicone actuator were brainstormed and sketched by participants.

Participants sketch silicone actuators shape ideas before seeing results of the initial brainstorming session and after.

All the sketches of silicone actuators shapes, including findings of 3.2.1 "Initial Brainstorming Session" were categorized in groups of different ways of evolving the movement:

Six categories of shapes' movement after brainstorming sessions.

1. Extruding (Figure 3.1)
2. Expanding and elongation (Figure 3.2)
3. Bending (Figure 3.3)

[1]https://zoom.us

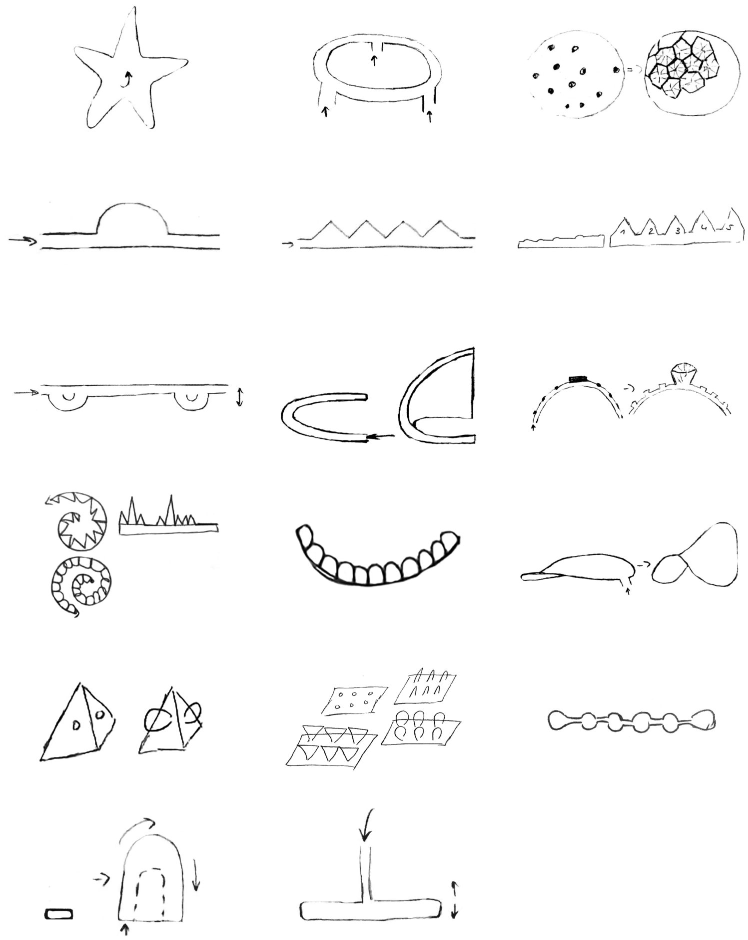

Figure 3.1: "Extruding movement" category of shapes.

4. Waving (Figure 3.4)
5. Twisting and rotation (Figure 3.5)
6. Compression (Figure 3.6)

Overall, 36 sketches of shapes.

After the categorization, there were six groups of shapes with 56 shapes in total. It became clear that some of shapes inside the categories are repetitive or could be generalized to the one idea. Therefore, as a result of two brainstorming sessions 36 shapes of silicone actuators were derived.

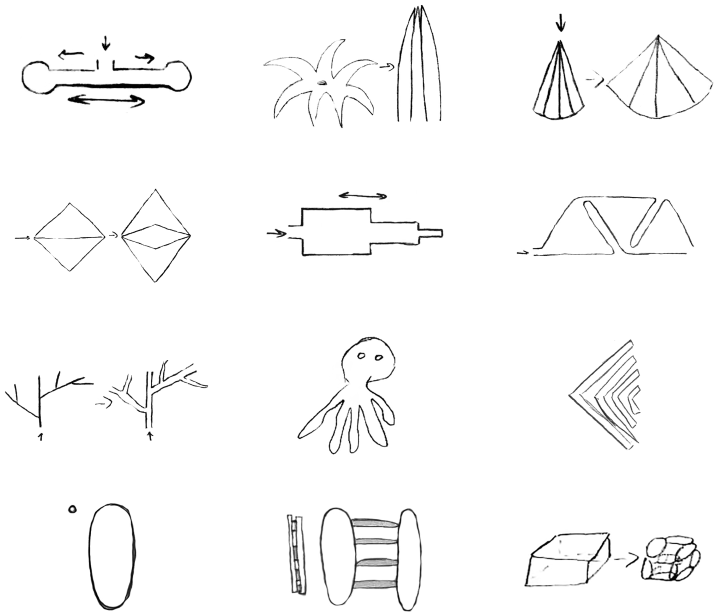

Figure 3.2: "Expanding and elongation movement" category of shapes.

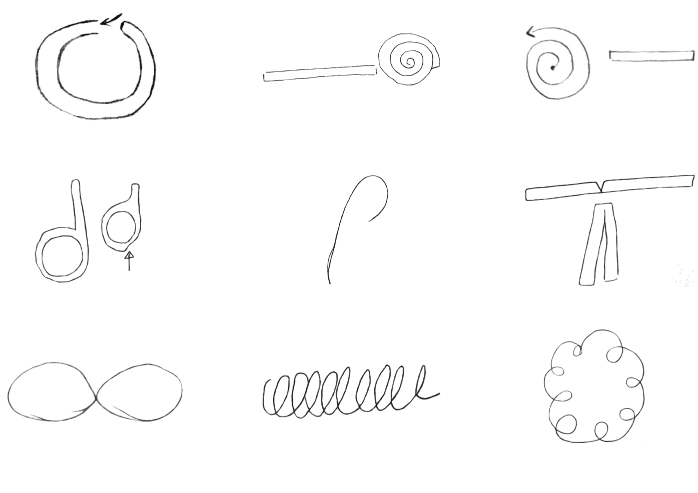

Figure 3.3: "Bending movement" category of shapes.

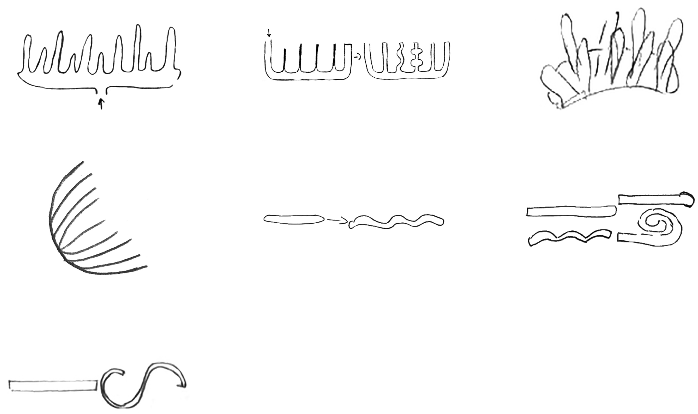

Figure 3.4: "Waving movement" category of shapes.

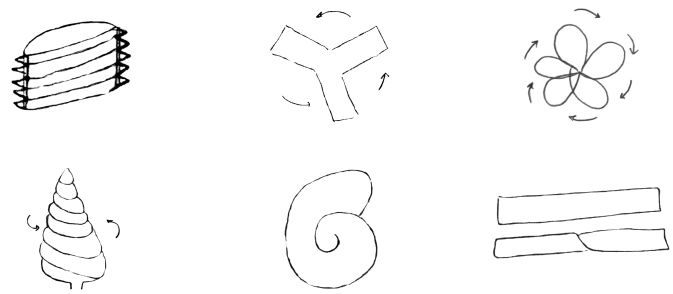

Figure 3.5: "Twisting and rotation movement" category of shapes.

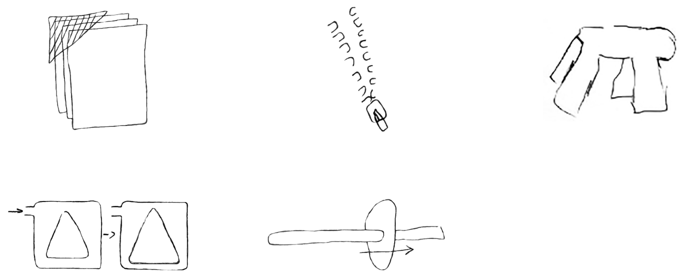

Figure 3.6: "Compression movement" category of shapes.

3.3 Design via Autodesk Maya

Initially, we planned to use Autodesk Fusion 360[2] for the design of 3D models of the silicone actuators. However, for our study aims it is crucial to provide also a simulation of the movement to prevent ambiguity of silicone actuators mechanisms that supposed to be tested during the experiment 4.1.5 "Experiment Procedure". Therefore, in order to implement together a 3D design of the shapes and realistic simulation of their movement we used Autodesk Maya[3]. Most often the software is used for modeling the animation of cartoons characters, because it is powerful in designing complex movements and natural deformations of the initial shape. That is the reason why it is also suitable for empowering a 3D shape of silicone actuator with realistic movement.

Shapes of silicone actuators and their movement are presented as 3D simulations.

3.3.1 Design of 3D Shapes

The first phase of the design in Maya is to create the shapes, that would be a 3D analogy of the sketched ones. For every shape, we used *Poly Modeling Primitives* as a basis of shapes' parts (Figure 3.8). In order to modify the primitives, turning them into advanced shapes, we were applying the following features to the mesh of the primitives and further to the deformed pieces of the shape:

Modeling primitives are used as a basis of shapes' design.

- Extruding the areas of mesh via Scale Tool
- Cutting off irrelevant areas via selecting the area of the mesh manually and delete it or using *Multi-Cut*
- Bending areas via Bend and adding curvature *Curves* to the shape in *Modeling* mode if the initial condition of the shape implied to be bent
- Squashing the shape with *Squash* in *Modeling* mode if the shape in the initial condition meant to

[2]https://www.autodesk.com/products/fusion-360
[3]https://www.autodesk.com/products/maya

be compressed (for instance, for further designed pumping movement)

All shapes supposed to be with smooth edges to look natural.

In addition, for every shape piece design we took advantage of *Smooth tool* in *Mesh* to exclude sharp edges and make the whole shape look more organic, preventing the rigid shape effect. Mentioned tool could be applied to the whole shape, if it's parts are previously combined. However, in most cases it makes the shape too rounded and conceal details, that needs to be visible. Finally, all the designed pieces were combined together into entire shape, trying to make smooth also the place of attachment to each other.

3.3.2 Design of Movements

Movement Simulation

Movements are designed via Blend Shape tool and various nonlinear deformations.

For the movement design, we continued working in Maya in *Animation mode*. Some of shapes were animated via *Blend Shape* in the *Deform* by duplicating the shape from the initial condition and applying shape modification only to the copied one. So we got at least two conditions of the same shape, that the initial could be transformed to the target one, using the slider controlling the *Weight* in *Attribute Editor* as presented in 3.7. However, not for all of the shapes this way to endue the shape with a movement is the optimal one. Sometimes during the shape design the initial mesh of the primitive were disturbed. Therefore, the application of *Blend Shape* also requires to reorder the vertices of the mesh. Instead, we applied *Nonlinear* movement design options from *Deform* where it was possible (Figure 3.8).

Creating Videos of Simulation

For every shape we created a 10 seconds video.

Since there is not a general way to animate the shape and therefore controllers of the movement for the shapes

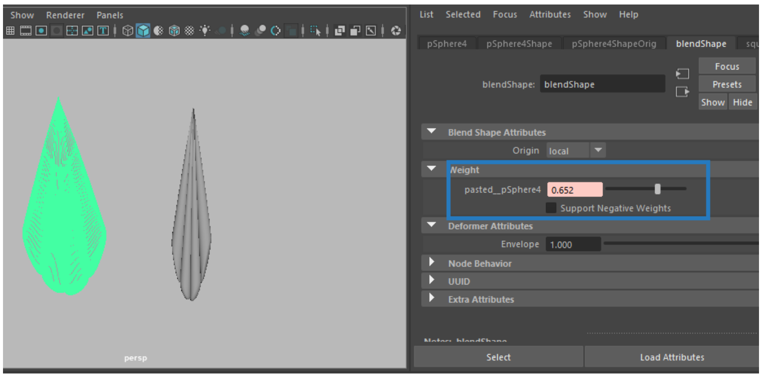

Figure 3.7: Controlling of Blend Shape tool in Maya.

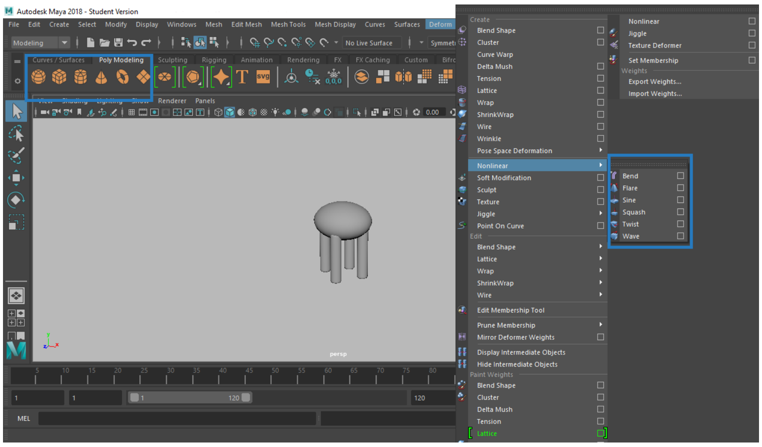

Figure 3.8: Interface of Autodesk Maya 2018.

differ, the procedure of testing the movement during the experiment in the software could be too complex for participants. For this reason, we recorded a video of every shape movement as transformation from the initial condition to the target condition and back. By doing this we emitting the process of filling in the shape of silicone actuator with air and releasing it out. In order to prevent occurrence of confounding variables, the speed of transformation of the shape from the initial condition to the target condition (speed of the movement) supposed to be equal. So we made videos with playback speed of 24 fps and playback range of 1 to 240, so the video duration for every shape is 10 seconds.

Chapter 4

User Study

4.1 Experimental Design

Experimental design combines within-subject and between-subject design features.

Initially, we planned to adhere to within-subject experiment design, so that every participant tests all the shapes. After all shapes were designed, the number of experiment conditions turned to be quite big (36) and therefore the experiment lead to fatigue for the participants to test all the shapes, as it was also proved during 4.1.6 "Pilot Study". At the same time, dividing shapes into predefined groups is problematic, since it might be the case that it already bias participants in terms of, for example, a specific way of movement. In addition, counterbalancing in this case will only prevent the order effect of shapes, but not the biasing of participants on a certain idea. Therefore, as a compromise between within-subject design and between-subject design we decided to assign to every participant a block of shapes consisted of twelve out of 36 randomly selected shapes. The detailed process of the randomization is described in 4.1.7 "Randomizing" This idea minimises the number of participants for the experiment (the advantage of within-subject design) and at the same time decreases the learning effect (the benefit of between-subject design).

4.1.1 Independent Variables

Independent variables define the movement.

In the study, the following independent variables were defined:

1. The type of the shape movement:
   a. Extruding
   b. Expanding and elongation
   c. Bending
   d. Waving
   e. Twisting and rotation
   f. Compression
2. The axis of the movement
   a. Horizontal
   b. Vertical
   c. Diagonal
   d. Flat
3. The area of motion
   a. Whole shape movement
   b. Partial shape movement
4. Degrees of freedom

4.1.2 Dependent Variables

Six dependent variables of the study were defined.

The following dependent variables were measured:

1. The familiarness of the shape (the association with any existing real world object)
2. The distinguishability of the shape movement
3. The comfortability of interacting with the shape

4. The ability to interact with other objects (to force the movement of other objects)
5. The trainability of the shape (the ability of the silicone actuator shape to evolve a different movement)
6. The type of interaction:
   a. No interaction (the movement of the shape of silicone actuator is done automatically)
   b. Indirect interaction (there is a need of action that user supposed to do in order to activate the movement of silicone actuator)
   c. Direct interaction (user directly controlling the air supply to assist the shape movement)

4.1.3 Hypothesis

With our study we wanted to examine the following hypothesis:

H1 Silicone actuators with intuitive shape designs and movement mechanisms are able to enhance soft robotics field and it's application area.

4.1.4 Experiment Setup

Apparatus

The whole experiment was conducted online via Zoom and online visual collaboration platform Miro[1]. We use this board in order to provide all needed experiment materials for users at one place. For every participant had an interactive board with twelve frames, that was designed as presented in Figure 4.1. Every frame consists of video of 3D simulation of the shape movement, questionnaire link and sticky note with the sketching option.

The experiment was conducted in Miro boeard via Zoom.

[1] http://www.miro.com

Figure 4.1: Miro board set up.

Semi-Structured Interview Design

Small discussion helps to formulate the ideas.

The interview with a participant about every shape is a combination of small discussion and questionnaire. Answering open-ended questions during the discussion should have helped participants to better formulate their ideas about the associations with the certain shape and its possible application further in the questionnaire. It was noted by participants, that the application scenario discussed in advance helps to fill out the questionnaire. These discussion questions are presented in 4.1.5 "Experiment Procedure".

Questionnaire consists of different types of question.

The second part of the interview of each shape is a questionnaire for gathering quantitative data. For all twelve shapes, questions are identical. It consists of five 5-point Likert scale questions, five yes-no questions, two open-ended questions, clarifying the previously provided answers and one multiple choice question. The questionnaire can be found in Appendix A "User Study Materials". Initially, participants' personal data should have been collected in the first of twelve shape questionnaires that they supposed to fill out. However, in order to obtain the same procedure for every shape and didn't split the procedure of watching the video simulation and conducting the interview, the personal data was collected before the experiment, as presented in

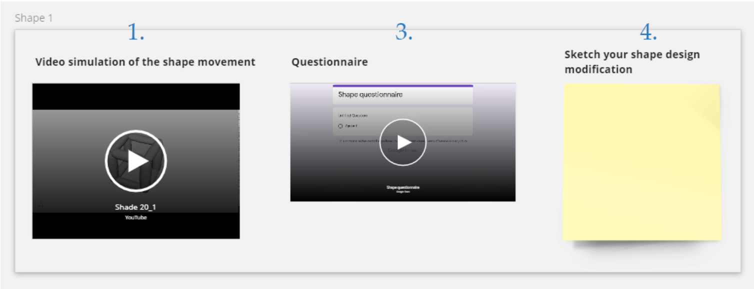

Figure 4.2: Miro board single shape frame with interview steps numbered, except the step 2 of a small discussion with the participant.

Appendix A "User Study Materials" as well.

4.1.5 Experiment Procedure

The experiment procedure for all shapes are the same.

First of all, participants reviewed and signed a consent form, that can be found in A "User Study Materials". The experiment starts with the 5-minutes introduction to soft robotics field. It contained the information about the soft actuators, examples of its' application in the medicine, wearable devices, smart jewellery and fashion. Also, during the introduction, we repeated the whole procedure of the experiment, research aim and goal to the participant. After the introduction part, during the experiment, participants were welcome to ask any questions. Next, participants got access to the Miro board by clicking on the link provided in the Zoom chat and log in there (no preparation in advance from participants' side is needed). Once participant is successfully logged in, they were able to see the experiment board with twelve frames. Next, we provide the explanation of the participant's task together with clarification of all questions in the questionnaire. When all the questions from the participant's side were answered, we asked the participant to start with the first shape. The procedure for every shape out of twelve ones were the same. The example of the single shape frame is presented in Figure 4.2.

Participants have the same tasks for every shape.

The task to perform by the participant for every shape is the following:

1. Watch the video of the simulation of soft actuator shape movement
2. Discuss with the experiment investigator two questions:
   - Does this shape remind you about something? Do you have an association with already existing real world object?
   - Can you imagine the application scenario of the soft actuator in everyday life when using this shape might be interesting and suitable?
3. Fill out the questionnaire that could be found in Appendix A "User Study Materials"
4. Sketch the modification of the shape design if it's needed by participant's opinion

The whole experiment usually took around one hour and a half. If participant were decided not to draw shape design modifications in the sketching option, the duration of the experiment was approximately by 30 minutes less.

4.1.6 Pilot Study

After pilot studies we minimized the number of shapes per participant.

After all the shapes were designed and the experiment procedure was defined, we conducted two pilot studies in order to test the whole process described in 4.1.5 "Experiment Procedure" before the main experiment sessions. The first participant had experience of using soft robotics actuators and the second had no experience with it, both are females. The initial experiment design had intended that every participant should test all 36 shapes, but both pilot studies reveal that the experiment with 36 shapes tend to be too long and quite fatigue for participants. After one hour and a half (predefined time for the experiment), less than a half of the shapes were tested by participants. By this reason, we decided to split the shapes between participants, so they are tested the same number of times, but not necessarily every participant test all the shapes as it is described in details in 4.1 “Experimental Design” and 4.1.7 “Randomizing”.

During a small discussion after watching the video of shape movement simulation besides two questions reported for main interviews in 4.1.5 “Experiment Procedure” there was a question *"Please, shortly explain the emotions that you got out of watching this movement."*. We conclude, that this question appeared to be not enough informative for this study and a bit confusing for participants. In addition, one participant noted, that not all the questions need a clarification in the phase of the questionnaire explanation, but we still decided to do it in the main experiment to minimize the wrong perception of the questions' meaning.

The question about emotions that the movement provokes were too broad.

4.1.7 Randomizing

For the randomization process, Random Sequence Generator[2] with atmospheric noise randomization was used with the smallest number of one and the largest value of 36. Twelve conditions (columns) as an optimal number of shapes per user, that also let us divide all 36 shapes to three participants. As a result, there were three sequences of twelve shapes covered all of the shapes. In order to test every shape same number of times with more participants, the randomizing procedure was repeated six times. Thus, we ended up with 18 participants with randomizing sequence of 12 shapes for each.

All shapes were divided into randomized sequences of 12 shapes.

4.1.8 Participants

In the experiment, 18 participants of different gender, study and (or) work fields, with the average age of 26 were involved. Among them 13 are males and five are females. There are 16 participants from computer science or

All participants had no experience with soft robots.

[2] https://www.random.org/sequences

ID of the participant	Number of the experiment condition											
	1	2	3	4	5	6	7	8	9	10	11	12
1	34	6	30	20	36	7	22	25	23	15	2	33
2	14	9	11	13	1	12	5	17	8	29	10	24
3	4	3	35	32	27	28	26	16	31	18	21	19
4	7	8	6	25	3	11	16	29	10	32	26	18
5	13	28	22	4	15	24	14	20	21	27	36	9
6	33	19	35	5	17	30	12	2	31	1	34	23
7	23	7	25	26	13	35	30	16	29	9	6	18
8	8	34	31	11	12	36	15	22	20	33	10	28
9	3	17	27	5	24	1	19	21	32	14	2	4
10	25	26	23	24	34	36	28	1	14	4	17	21
11	20	3	30	13	19	18	6	16	32	2	11	15
12	31	9	7	12	22	29	10	33	35	8	27	5
13	29	28	14	30	15	2	12	11	26	6	17	1
14	8	13	25	21	35	24	33	27	34	23	10	4
15	16	22	32	20	3	31	19	9	7	18	5	36
16	19	23	17	33	13	14	25	10	27	12	18	32
17	5	16	34	31	9	22	1	3	30	11	28	2
18	26	21	8	29	4	20	36	6	15	35	24	7

Table 4.1: Randomizing of 36 shapes by sequences of twelve for 18 participants via Random Sequence Generator.

related fields, one participant from environmental sciences and one from sociology filed. All the participants have an experience of using Zoom. None of the participants had experience with using soft robots and shape changing interfaces, however one participant wrongly consider the device they previously used as a soft robot. 14 participants agreed to provide a permission for video recording. However in this study, video recording appeared to be not necessary option.

4.2 Data Analysis

4.2.1 Quantitative Analysis of Questionnaire Results

Questionnaire data was analyzed quantitatively.

After conducting the experiment with all the participants, we sort the collected data by the questions' number of the questionnaire (numbers are related to Questionnaire in Appendix A “User Study Materials”):

- 5-point Likert scale questions 1, 3, 6, 7, 8
- Yes-no questions 2, 5, 9, 10, 11
- Multiple choice question 4

Questionnaire data is not normally distributed.

Consequently, we got eleven input files with 18 variables and twelve conditions each. First of all, Gaussian distribution reveal that there is no equal variances interval data. The subsequent statistical analysis in this study consists of two parts: the main Skillings-Mack test[3] for block design data and post-hoc analysis test Nemenyi[4]. Therefore for each test we formulated a hypothesis H0.

Skillings-Mack test

Skillings-Mack test was used because of missing data structure.

Since there are more than two levels of the variable in each question (twelve), we initially thought about conducting Friedman analysis test[5] to examine the hypothesis H0. However, the testing data had missing values due to the fact that every participant tested only a one third of all shapes. Therefore, Friedman analysis test cannot operate with the data correctly. For that reason, we used Skillings–Mack test as an adaptation of Friedman statistics for "missing-data structure". It is based on Monte Carlo method, so the result of the test depends on random resamplings. In our study, we leave this number B by default equal to 10000. The significance level to compare the p-value with is 0.05.

For the non-parametric Skillings-Mack test, the assumption for hypothesis H0 is the following (stated in null form, i.e. expected to be rejected):

[3] Skillings-Mack test in R: https://cran.r-project.org/web/packages/Skillings.Mack/Skillings.Mack.pdf

[4] Nemenyi test in R: https://cran.r-project.org/web/packages/PMCMRplus/PMCMRplus.pdf

[5] Friedman test in R: https://www.rdocumentation.org/packages/stats/versions/3.6.2/topics/friedman.test

H0 There is no significant deference between shapes of silicone actuators.

Post-hoc Analysis with Nemenyi Test

Since Slillings-Mack test has rejected the hypothesis H0 almost in every question, in other words, has revealed that groups of participants' answers for shapes are different, we decided to do the comparison of shapes pairwise in every question. Therefore, we did Nemenyi post-hoc analysis test. All the tests were conducted via R programming language in RStudio[6].

Nemenyi test was used for post-hoc analysis.

For Nemenyi post-hoc analysis test, we formulated the following hypothesis (stated in null form, i.e. expected to be rejected):

H0 There is no significant deference between pairs of shapes of silicone actuators.

4.2.2 Qualitative Analysis

Analysis of Open-Ended Questions of the Questionnaire

To finish the analysis of the questionnaire, we had to analyse two open-ended questions that are the extensions of *Question 2* and *Question 5* (numbers are related to the Questionnaire in Appendix A "User Study Materials"). As it was noticed, to the *Question 2* "Did your opinion related to the application scenario change after watching the whole video of movement simulation (in comparison with the initial static view of the shape)?" participants were tend to answer in terms of movement, not application scenario directly. So we consider that the question helps us to understand, whether participants' view on what kind of movement might a certain shape do has changed after watching the whole simulation.

[6] https://www.rstudio.com/

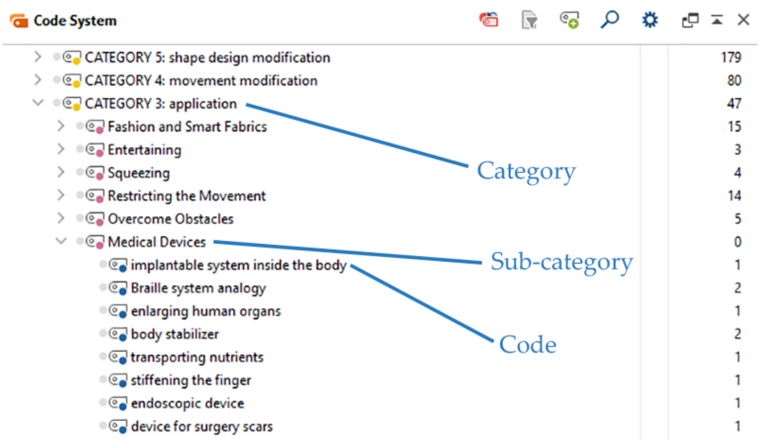

Figure 4.3: Code system in MAXQDA.

The second open ended question in the questionnaire is *Question 5* (numbers are related to Questionnaire in Appendix A "User Study Materials") "Does this shape movement help to provide certain/predefined feedback to users?". Obviously, all the shapes are able to provide visual and tactile feedback by doing its movement. However, it is valuable to highlight, whether participants consider this possible application for the shape at all and whether they find it useful.

Open-ended questions of the questionnaire were analysed qualitatively.

Analysis of Interview Transcriptions

All interview were transcribed via speech to text transcription application Outter[7], based on artificial intelligence and machine learning. For the qualitative data analysis of the interview answers, we used MAXQDA[8]. First, codes were manually assigned to the participants' replicas. Each code we associated with the shape in the comments section it's related to for the future comparison of the opinions about every certain shape and making conclusions out of it. Inside of some codes, there are also sub-codes. From our point of view, the difference between them is small enough to consider them as a one code. For

Interviews were transcripted and analyzed qualitatively.

[7]https://otter.ai
[8]https://www.maxqda.com

example, coded replicas as *worm* (Participant 11) and *rain worm* (Participant 9) are sub-codes of the code *worm*.

Codes were grouped into categories.

Next, we grouped codes into twelve main categories:

1. *Associations*: participants' ideas related to the associations with tested shapes as an answer to the first question of small discussion in the interview (4.1.4 "Semi-Structured Interview Design")
2. *Application*: participants' ideas related to the possible application with tested shapes as an answer to the second question of small discussion in the interview (4.1.4 "Semi-Structured Interview Design")
3. *Shape modification*: participants' explanation of ideas related to the shape modification during the sketching process (4.1.5 "Experiment Procedure")
4. *Movement modification*: participants' explanation of ideas related to the movement modification assigned to the modified shape design during the sketching process (4.1.5 "Experiment Procedure")
5. *No functionality improvement*: modification of the shapes doesn't provide any improvement of functionality in participants' opinion, but improve the appearance of the shape
6. *Shape design discussion*: participants asked to clarify the shape design
7. *Movement design discussion*: participants asked to clarify the the way movements evolves
8. *Uncertainty and problems*: participants' uncertainty related to their answers or questions of the questionnaire and mentioned by participants problems that they faced during the experiment
9. *Comparison with other shapes within one experiment*: participants provided a comparison of the current shape with previously tested by them
10. *Questionnaire clarification*: participants asked to explain the question again

11. *Questionnaire answers discussion*: participants explained their ideas of the questionnaire answers more precise

12. *Side comments*: comments, usually in a form of a short characteristic of the shapes, their movement and experiment procedure

Main categories consists of sub-categories, that makes the segregation of codes more precise. For example, inside the *Application* category there are sub-categories of fields of application (*Medical devices, Fashion and Smart Fabrics, Smart Jewellery*, etc.). Also, there are sub-categories named by the purpose of the movement (*Overcome Obstacles, Restricting the Movement*, etc.). They combine codes that represent application ideas of users based only on the action that supposed to be done via the shape, rather than a precise use case scenario. Undoubtedly, these ideas are quite rough to derive a specific application scenario out of it, however it might be useful for formulating application scenarios on top of it in the future. The example of categorization in the code system is presented in Figure 4.3.

Subcategories helps to organize the data more precise.

Finally, in order to do step forward on formulating findings we did thematic analysis inside categories of data, extracting themes that are oriented to the hypothesis of the study (4.1.3 "Hypothesis").

Chapter 5

Results

5.1 Quantitative Analysis Results

Participants' answers to the questionnaire provide us with the data for quantitative analysis. After the analysis we got the following results presented below. It revealed

There is no significant difference between answers in two questions.

Number of question	p-value	Rejecting or accepting H0
1	0.015	reject
2	0.001	reject
3	0	reject
4	0	reject
5	0	reject
6	0	reject
7	0.003	reject
8	0.003	reject
9	0.103	accept
10	0.073	accept
11	0.002	reject

Table 5.1: Significant differences for eleven questions achieved from Skillings-Mack test.

that there is no significant difference between participants' answers only in Question 9 *"Would you have liked to have* *more noticeable movement of the shape?"* and Question 10 *"Would you have increase the speed of the shape's motion?"*. A possible reason behind that could be that the speed of movement for the shapes was unified in the simulation and participants perceived this speed as normal for all the shapes. Furthermore, the meaning of these two questions were too close for participants, so they even might consider the answer to the second question be dependent on answer to the first.

Post-hoc test compared answers for all shapes pairwise.

Post-hoc analysis tests for every question highlighted more precise comparison between every two shapes. Results of comparison are represented as comparisons of p values for every question from Figure 5.1 til Figure 5.11. The output is providing plots of p values, where each value is a result of comparison of two shapes. We used a cutoff of p=0.05. Therefore only the shapes with values rounded up to 0 (pink color) are significantly different. The script in R can be found in Appendix B "Results of Silicone Actuators Shape Design in Maya".

5.2 Qualitative Analysis Results

5.2.1 Open-Ended Questions of the Questionnaire

Some shapes cannot provide a fedback.

After the analysis, we have the following results about providing visual and tactile feedback by shapes (if feedback is marked by a tick, at least one participant mentioned it). By participants opinion, only Shape 3, 9, 13, 26, 27, 29 cannot provide any type of feedback.

Sound and light were suggested as extra features.

Some participant were interested in assigning to the shape a combination of feedback, for example, add to the shape the option of producing light or sound. However, some of participants unexpectedly reported about the application idea, not about the feedback, that the shape is able to provide.

Question 2 data helps to report about the predictability of the movement.

In the open-ended Question 2, the initial participants' idea of movement can be considered as a prediction of what

Number of shape	Visual feedback	Tactile feedback
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	✓	
31	✓	✓
32	✓	✓
33		✓
34	✓	✓
35		✓
36	✓	

Table 5.2: Analysis of open-ended Question 5 in terms of feedback types highlighted by participants for the shapes.

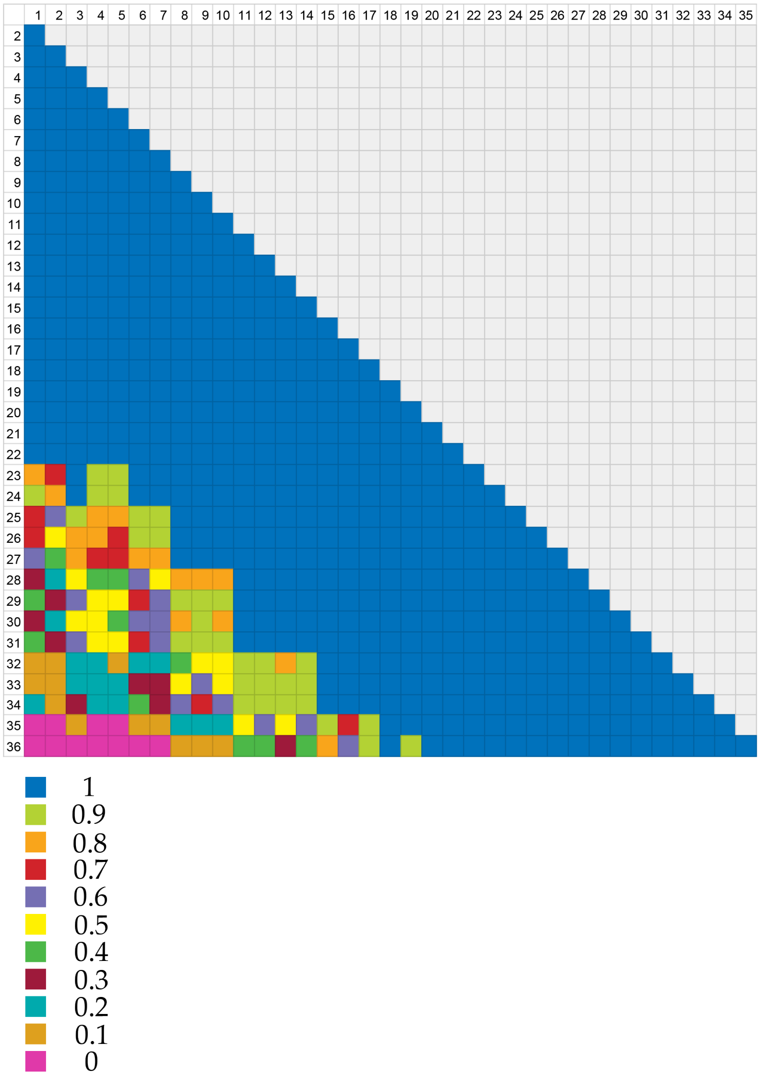

Figure 5.1: Post-hoc Nemenyi test result: pairwise comparison of shapes based on participants' answers on Question 1.

participant was expected to see. Therefore, we made a conclusion of predictability of the shape movement.

Number of shape	**Predictability of the movement**	**Ranking**
1	predictable	6/6
2	predictable	6/6
3	hardly predictable	3/6
4	predictable	5/6
5	hardly predictable	3/6
6	predictable	5/6
7	hardly predictable	3/6
8	hardly predictable	3/6
9	hardly predictable	3/6
10	hardly predictable	3/6
11	hardly predictable	4/6
12	hardly predictable	3/6
13	hardly predictable	3/6
14	not predictable	2/6
15	hardly predictable	3/6
16	hardly predictable	3/6
17	predictable	6/6
18	predictable	6/6
19	hardly predictable	4/6
20	hardly predictable	4/6
21	hardly predictable	4/6
22	hardly predictable	3/6
23	predictable	6/6
24	predictable	5/6
25	predictable	6/6
26	hardly predictable	4/6
27	predictable	5/6
28	predictable	6/6
29	predictable	6/6
30	hardly predictable	4/6
31	not predictable	1/6
32	hardly predictable	4/6
33	predictable	5/6
34	hardly predictable	4/6
35	hardly predictable	4/6
36	hardly predictable	4/6

Table 5.3: Analysis of open-ended question 2 from the questionnaire.

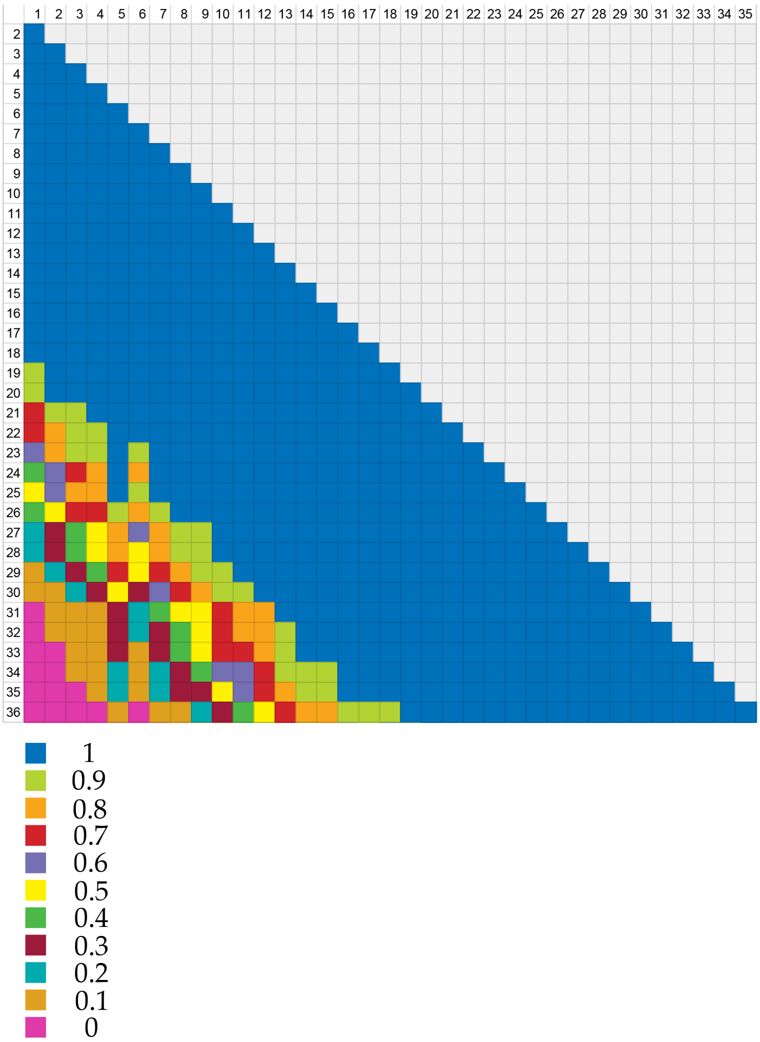

Figure 5.2: Post-hoc Nemenyi test result: pairwise comparison of shapes based on participants' answers on Question 2.

5.2.2 Results of Interviews' Analysis

Themes as valuable finding were highlighted.

After examining the data from interviews' transcriptions, we highlighted the following themes inside of categories:

- *Associations*
  - Most often shapes are tend to be associated with

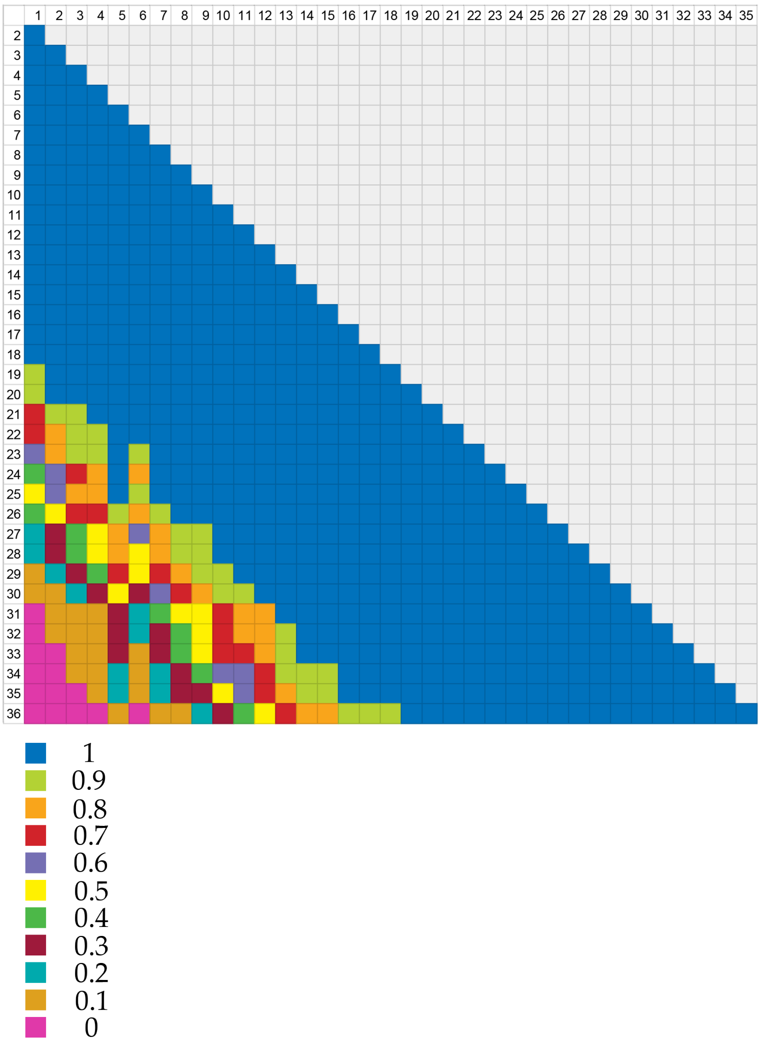

Figure 5.3: Post-hoc Nemenyi test result: pairwise comparison of shapes based on participants' answers on Question 3.

marine environment organisms, animals, that produce organic and natural way of movement as well as plants

– Shapes as well associated with objects that we see frequently: food, well-known logos and symbols and objects that are used on daily basis (scissors, wrist rest, plaster, etc.)

– Surprisingly, some quite popular among

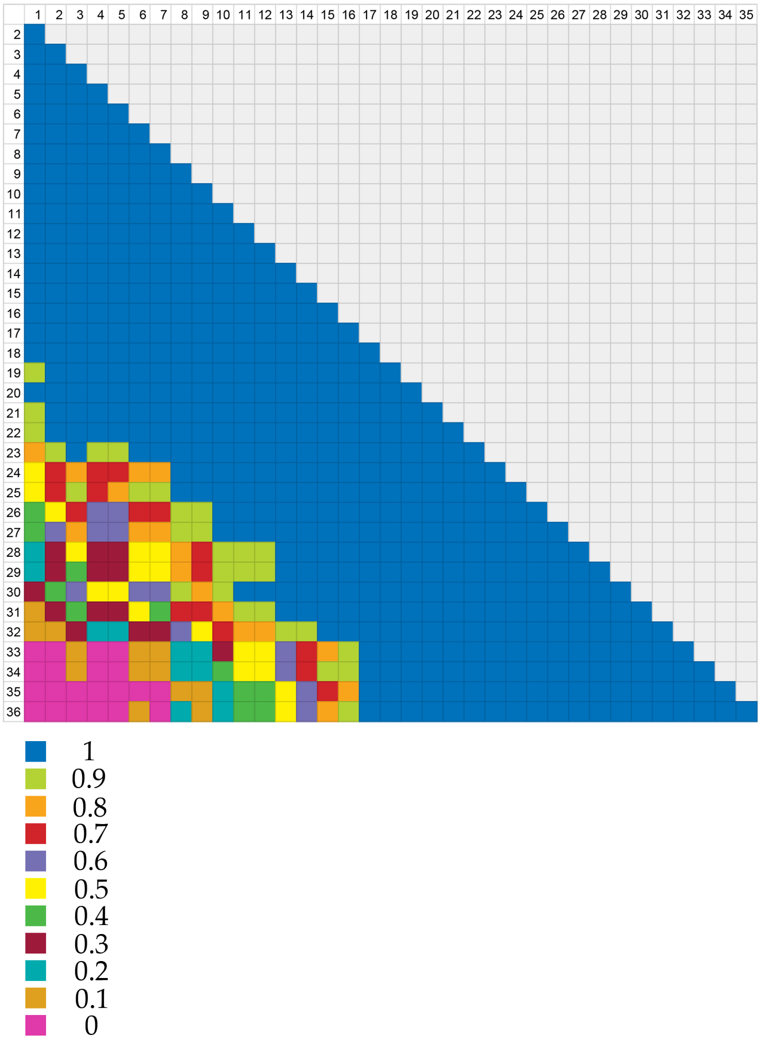

Figure 5.4: Post-hoc Nemenyi test result: pairwise comparison of shapes based on participants' answers on Question 4.

participants associations are car details, screws, construction parts, furniture and other rigid objects

– Some shapes clearly associated with the one object by almost all participants who had tested the shape: Shape 1 - flower, Shape 9 - shell, Shape 15 - starfish, Shape 23 - zipper, Shape 36 - screw

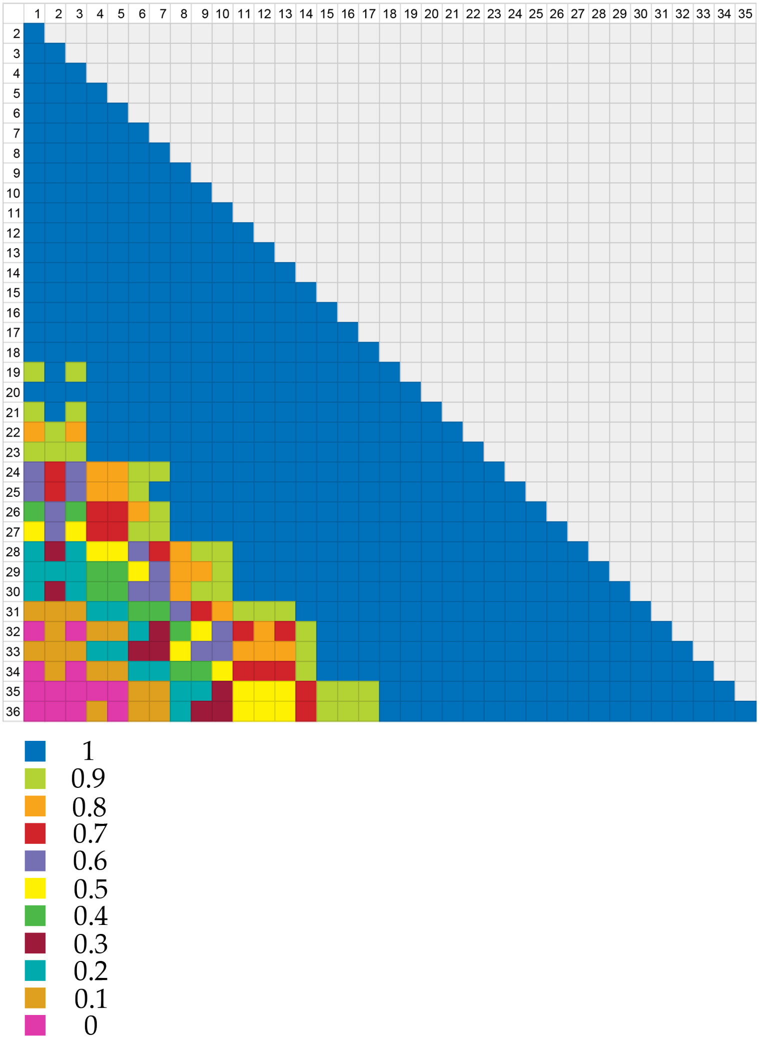

Figure 5.5: Post-hoc Nemenyi test result: pairwise comparison of shapes based on participants' answers on Question 5.

- *Application*
  - The most popular among participants application groups are medical devices, including massaging devices that could be even separated to the own group because of the number of references to it. As well as smart jewellery, smart fabrics and fashion field. Slightly less mentioned application is

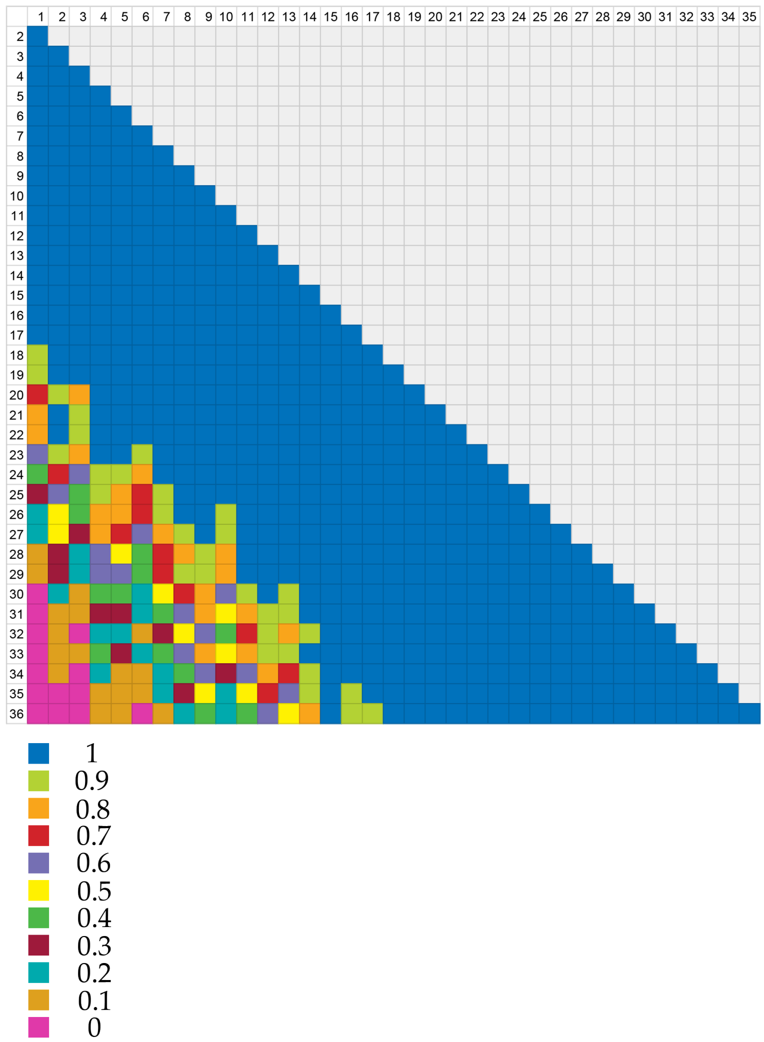

Figure 5.6: Post-hoc Nemenyi test result: pairwise comparison of shapes based on participants' answers on Question 6.

notification system and providing a feedback

- A big group of categories based on not precise applications, but the action that the shape is aiming to provide. For instance, grasping and holding objects, pushing other objects, restricting the movement of other objects, crawling and overcoming obstacles

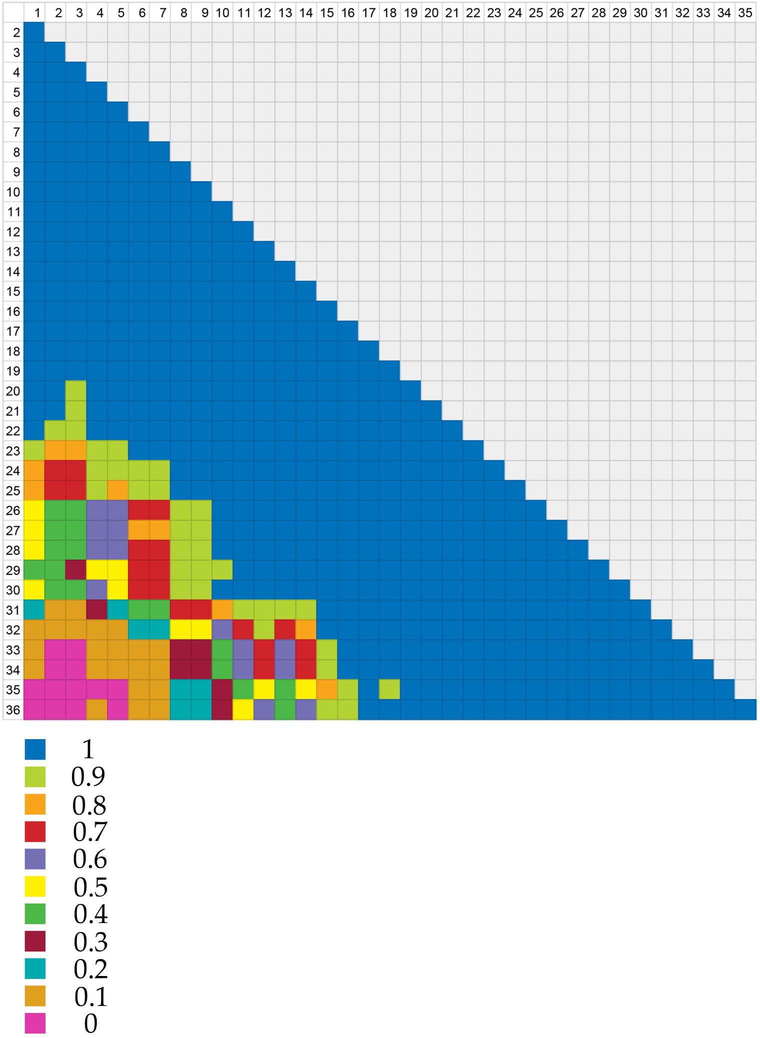

Figure 5.7: Post-hoc Nemenyi test result: pairwise comparison of shapes based on participants' answers on Question 7.

- *Shape modification*
  - Besides the shape modifications that were sketched by participants as the last step of testing every shape, participants noted that in some cases they would prefer circular-based shape instead of other geometric figures
  - Participants evenly were interested in adding

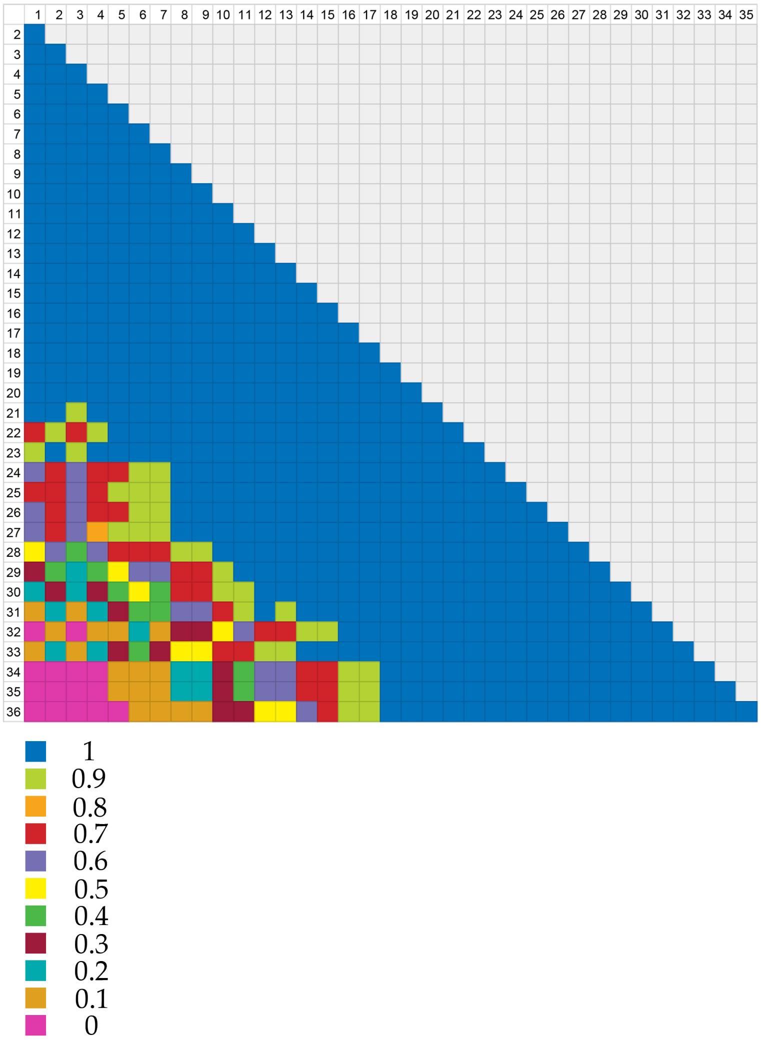

Figure 5.8: Post-hoc Nemenyi test result: pairwise comparison of shapes based on participants' answers on Question 8.

more details to some of shapes and, vice versa, in simplification of them

- Also, some parts of shapes were modified into more flatter ones
- Participants mentioned, that some modifications are done to improve shapes' appearance, but not its' functionality

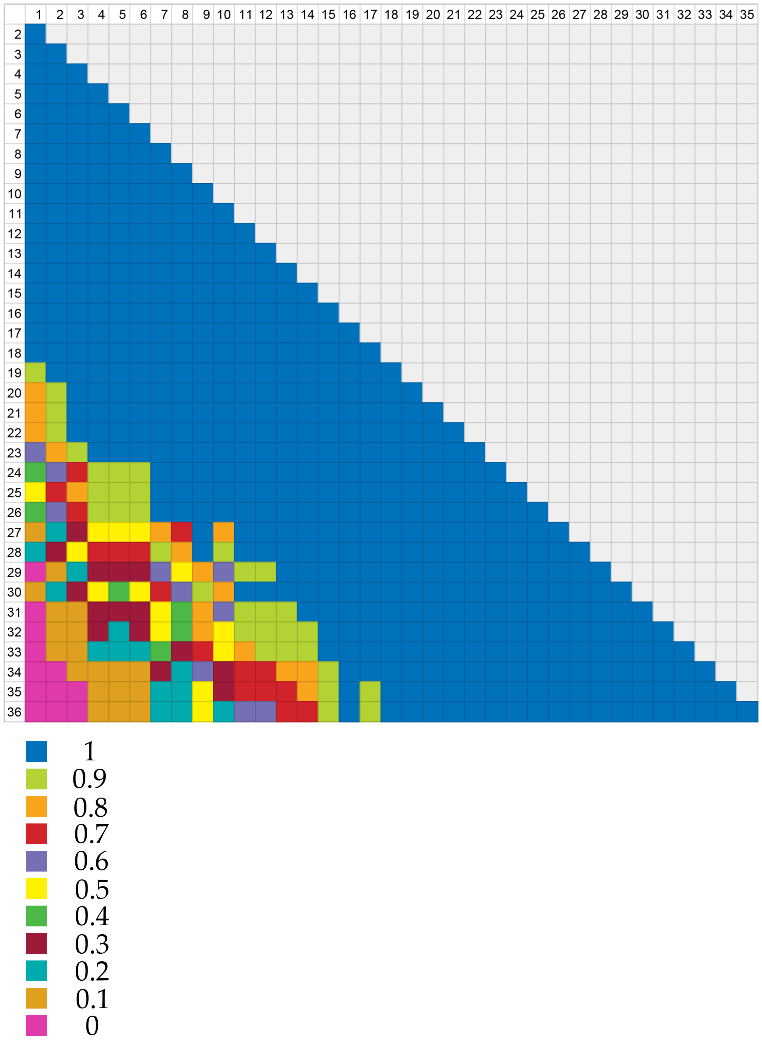

Figure 5.9: Post-hoc Nemenyi test result: pairwise comparison of shapes based on participants' answers on Question 9.

- *Movement modification*
  - Almost all modifications of existing movements were based on expanding or elongation followed by shrinking
  - Relatively small groups are based on designing bending or even wrapping around the object movement

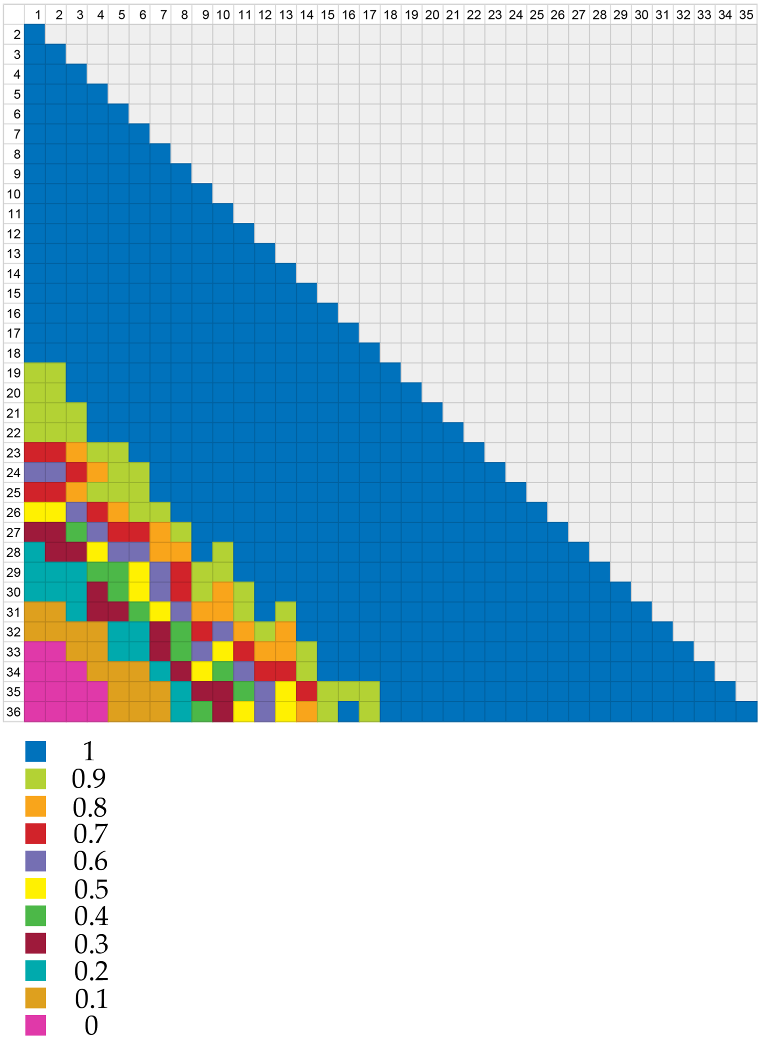

Figure 5.10: Post-hoc Nemenyi test result: pairwise comparison of shapes based on participants' answers on Question 10.

- *Shape and movement design discussion*
  - Almost all shape designs were understandable by users, only the Shape 34 were mentioned by two participants in order to clarify it's design
  - Shapes' movement that were not absolutely clear for participants is have Shape 3, Shape 12, Shape 21, Shape 33

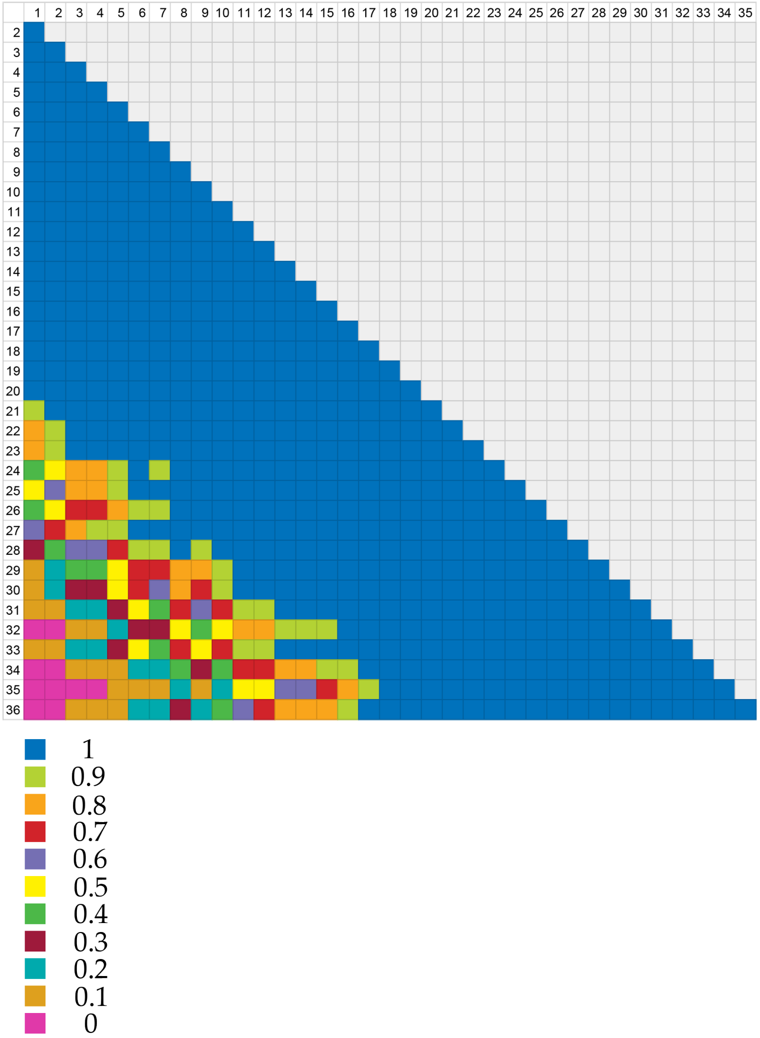

Figure 5.11: Post-hoc Nemenyi test result: pairwise comparison of shapes based on participants' answers on Question 11.

- *Uncertainty and problems*
  - By many participants opinion, predefined in advance application for every shape might help to visualise a modification of the design, otherwise it is quite challenging
  - Without having experience of using soft robots it is hard to imagine its application

- No information about shapes' dimensions mentioned as an issue
- No illustration of where the air supply is attached to the shape, therefore some movements ideas might be unrealistic
- Some participants have noticed that they are sticking to one application area, most often to medical devices ideas

• *Questionnaire clarification*

- The most problematic question appeared to be Question 4. A possible reason behind that might be a difficulty with assigning the application to the shape and therefore some uncertainty with the type of interaction with the user that shape supposed to provide
- Question 2 and Question 3 also needed a clarification for seven participants

Chapter 6

Discussion

In the following chapter, we provide a summary of the study, formulate key findings from the analysis part and contribution of the thesis to the field of soft robotics. We observe remaining questions, limitations of the study and suggest research directions for the future work in order to tackle these questions.

6.1 Summary and Contributions

We found that limited design variety of soft actuators might be a problem for further development in the soft robotics field, that restricts an application range. Therefore, we designed new shapes of soft actuators to address this issue. In order to increase the number of shape ideas we conduct brainstorming sessions with users. That helped us not only to generate more ideas of soft actuators, but also take into account participants' point of view already in the predesign stage. To every shape we assigned a movement that we found intuitive. Overall, 36 shapes of silicone actuators and their movement mechanisms were designed.

We designed 36 shapes of silicone actuators.

We conducted an experimental study in order to explore shapes' design with participants, and in particular, how familiar the shape design to them. This characteristic affect

Qualitative analysis outcomes reveal application groups are defined.

the easiness of the perception of the shape, since participant might have an association with a real world object. As a result of qualitative analysis of interviews, we investigated several group of possible application for designed shapes. Via further thematic analysis we made several conclusions in terms of: shape associations, application areas, shape modification possibilities, shape modification possibilities, uncertainty and problems that participants faced during the experiment.

Characteristics of movement were measured via quantitative analysis.

The questionnaire data helped us to investigate several aspects of shapes' movement via quantitative analysis. These aspects are the ability of shape to enhance the process of interaction with users, it's trainainability, dynamics of the movement and the ability to force the other objects. We also measure, whether the movements comfortable and distinguishable for participants.

Design modifications are collected and can be used for the future design.

Finally, in order to do the first step on silicone actuators shapes' design improvements, we asked all participants to sketch their ideas of shape modifications during the experiment sessions. These sketches might be useful for future analysis and redesign of the shapes. All the modification sketches are collected in Appendix C "Study Analysis Materials".

6.2 Limitations and Future Work

It has to be proven and evaluated that shapes in the reality moves in the same way as on simulation.

3D design of shapes and 3D simulation of their movements is optimal way of conducting the first study with big number of shapes of silicone actuators. But further, the most valuable and interesting shapes can be fabricated via standard procedures of molding and casting. This would be an evaluation and prove that shapes of silicone actuators act the same in the reality as on video simulation.

To the basic design new features could be added.

Applications in the field of smart jewellery were quite frequently mentioned by participants during the experiment sessions. In particular, participants were interested in the idea of augmenting silicone actuators body with light or sound option, for providing extra visual and audio feedback respectively if it's needed. These features can be further embedded to the design of silicone shapes actuators.

In this study, it was significant, whether participants can assign an application ideas to the shape. However, participants reported that already defined application area for the shapes of silicone actuator might help them to come up with a precise application use case. Moveover, for testing shapes via 3D simulations we recommend to provide dimensions of the shape to help participant to visualize the shape clearly and make their application ideas more precise.

Predefined application areas help to evaluate shapes design and movement.

Appendix A

User Study Materials

This appendix consists of experiment materials for participants.

A.1 Recruitment Email

The following template has been used to invite participants to the online experiment and to the brainstorming session.

Dear participant,

I am happy to invite you to the online experiment (or online brainstorming session) "Evaluation of Shapes and Movement Mechanism Designs of Silicone Actuators". The online meeting has been scheduled for [Date]. The duration is 1h and 40 minutes (or 1h and 30 minutes for a brainstorming session) approximately. To participate, please, follow these steps:

1 Read the consent form (attached to the email) to get to know about the experiment more

2 Join the Zoom meeting on [Date] by the following link: [Zoom link]

Thank you very much for participation and I look forward to see you soon!

Best regards,

Ekaterina Nedorubkova

A.2 Consent Form

In the following section consent forms for participation in brainstorming session and online experiment are presented.

Informed Consent

Online Brainstorming Session With Users Regarding Shapes of Soft Actuators Design

PRINCIPAL INVESTIGATOR Ekaterina Nedorubkova
Media Computing Group, RWTH Aachen University
Email: ekaterina.nedorubkova@rwth-aachen.de

Purpose of the study: The goal of the study is to enrich the silicone actuators shapes pool by participants' ideas. During the experiment participants will be asked to sketch their shape ideas and shortly explain them afterwards. Participants' ideas will be analyzed. Accepted ones will be further corrected (if it's needed) and turned into 3D models of actuators' shapes.

Procedure: During the participation in this experiment you will be asked to listen to the introduction of soft robotics and silicone actuators, then draw sketches of shapes of soft actuators with ability to perform a movement in the future. Drawing could be done by any preferable way (pen and paper, digital device). The next step is to take a photo/screenshot of the drafts and send it to the Zoom chat. Further you will be asked to listen to other participant ideas and have a look at the presentation of already designed shapes in Autodesk Maya by the principal investigator of the experiment. Afterwards, there will be the second part of the brainstorming session, where you can sketch more shapes. Finally, you will be asked to take a photo/screenshot of sketches and send it by the provided email address of the principal investigator. The whole procedure will take about 1h 30 minutes approximately to complete.

Risks/Discomfort: You may become fatigued during the experiment, because of its duration, but there will be a mixture of creative/perceptive activities to prevent this situation. Also, you will be provided with all needed instructions to prevent misunderstanding of the procedure. There are no other risks associated with participation in the study. If task performance or questions answering become distressing to you, it will be terminated immediately. Since the results of the brainstorming will be analysed afterwards, there will be a recording of your voice during the session.

Benefits: The results of the experiment will be useful for the master's thesis "Shapes and Movement Mechanism Designs of Silicone Actuators" conducted by Nedorubkova Ekaterina by supervision of Anke Brocker, providing users' opinion related to shapes of silicone actuators design.

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

Cost and Compensation: Participation in this study will involve no cost to you.

Confidentiality: All information collected during the online experiment, including voice recording, shape drafts and participants' personal data will be kept strictly confidential and only for study purposes. No publications or reports from this project will include identifying personal information of any participant. 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

If you have any questions regarding this study, please contact the investigator by email: ekaterina.nedorubkova@rwth-aachen.de.

Informed Consent

Online Experiment: Evaluation of Shapes and Movement Mechanism Designs of Silicone Actuators

PRINCIPAL INVESTIGATOR Ekaterina Nedorubkova
Media Computing Group, RWTH Aachen University
Email: ekaterina.nedorubkova@rwth-aachen.de

Purpose of the study: The goal of the study is to enrich the silicone actuators shapes' pool via testing the shapes' design and their movement mechanisms with participants. During the online experiment, the participant will be asked to test the simulation of the movement of each silicone actuator's shape, answer provided questions and have an opportunity to modify the shape if needed via sketching option. Participant's opinion and ideas will be further analyzed in order to evaluate each shape and its movement mechanism.

Procedure: During the participation in this experiment you will be first asked to listen to the introduction of soft robotics and silicone actuators and sign up to the collaborative platform Miro to perform the tasks. The testing procedure is conducted via Miro and consists of the following steps: watching the video of simulation of soft actuator's movement, answering interview questions, filling out the questionnaire and sketching your modification of the design. The whole procedure will take approximately 1h 40 minutes to complete.

Risks/Discomfort: You may become fatigued during the experiment, because of its duration, but there will be a mixture of creative and perceptive activities to prevent this situation. Also, you will be provided with all needed instructions to prevent misunderstanding of the procedure and a short break during the experiment. There are no other risks associated with participation in the study. If task performance or questions answering become distressing to you, it will be terminated immediately. Since the results of the experiment will be analysed afterwards, there will be a voice and video recording during the session.

Benefits: The results of the experiment will be useful for the master's thesis "Shapes and Movement Mechanism Designs of Silicone Actuators" conducted by Nedorubkova Ekaterina by supervision of Anke Brocker, providing users' opinion in terms of shape designs, movement characteristics and future application.

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

Cost and Compensation: Participation in this study will involve no cost to you.

Confidentiality: All information collected during the online experiment, including video and audio recording, personal data will be kept strictly confidential and used only for the purposes of this study. No publications or reports from this study will include identifying personal information of any participant. 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

If you have any questions regarding this study, please contact the investigator by email: ekaterina.nedorubkova@rwth-aachen.de.

A.3 Questionnaire

A questionnaire for every shape that participant supposed to test during the experiment is presented below.

Shape questionnaire

Please, answer the following questions related to the shape that you have just seen.

1. How familiar is the shape's design to you? *

	1	2	3	4	5	
Not familiar at all	◯	◯	◯	◯	◯	Very familiar

2. Did your opinion related to the application scenario change after watching the simulation of the movement (in comparison to the initial static view of the shape)? *

- ◯ Yes
- ◯ No

If yes, please, briefly explain how it was changed

____

____

____

____

____

3. Is there any way to enhance the interaction process via this shape model? *

	1	2	3	4	5	
No, not useful for the interaction process	◯	◯	◯	◯	◯	Yes, may help users

4. How do you imagine the type of interaction with the shape? *

- ◯ No interaction
- ◯ Indirect interaction
- ◯ Direct interaction

5. Does this shape movement help to provide certain/predefined feedback to users? *

- ◯ Yes
- ◯ No

If yes, please, briefly describe the type of feedback, that you can imagine

6. Can you imagine the shape doing different kinds of movement in comparison to the movement presented in the video? *

	1	2	3	4	5	
No, I cannot imagine different type of movement for the current shape	◯	◯	◯	◯	◯	Yes, shape design is able to adapt to other mov

7. How comfortable might it be for you to use this movement mechanism as a part of the device in daily life? *

	1	2	3	4	5	
Not comfortable at all	◯	◯	◯	◯	◯	Very comfortable

8. How dynamically the movement evolves? *

	1	2	3	4	5	
The movement is quite hard to notice	◯	◯	◯	◯	◯	Very dynamic movement

9. Would you have liked to have more noticeable movement of the shape? *

- ◯ Yes
- ◯ No

10. Would you have increase the speed of the shape's motion? *

- ◯ Yes
- ◯ No

11. Does this shape's movement have an ability to force the movement of other objects? *

- ◯ Yes
- ◯ No

Appendix B

Results of Silicone Actuators Shape Design in Maya

In this section, all 3D models of 36 shapes could be observed. Three pictures for every shape demonstrate the simulation of the movement from the initially designed shape to the target one. Every video, that participants watched during the online experiment, consists of the movement simulation from the initial shape to the target one followed by a reverse movement back the initial shape. This way of presenting the movement supposed to imitate the process how air moves in and out from the shape via air supply mechanism.

Shape 4 consist of two 3D models, that were presented to participants as one shape with due to the reason that the design and the movement character of these models are quite similar. It is also related to the Shape 17.

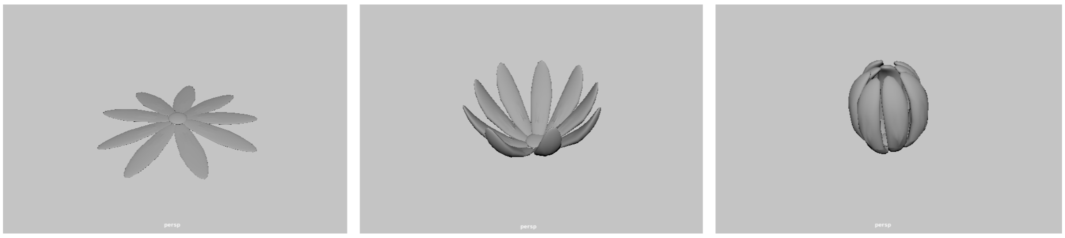

Figure B.1: 3D model of Shape 1.

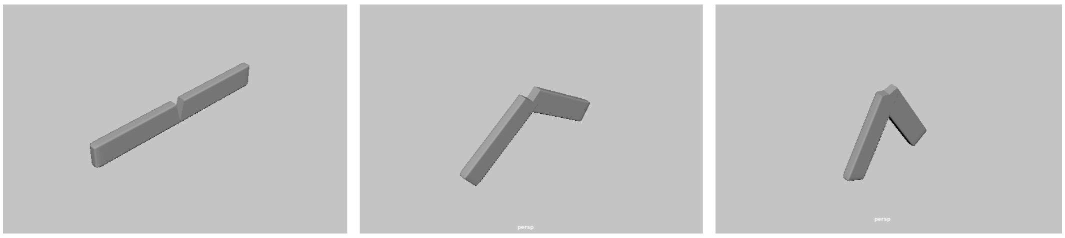

Figure B.2: 3D model of Shape 2.

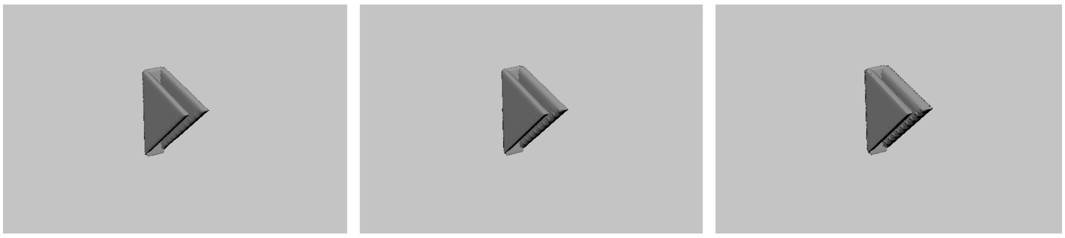

Figure B.3: 3D model of Shape 3.

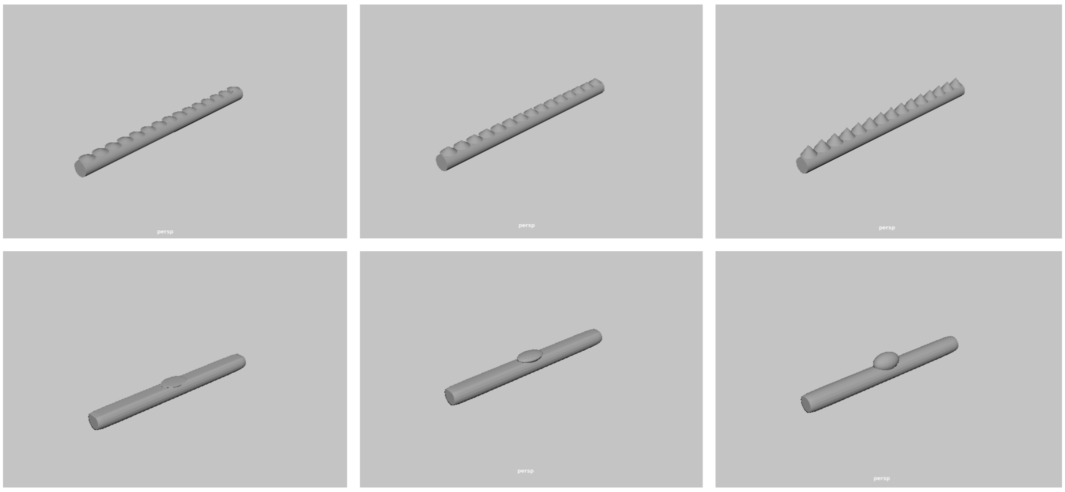

Figure B.4: 3D model of Shape 4.

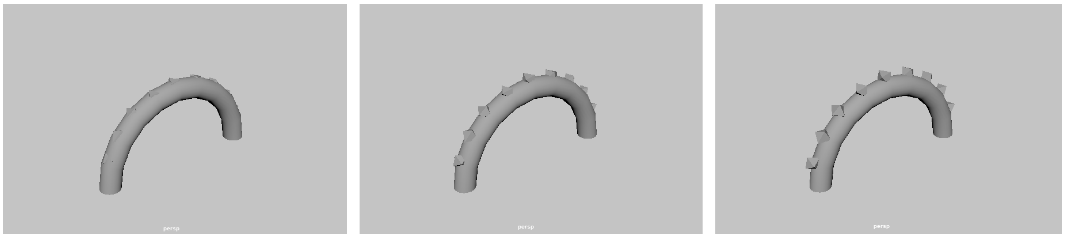

Figure B.5: 3D model of Shape 5.

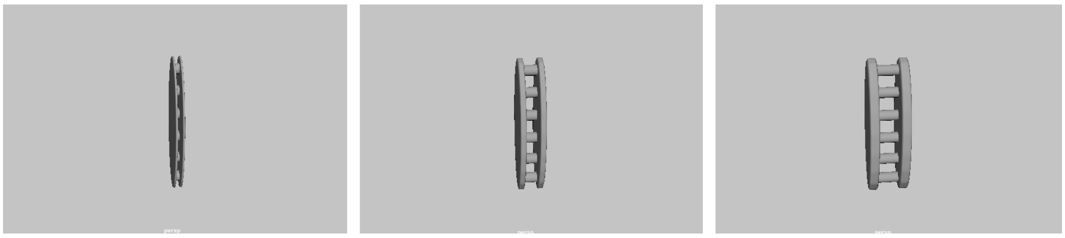

Figure B.6: 3D model of Shape 6.

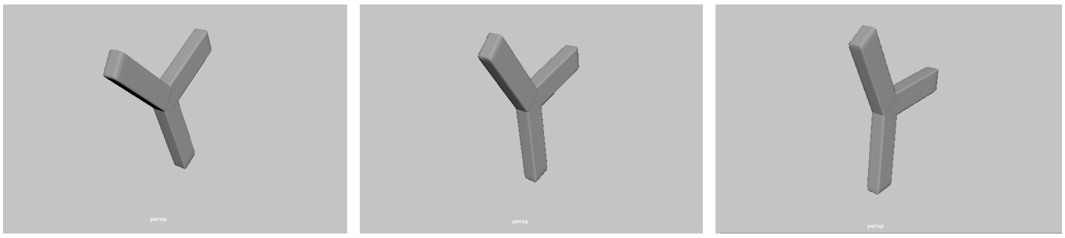

Figure B.7: 3D model of Shape 7.

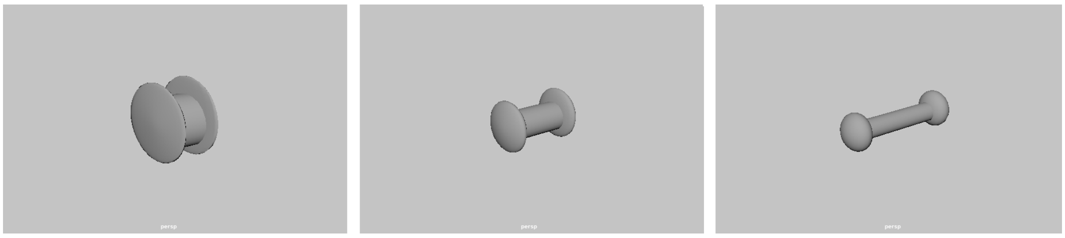

Figure B.8: 3D model of Shape 8.

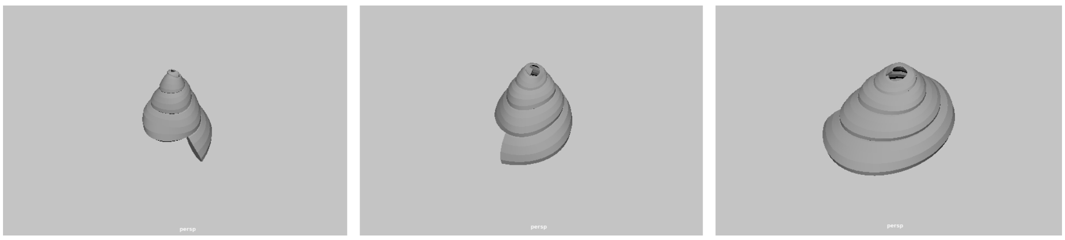

Figure B.9: 3D model of Shape 9.

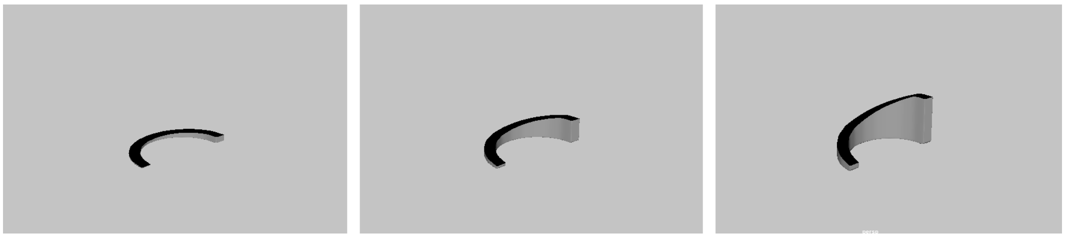

Figure B.10: 3D model of Shape 10.

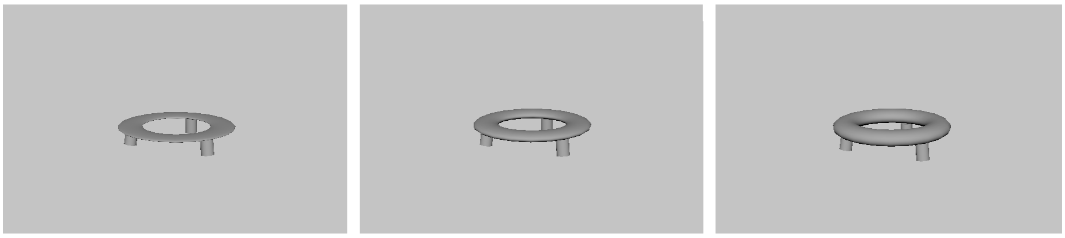

Figure B.11: 3D model of Shape 11.

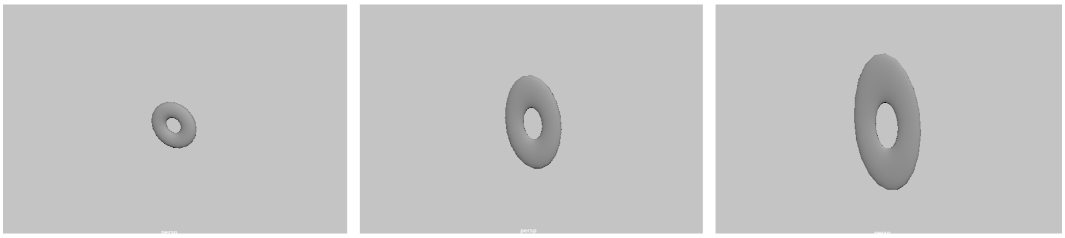

Figure B.12: 3D model of Shape 12.

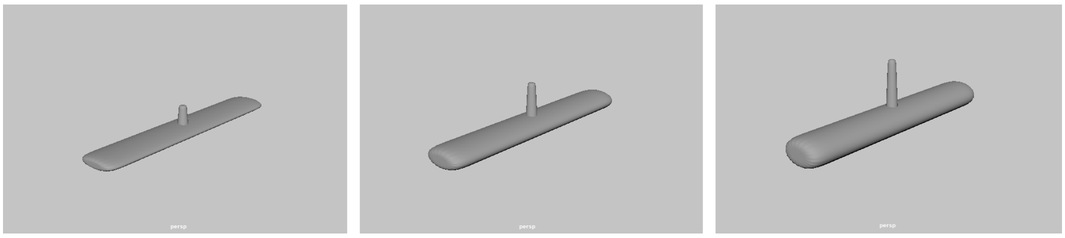

Figure B.13: 3D model of Shape 13.

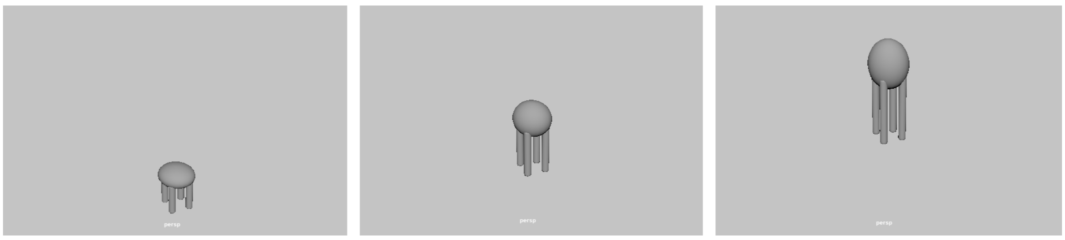

Figure B.14: 3D model of Shape 14.

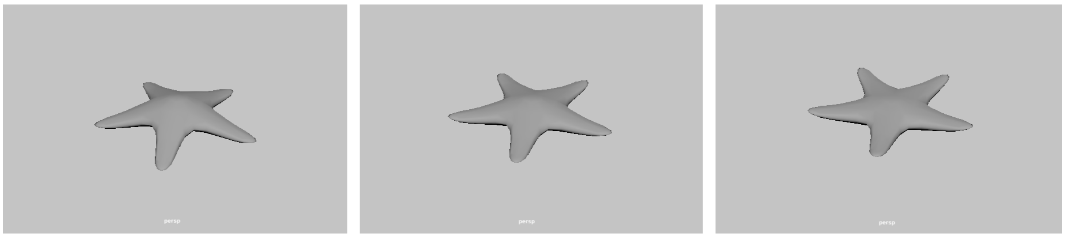

Figure B.15: 3D model of Shape 15.

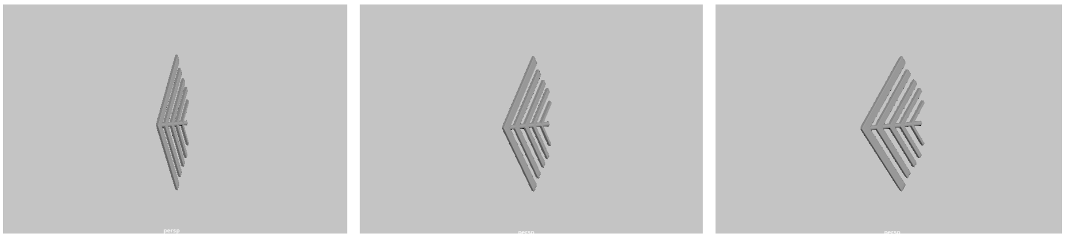

Figure B.16: 3D model of Shape 16.

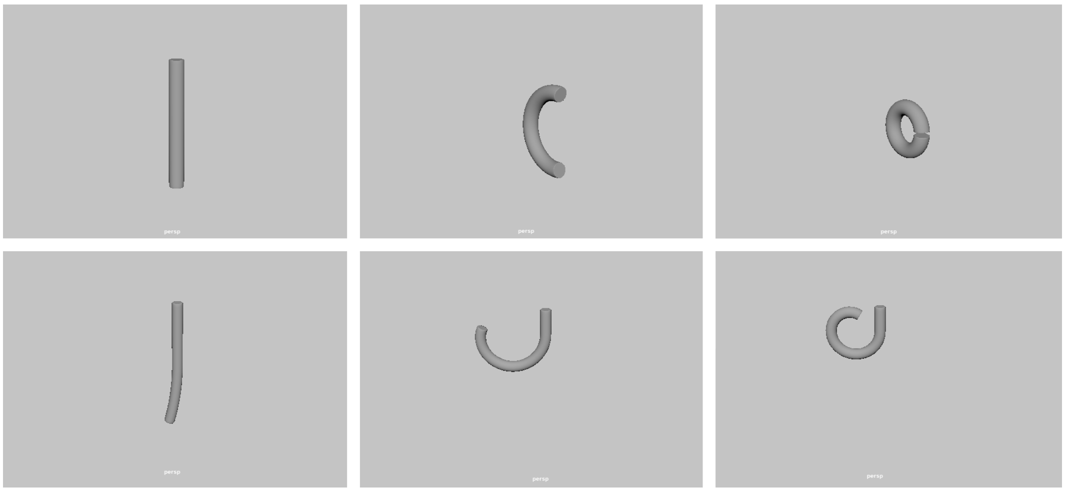

Figure B.17: 3D model of Shape 17.

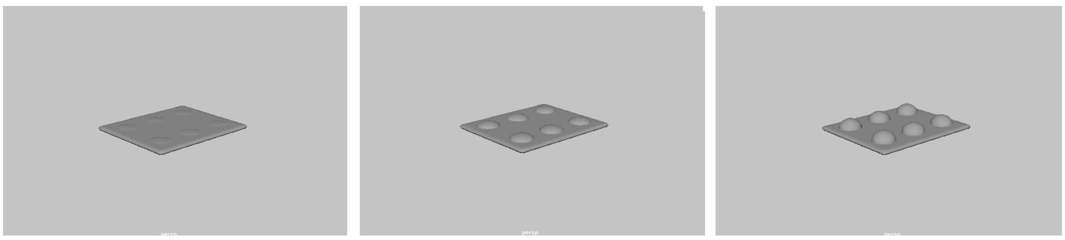

Figure B.18: 3D model of Shape 18.

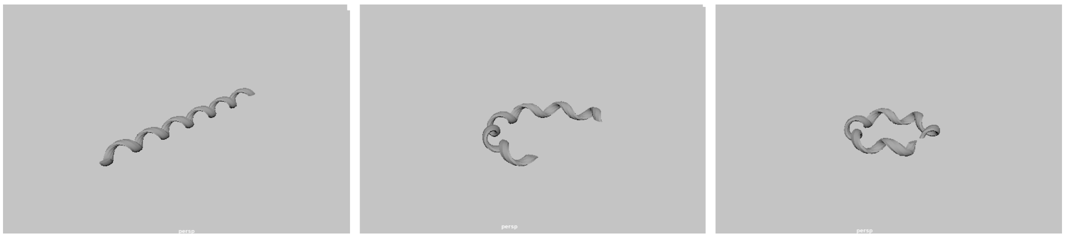

Figure B.19: 3D model of Shape 19.

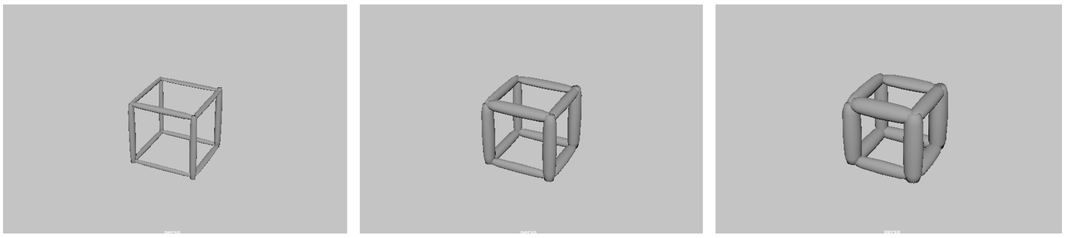

Figure B.20: 3D model of Shape 20.

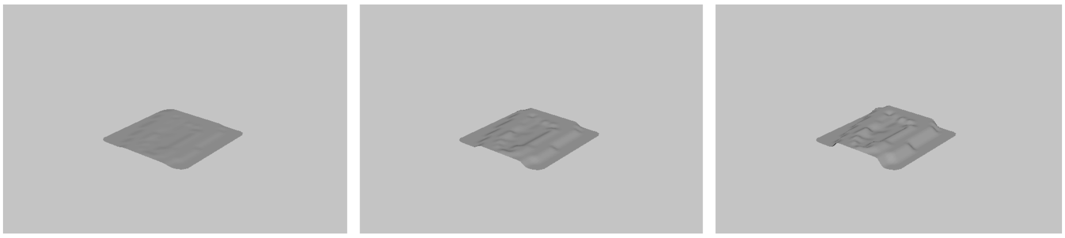

Figure B.21: 3D model of Shape 21.

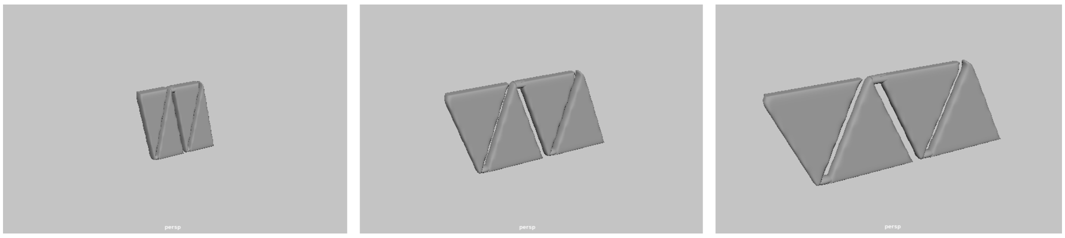

Figure B.22: 3D model of Shape 22.

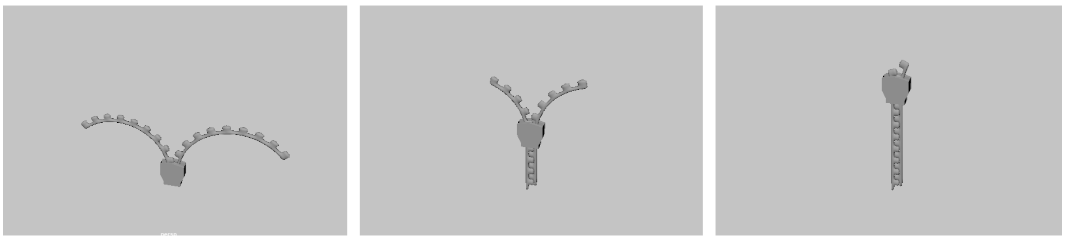

Figure B.23: 3D model of Shape 23.

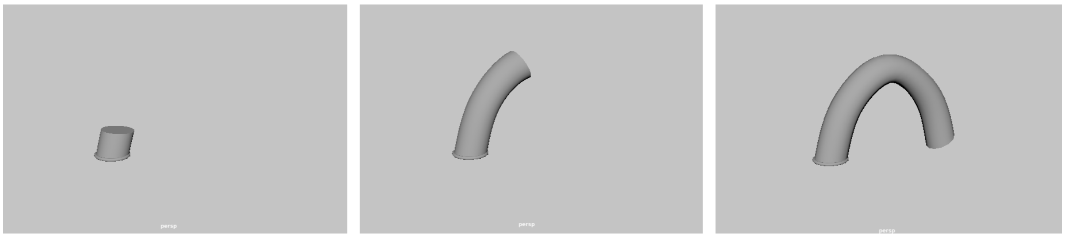

Figure B.24: 3D model of Shape 24.

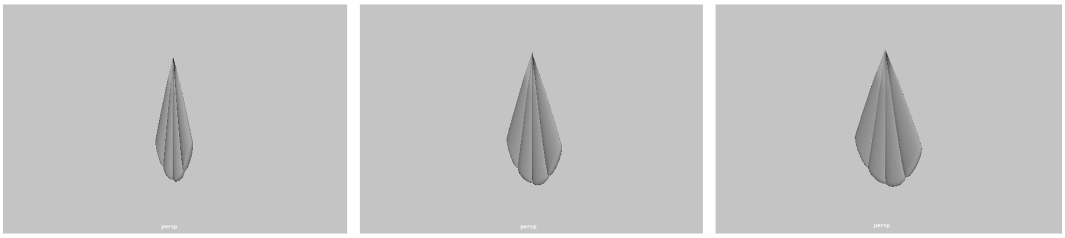

Figure B.25: 3D model of Shape 25.

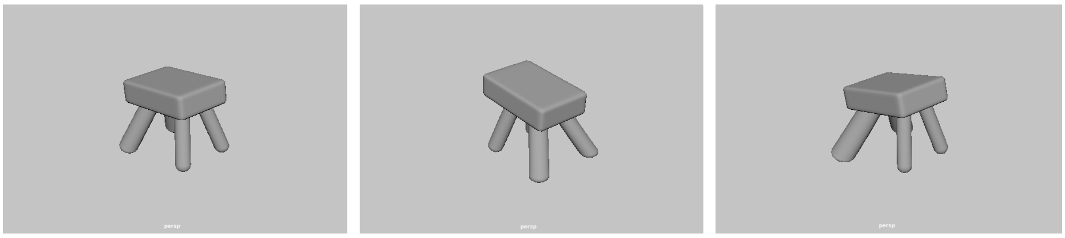

Figure B.26: 3D model of Shape 26.

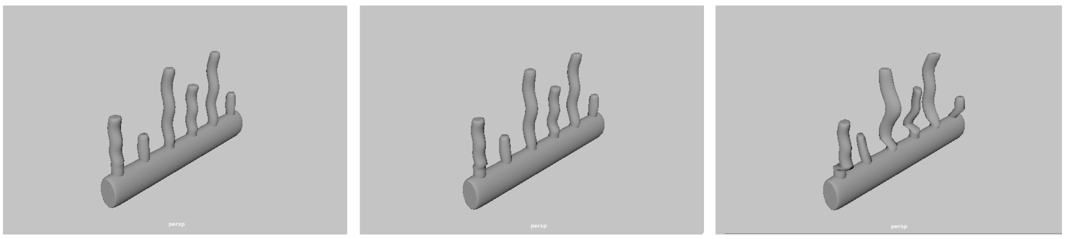

Figure B.27: 3D model of Shape 27.

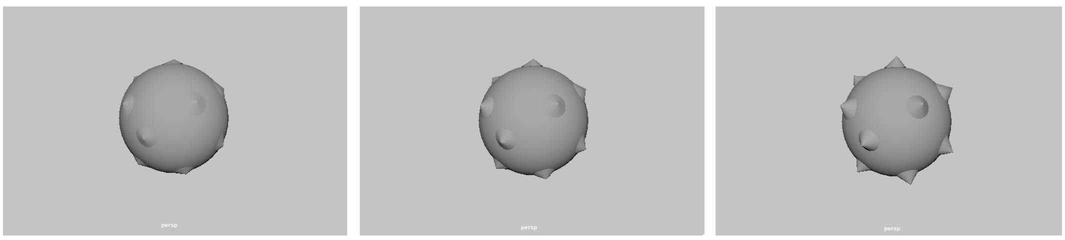

Figure B.28: 3D model of Shape 28.

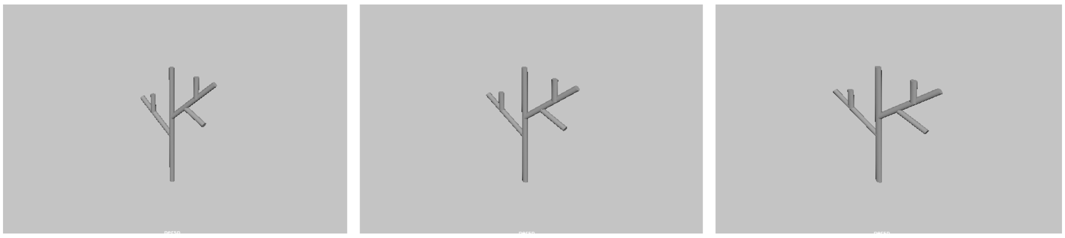

Figure B.29: 3D model of Shape 29.

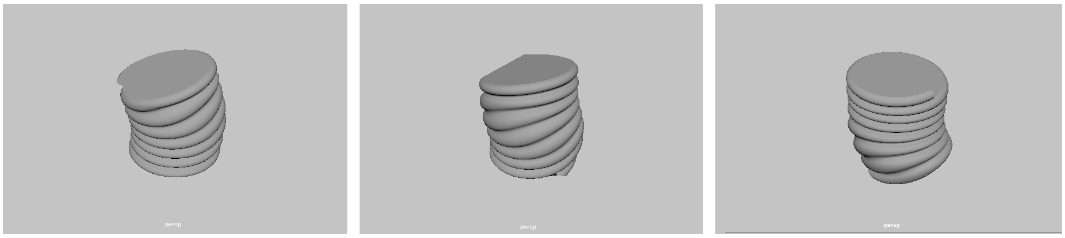

Figure B.30: 3D model of Shape 30.

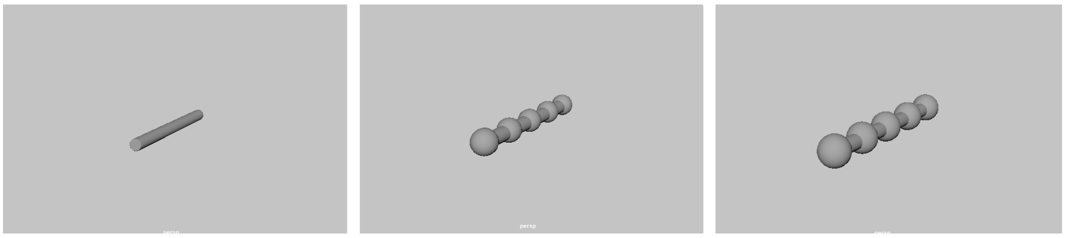

Figure B.31: 3D model of Shape 31.

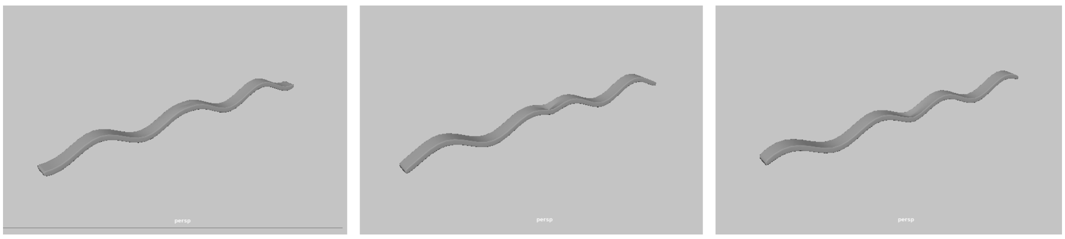

Figure B.32: 3D model of Shape 32.

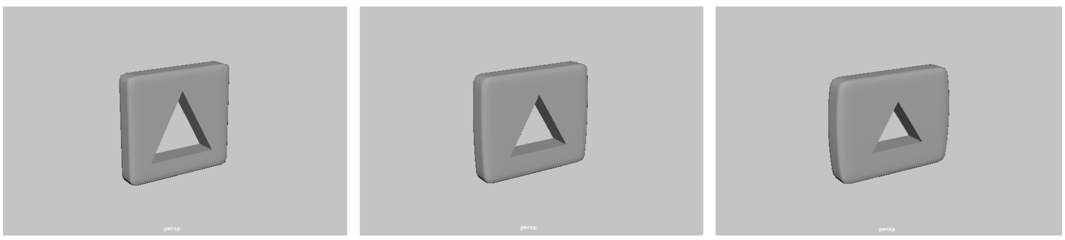

Figure B.33: 3D model of Shape 33.

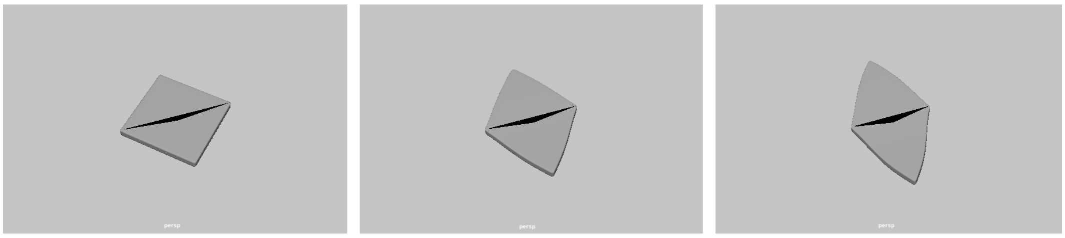

Figure B.34: 3D model of Shape 34.

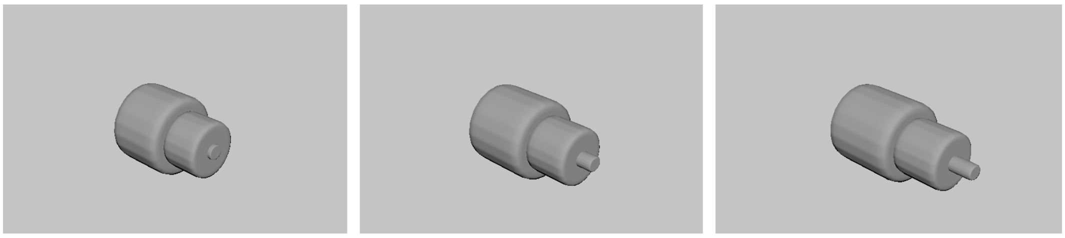

Figure B.35: 3D model of Shape 35.

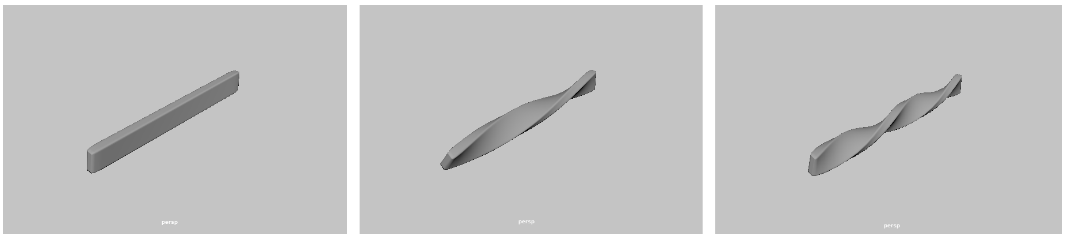

Figure B.36: 3D model of Shape 36.

Appendix C

Study Analysis Materials

C.1 Quantitative Analysis: R Script

For the quantitative analysis in R we used the following libraries and commands as showed in Figure C.1.

C.2 Participants' Sketches of Silicone Actuators Shapes Design

The following silicone actuator shapes' modifications were sketched and written down by participants during the experiment. No modifications were provided for Shape 21 and Shape 28.

```
install.packages("readxl")
install.packages("psych")
install.packages("Skillings.Mack")
install.packages("PMCMRplus")

#load the data in XLSX format
library(readxl)
dataQuestion <- read_excel( , na = "NA")
View(dataQuestion)

#convert the data into the matrix form
attach(dataQuestion)
datamartrix <- as.matrix(dataQuestion)
library(psych)

#do the Friedman analysis based test -
#Skillings-Mack test for data with missing values
library(Skillings.Mack)
Ski.Mack(datamartrix, simulate.p.value = TRUE, B = 10000)

#do the post-hoc pairwise test - Nemenyi test
library(PMCMR)
posthoc.friedman.nemenyi.test(datamartrix,
p.adjust.methods = "none",plottype = c("mcb"))
```

Figure C.1: R script for the quantitative analysis of interview data.

Figure C.2: Sketched design modifications for the Shape 1.

Figure C.3: Sketched design modifications for the Shape 2.

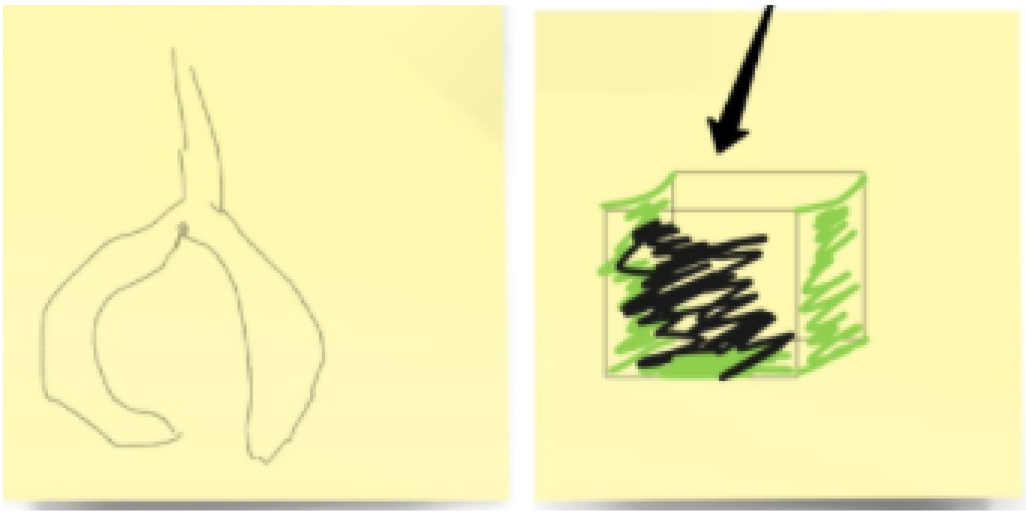

Figure C.4: Sketched design modifications for the Shape 3.

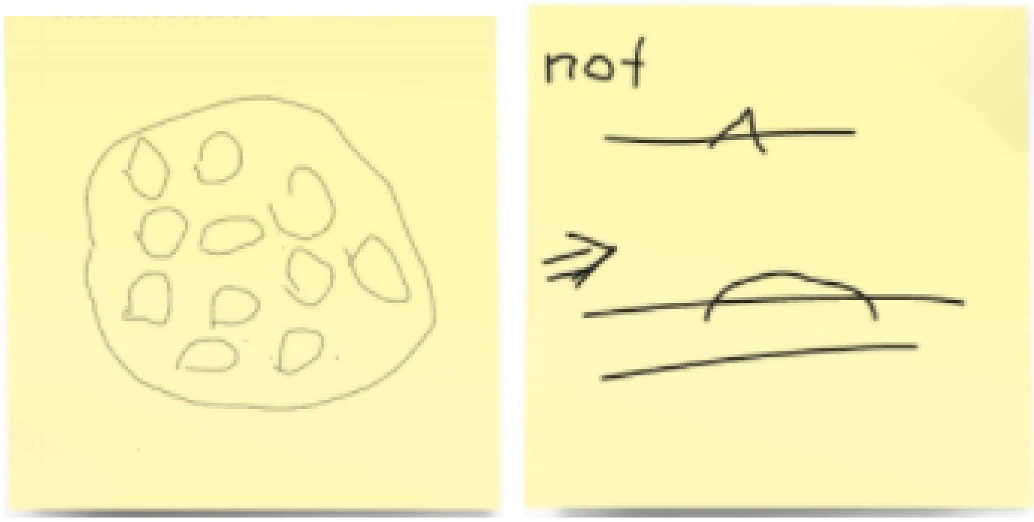

Figure C.5: Sketched design modifications for the Shape 4.

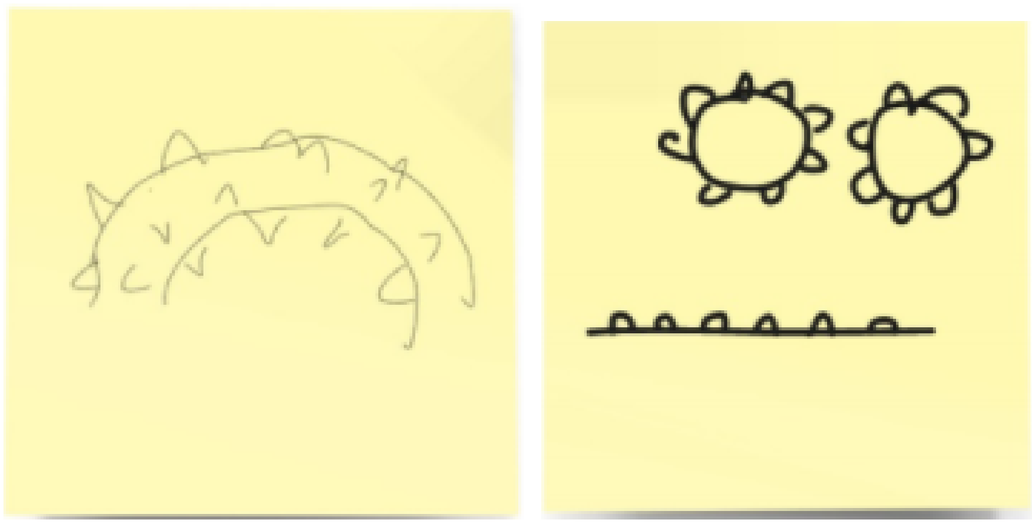

Figure C.6: Sketched design modifications for the Shape 5.

Figure C.7: Sketched design modifications for the Shape 6.

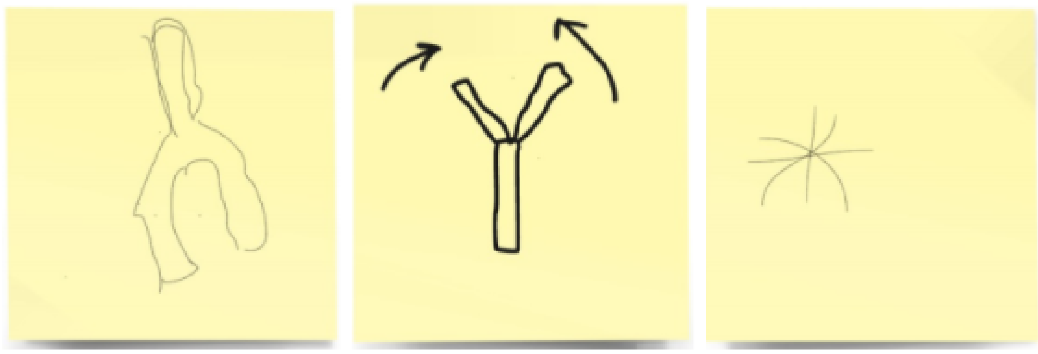

Figure C.8: Sketched design modifications for the Shape 7.

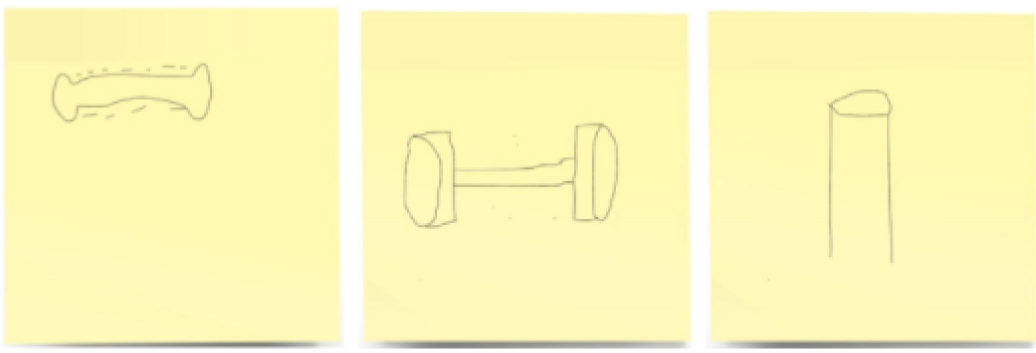

Figure C.9: Sketched design modifications for the Shape 8.

Figure C.10: Sketched design modifications for the Shape 9.

Figure C.11: Sketched design modifications for the Shape 10.

Figure C.12: Sketched design modifications for the Shape 11.

Figure C.13: Sketched design modifications for the Shape 12.

Figure C.14: Sketched design modifications for the Shape 13.

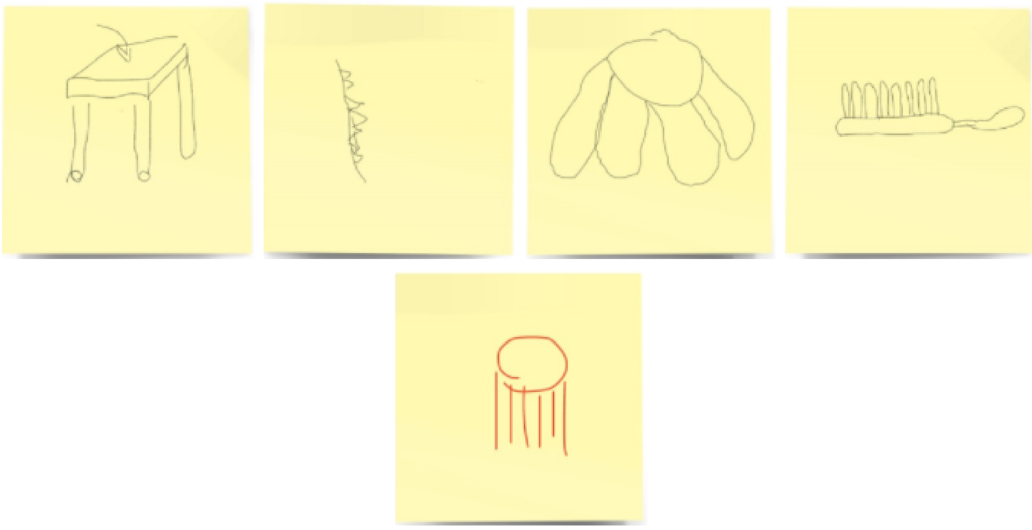

Figure C.15: Sketched design modifications for the Shape 14.

Figure C.16: Sketched design modifications for the Shape 15.

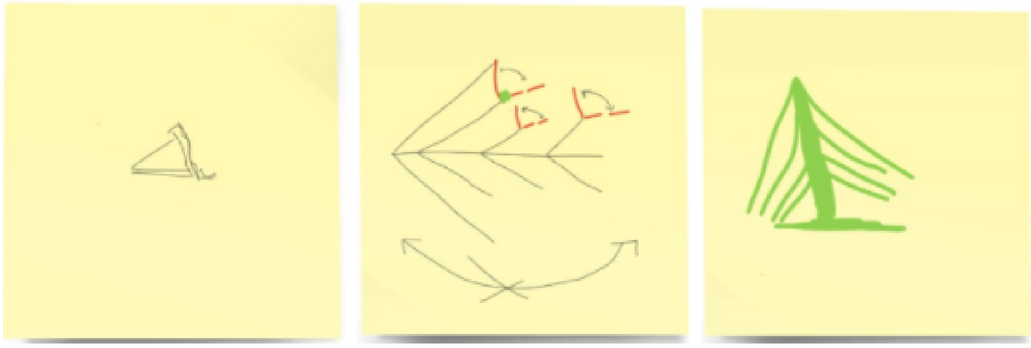

Figure C.17: Sketched design modifications for the Shape 16.

Figure C.18: Sketched design modifications for the Shape 17.

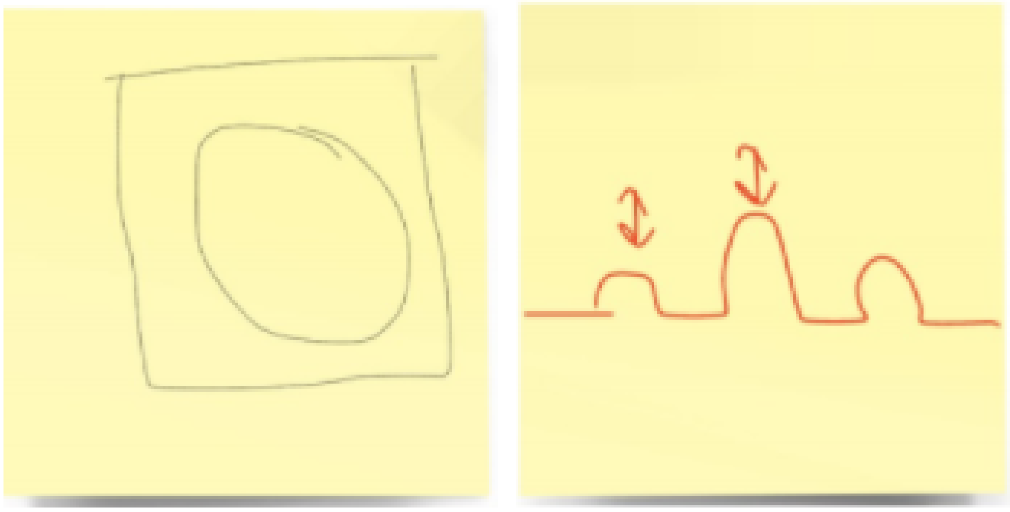

Figure C.19: Sketched design modifications for the Shape 18.

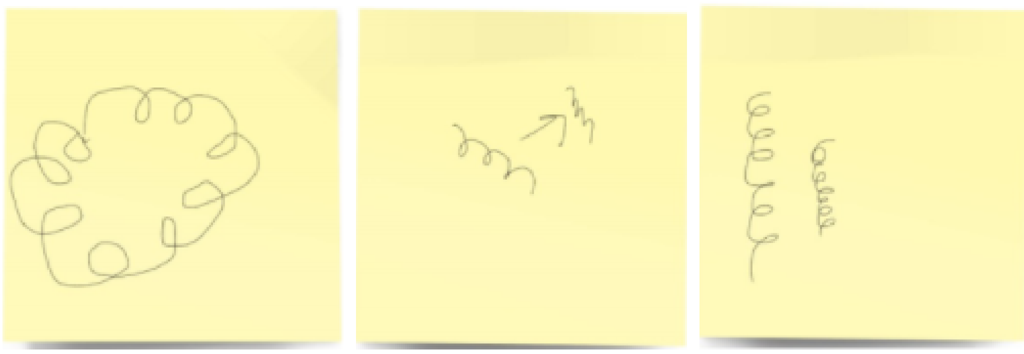

Figure C.20: Sketched design modifications for the Shape 19.

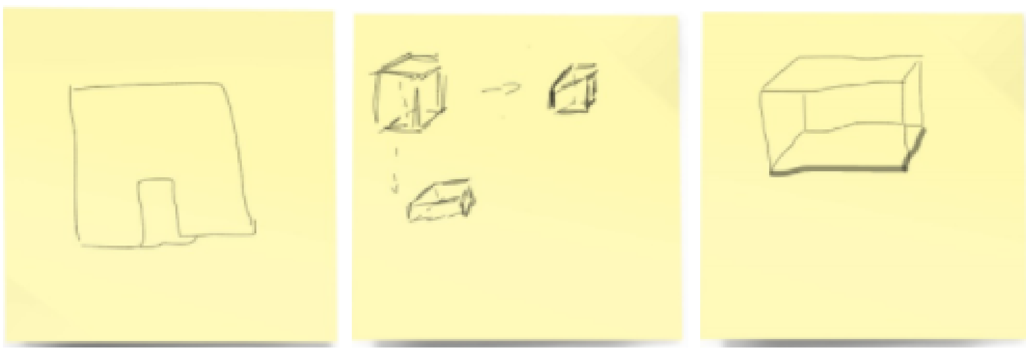

Figure C.21: Sketched design modifications for the Shape 20.

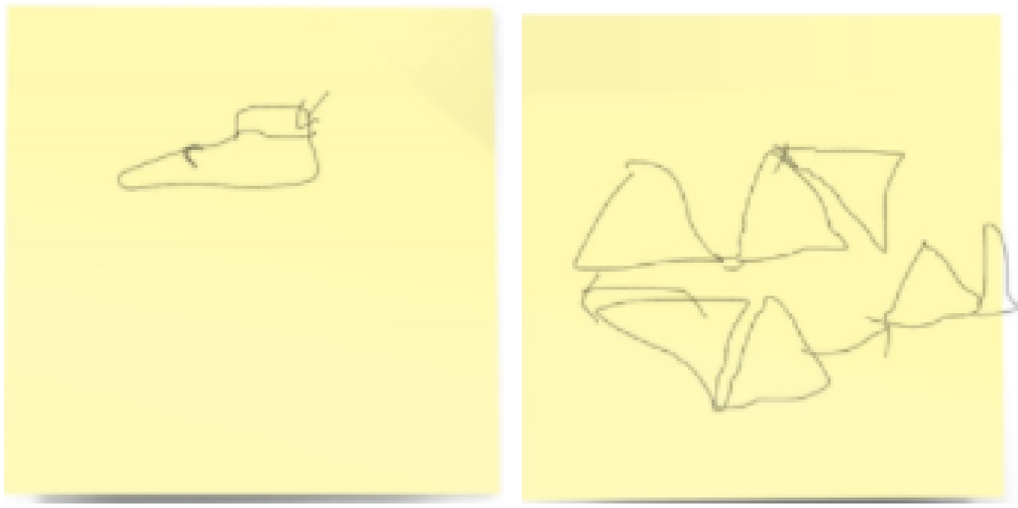

Figure C.22: Sketched design modifications for the Shape 22.

Figure C.23: Sketched design modifications for the Shape 23.

Figure C.24: Sketched design modifications for the Shape 24.

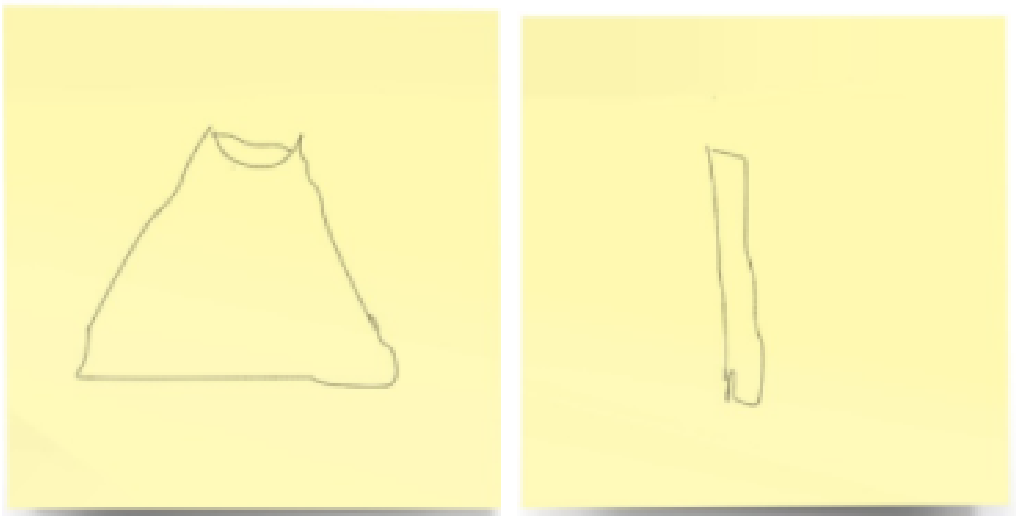

Figure C.25: Sketched design modifications for the Shape 25.

Figure C.26: Sketched design modifications for the Shape 26.

Figure C.27: Sketched design modifications for the Shape 27.

Figure C.28: Sketched design modifications for the Shape 29.

Figure C.29: Sketched design modifications for the Shape 30.

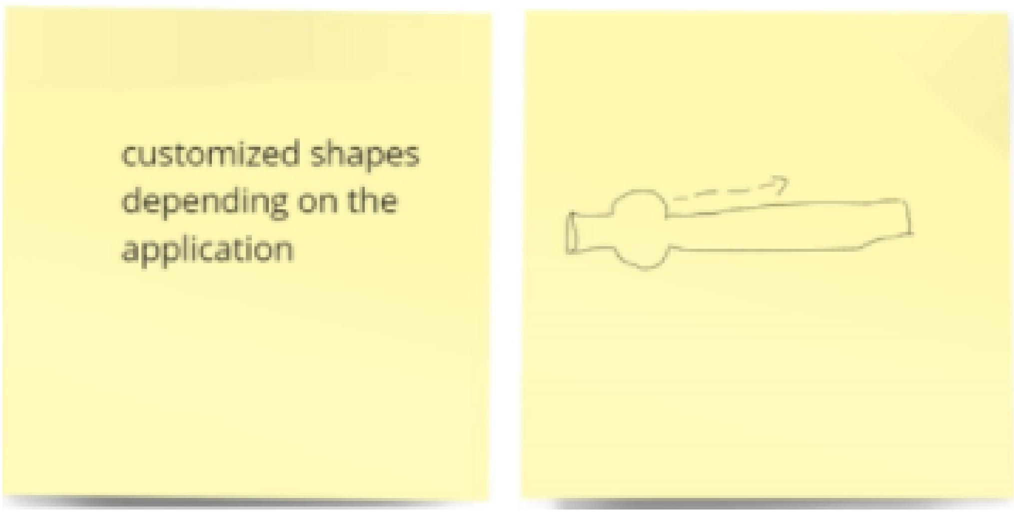

Figure C.30: Sketched design modifications for the Shape 31.

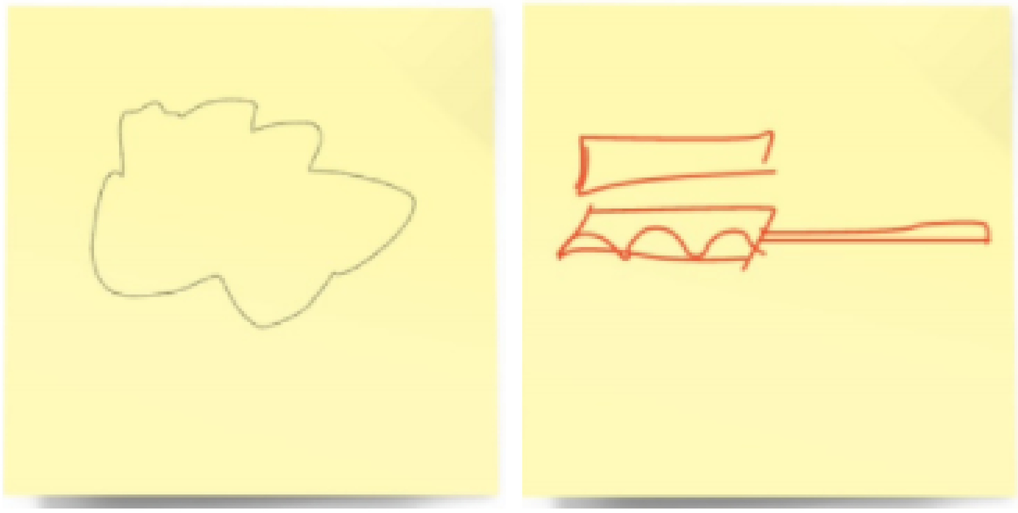

Figure C.31: Sketched design modifications for the Shape 32.

Figure C.32: Sketched design modifications for the Shape 33.

Figure C.33: Sketched design modifications for the Shape 34.

Figure C.34: Sketched design modifications for the Shape 35.

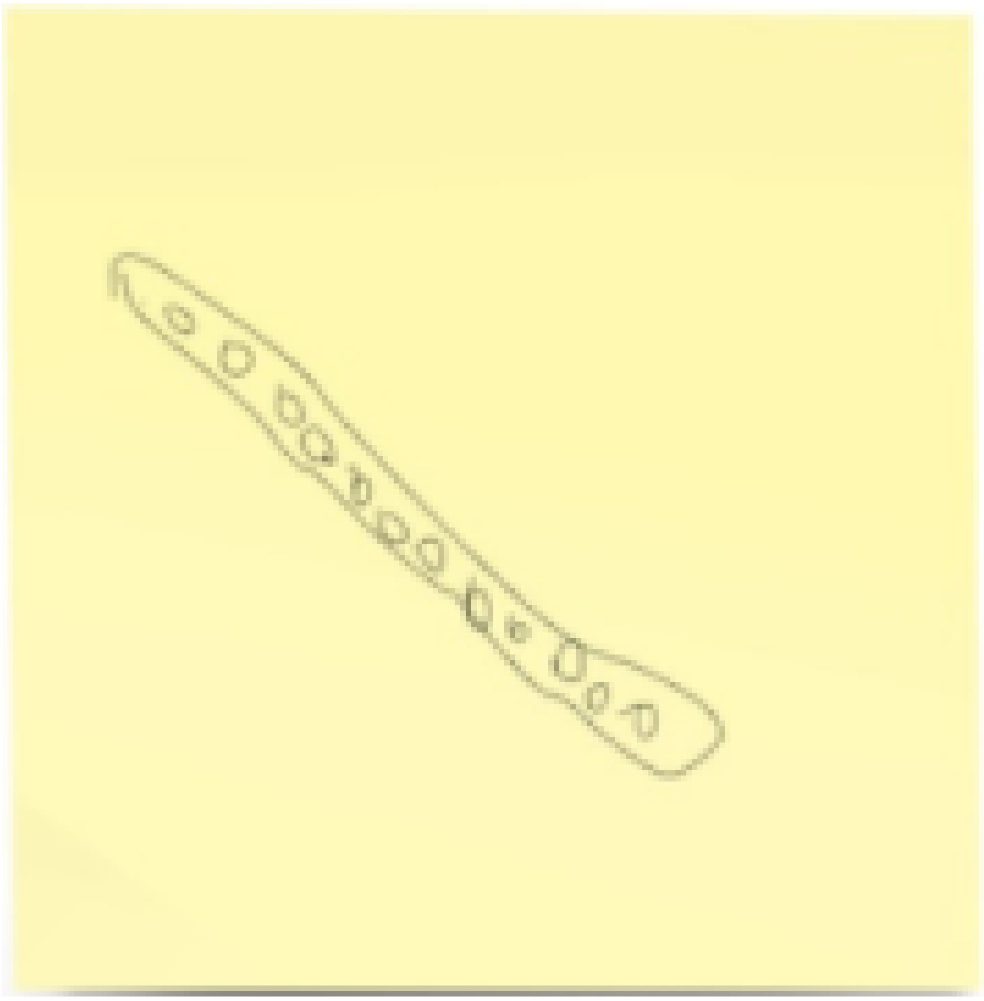

Figure C.35: Sketched design modifications for the Shape 36.

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