DEPARTMENT OF COMPUTER SCIENCE

Embracing the Air: A Study on the Huggablity of Large-scale Inflatable Soft Robots

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Abstract

Building robots using compliant and flexible materials has become an increasingly popular area of research. However, soft robots that operate at a human scale are not yet fully explored. In this research, I focus on people's interactions with these large-scale inflatable robots and how shape affects their huggability. This project has delivered five core outputs, which are:

- A design space that summarises and explores the field of soft robotics.
- Qualitative research (N=6) generated through bodystorming with experts in the field.
- Five guiding principles for the shape of large-scale inflatable soft robotic generated through qualitative research (N=12) using semi-structured interviews and low fidelity prototyping.
- An in-depth investigation (N=28) of one of these principles quantitatively to confirm its validity.
- Development of a low-cost low-pressure pneumatic joint system.

Dedication and Acknowledgements

Thank you to everyone who helped in writing this thesis.

To Mum and Dad, thank you for everything.

Declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Taught Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, this work is my own work. Work done in collaboration with, or with the assistance of others, is indicated as such. I have identified all material in this dissertation which is not my own work through appropriate referencing and acknowledgement. Where I have quoted or otherwise incorporated material which is the work of others, I have included the source in the references. Any views expressed in the dissertation, other than referenced material, are those of the author.

Connor Hamilton, Thursday 4$^{\text{th}}$ May, 2023

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Ethics Statement

This project fits within the scope of ethics application 0026, as reviewed by my supervisor, Professor Anne Roudaut.

Chapter 1

Introduction

Emerging from the premise of bio-inspired technology, the field of soft robotics is tackling problems not yet addressed by traditional hard robots. Soft robots are currently used across an array of industries. Robots consisting of flexible and compliant materials are: supporting those in long-term care [1], packing food produced on the factory floor[2] and may soon head to space[3]. As they have become increasingly popular, one area that their growth has been limited is in their size. Through the use of inflatable actuators, a handful of human-scale soft robots have been made attempting to fill this gap [4, 5, 6]. However, all of them have taken a robot-centric perspective. They focus only on the technical challenge of creating these robots and fail to utilise one of soft robotics most precious advantages. They are trustworthy and safe.

I have used an interaction-focused perspective to explore human-scale inflatable soft robotics. The project outline as well as the process of divergent and convergent thinking used in this project can be seen in Figure 1.1.

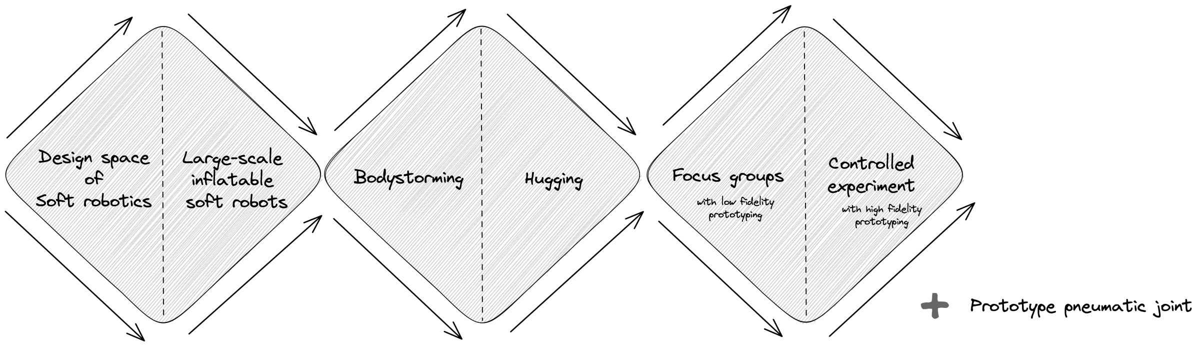

Figure 1.1: Project outline

In this work, I will present a design space (a method of presenting a collection of ideas or examples) that gives an overview of the field of soft robotics and reveals the underlying patterns and relationships that exist in the research.

I will describe and discuss a bodystorming exercise (N=6) used to perform qualitative research about inflatable soft robotics and as well as generate four additional interesting avenues for future work.

Using a series of two-part focus groups (N=12) that comprises a discussion task and a low-fidelity design task I explored how people feel about hugging soft robots. Some examples of these prototypes can be seen in Figure 1.2.

This qualitative research resulted in five guiding principles for designing the shape of large-scale inflatable soft robots, which are:

- **Animism** - Incorporate features that allude to the robot being alive in some way. Good choices for these might be including a face or limbs as well as more general features like malleability akin to a human or animal. These features can stem from both anthropomorphism and zoomorphism

Figure 1.2: Low fidelity prototype

and should indicate that the soft robot is able to interact with someone hugging it. However, when an inflatable is considered "alive" participants may feel uncomfortable if consent to hug the robot has not been established.

- **Optimal diameter** - The perfect diameter will depend both on the arm span of the who is person hugging and the type of hug that is being performed. The person who is hugging should feel that there are clear locations where their body can dock with the robot. While fitting arms completely around the robot is not necessary, the person or group of people hugging should be able to envelop the robot.
- **Avoid spikes** - Spikes produce a highly negative effect on huggability that may not track with other positive characteristics like cuteness.
- **Non-prescriptive** - Avoid limiting how people can hug the soft robot to specific hugging styles.
- **Robustness** - The shape (or other factors like material or construction) should convince the hugger that the soft robot will not be damaged by being hugged. Huggers will be more likely to hug these robots and deliver hugs that are tighter.

I then dived further into one of these guiding principles, using three inflatables which can be seen in Figure 1.4 to investigate the huggability of inflatables with spikes under controlled experimental conditions (N=28). I was able to confirm that inflatables bearing protrusions are less huggable than those without. I also discovered that a negativity bias[7] appears where the negative components of a design dominate over the positive components resulting in a perception of huggability that is significantly lower than the reported huggability after they have hugged the soft robots.

Finally, to push my objective further I embedded my knowledge into a functional prototype which has three key advantages over the current state-of-the-art large-scale actuated inflatable robots. Firstly, a very low cost. The total cost for all parts needed to recreate the prototype is under £50. Secondly, the system does not require an air compressor or any form of high-pressure fluid. Finally, a greater array of shapes are possible compared to recently developed systems like Niiyama et al. [8].

In summary, this project is a contribution to “understanding users” which is a typical track in HCI which revolves around investigating human behaviour and technologies through empirical studies. My contributions are:

- A design space. This contribution goes beyond a traditional background chapter by proposing a framework to characterize the area of soft robots and highlights gaps in the field.
- A bodystorming study (N=6) showing inflatables are a naturally good choice for investigating hugging interactions.
- A focus group study (N=12) showing that there are underlying rules governing what shapes are huggable, which may differ from that which is "appealing" or "cute".
- A controlled user experiment (N=28) confirming the analysis that resulted from the focus group study that inflatables with protrusions are significantly less huggable than those without.

Figure 1.3: Inflatable with spikes (left), Inflatable with tubes (middle) and Inflatable with no protrusions (right)

Figure 1.4: Prototype pneumatic joint in 180-degree position (left) and 90-degree position (right)

- The design and implementation of a working prototype that instantiates some of the findings revealed in my studies. Note this part goes beyond the typical understanding user contribution: I wanted to produce a working prototype to demonstrate some of the potential experiences such robot could create.

Chapter 2

A Design Space

2.1 Introduction

In this chapter, I will present a design space of the field of soft robotics and use this to provide the reader with both a high-level and an introductory-level overview of the field. It also outlines the gap in research where my work is situated in.

Soft robotics is a sub-field within robotics concerned with using materials that are flexible and compliant. Therapeutic companion robots and silicon finger joints are just two of the many applications soft robotics has across a range of industries and research domains. As a result much of the subject literature is disparate and unrelated, making it hard to follow threads through to a conclusion. A majority of the summary works focus on a specific research discipline and therefore do not describe the variety that is present in the field of soft robotics. The section below details a design space created in order to present a high-level overview of the field as it relates to contexts explored later in this work.

Figure 2.1: Design space - Main

2.2 Design Space Overview

Figure 2.1 shows the design space I created to represent the field of soft robots. Individual robots and collections of similar robots are positioned along the three axes of Performance, Scale, and Trust. The design space helps to visualise and aid understanding of some of the relationships that occur between different soft robots as a result of them having similar features like material and application.

The definitions of each of the axes are:

- **Performance** - The ability of a soft robot to move with precision and accuracy, while completing a specific task.
- **Scalability** - The ability of the underlying technology, material, and design to work at, and be cost-effective, as the scale moves to human scale or above.
- **Trust** - The ability of the soft robot to engender trust and safety.

The majority of robots shown on this chart are designed to maximise one of the three axes. This results in them clustering toward the corners of the chart. A smaller category fills spaces between two of the axes. For example, pneumatically actuated humanoid fabric robots have two goals, to mimic humans, which constrains the scale, and to interact with people, which requires them to be trusted. These robots sit between Scalability and Trust on the chart. There is a central cluster of robots that satisfy the characteristics of all three axes. However, all of the robots in this central part of the chart might not classify as soft robots under a stricter definition of soft robots as they are all made from a hybrid of both hard and soft materials. I investigated over 50 different soft robots in the creation of this chart, all failed to both meet a strict definition of a soft robot as well as join the cluster in the centre of the chart.

In the following sections of this chapter, I will examine the design space by looking at it through the lens of Materials, Applications, and Research fields (see Figures 2.2, 2.3 and 2.4). These were created by colour-coding the original design space (Figure 2.1), and then drawing boundary lines around the various patterns that emerged. Looking through these lenses we can identify why different soft robots relate to each other and understand the underlying constraints that are present in the field.

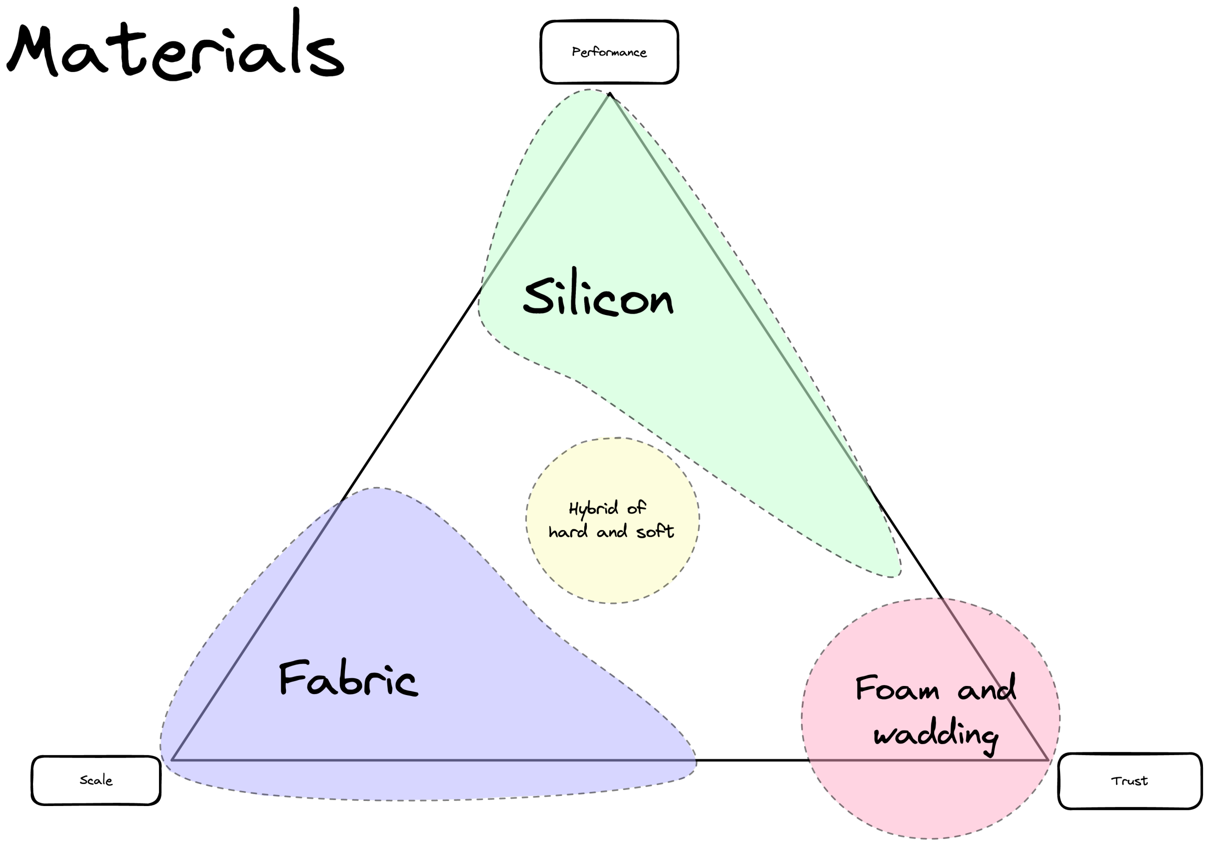

Figure 2.2: Design space - Material

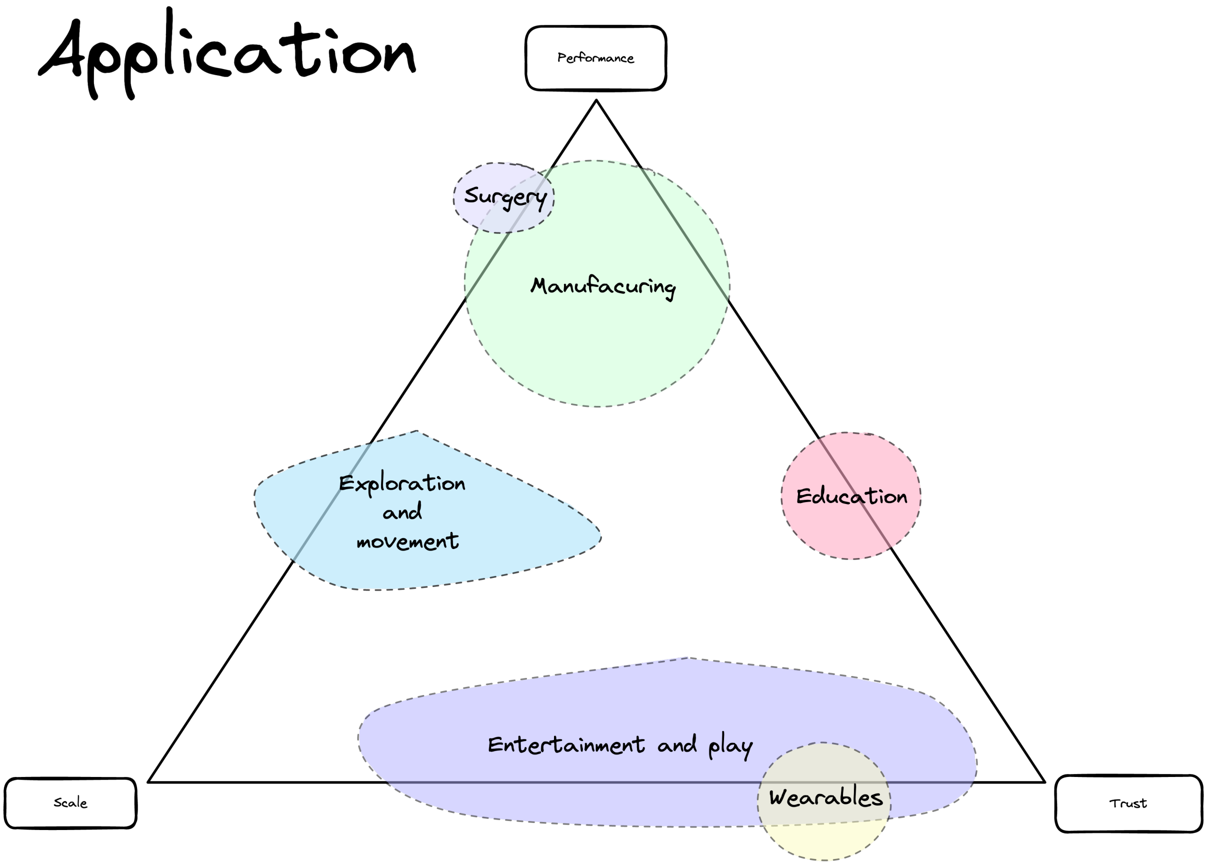

Figure 2.3: Design space - Application

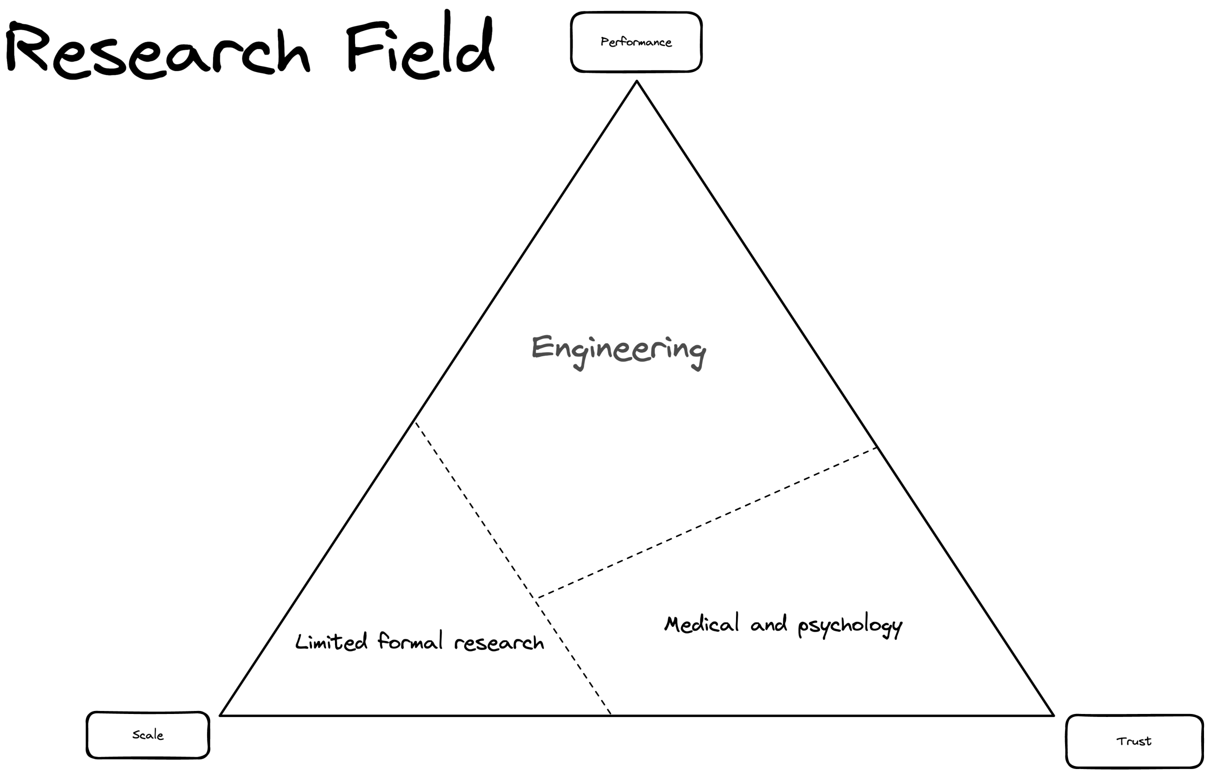

Figure 2.4: Design space - Research Field

2.3 Materials

2.3.1 Silicon

Silicon robots tend towards the high performance area of the design space. They are typically made by layering materials with different stiffness. A fluid, like air or water, is pumped into internal chambers in the robot to cause motion in ways dictated by its shape and the stiffness of the materials used. Various manufacturing techniques are used, including moulding, casting, spin coating, and 3D printing [9]. The most common silicon robots are gripper robots. These have the advantage over traditional rigid robots of being able to grasp objects of different shapes without the requirements of high precision adjustments [10].

The silicon robots that have a greater focus on creating trust are breathing robots [11]. Asadi et al.[12] were able to demonstrate that these robots can induce changes in human breathing patterns. The authors asked the participants to place one hand on a soft robot while playing a game on an Apple iPad. The authors then matched the breathing rate of the participant and began to slow it using the breathing rate of the robot. They found that participants breathed more deeply and more regularly when influenced by the robot, and had a higher level of arousal and positive emotional valence. However, the participants did not match the breathing rate of the robot.

2.3.2 Foam and Wadding

These silicon breathing robots described above, are closely linked to the breathing pillow demonstrated by [13] which was able to “ease state anxiety in the student population when anticipating a test”. These robots were manufactured by placing a pneumatic chamber inside of a padded cushion.

This method of manufacture where the mechanical component is placed inside a foam or wadding skin is common for soft robots with a focus on high trust. The robot PARO [14] is a good example of this. Designed to look like a baby harp seal, PARO was developed to support pet therapy for older adults with dementia. PARO uses internal actuators to move its tail and flippers as well as blink its eyes. PARO is one of many robots designed to help support healthcare and pet therapy. This subclass of soft robots all tend towards using this type of manufacturing process and materials.

For example, the Haptic Creature [15], uses a moving rib cage and stiffing ears to simulate breathing. The robot is covered by a furry coat to create a nondescript mammalian creature. The researchers found that both self-reported relaxation scores and biometrics (respiratory rate, hate rate, and changes in sweat gland activity) indicate relaxation increased when stroking the Haptic Creature.

Figure 2.5: Pet robots(from left to right) Probo, The Huggable, DragonBot, Leonard and eMuu

Figure 2.5 includes a collection of zoomorphic pet robots, all of which use the manufacturing style of internal hard actuators similar to both PARO and the Haptic Creature. [16, 17, 18, 19, 20]

Shuguang et al [6] apply a different approach to actuation to develop a metre-scale and modular robot system. The authors use a vacuum pump to contract a muscle made from foam covered in a nylon skin. Each module is able to move in eight directions and can be attached together using Velcro strips.

Tendons are a method of actuation used across a variety of different types of soft robots. These operate like muscles in the human body contracting and relaxing to produce movement. Kastor et al. [21] uses a single tendon anchored across the foam block and is able to crawl, turn and flip over. Niiyama et al.[8]

demonstrates how tendons can be used in low-pressure fabric structures and Almubarak et al. [22] uses a shape memory alloy embedded inside a silicon-like material to create a jellyfish-like robot.

2.3.3 Hybrid

Just as the boundary between what classifies a material as rigid is a grey area, the boundary between soft and hard robots is not clear or easily distinguishable. For the purpose of this design space, the category of 'hybrid of hard and soft material' is used to describe robots that externally present a mixture of both hard and soft materials. Hybrid material robots seek to utilise the advantages of soft robotics while using more rigid materials to mitigate the downsides.

The untethered isoperimetric soft robot[23] created by Usevitch et al. is a perfect example of this. It contains hard components that are used to move but uses inflatable tubing to provide the robot's structure. By rolling out material, the robot is able to change the shape of each component triangle while maintaining a constant total edge length. This allows the robot to shift its centre of gravity and roll/walk along. The combination of both types of material allows this robot to be 'robust and safe'.

Social robots often utilise a combination of both hard and soft materials. Social scientist Kate Darling provides this definition of a social robot "A social robot is a physically embodied, autonomous agent that communicates and interacts with humans on an emotional level." [24] Social robots often take advantage of people's preference towards robots that have soft outer skins [25]. This is why social robots like Ommie [26] are built predominantly out of hard materials, but have silicon skin covering the plastic plates beneath. Ommie is used to reduce anxiety through deep breathing, in a way akin to the previously mentioned silicon breathing robots.

Disney Research has also used this property of human behaviour in a soft robot inspired by the character BayMax from the film Big Hero 6 [27]. This soft robot[28] concept uses traditional hard motors covered by 3D-printed skin.

2.3.4 Fabric

Fabric inflatables dominate the high-scale area of the design space. These often operate akin to a bouncy castle. Air is pumped in at a sufficiently high enough rate such that the air escaping through the material itself or through seams between panelling does not impact the structural integrity of the robot.

The company Otherlab has produced a series of these robotic inflatables. Ant-Roach is a 15ft long six-legged inflatable capable of walking while carrying multiple people. Ant-Roach moves using compressed air that fills pressure chambers that contract when inflated[4]. They have also created several large-scale pneumatic arms and a walking elephant[29, 5].

Yeong et al.[30] present a simpler approach to fabric inflatable. They present an easy-to-assemble pneumatic joint which is bidirectional and reversible. Yeong et al. use this to build a locomotive quadrupled robot.

2.4 Applications

2.4.1 Wearable

Researchers in wearable technology focus on developing devices that are attached to the body directly or embedded into clothing.[31] For these devices to be comfortable, they necessitate using soft interactive components or utilising soft robotic accusation methods.

Many wearables incorporate touch-sensing conductive threads integrated into the fabric of clothing. These sensors typically use either resistive touch measurement or capacitive touch measurement systems.

Capacitive touch sensors measure the change in the electrical signal caused by a touch. Teyssier et al. [32] uses a grid location system where the detection of touch on two wires, one running horizontally, and the other vertically, is used to calculate a location. Takamatsu et al. [33] use this methodology and a weaving process to integrate the wires to create a metre-scale touch-sensing fabric flooring. Vallet et al. [**cap'knit**] demonstrate a touch sensor knitted into a jacket that can adjust music audio on the go. This system uses a single-wire system in a serpentine pattern and measures the position of touch along the wire to calculate location. The authors also display a knitted keyboard and upholstered touchpad TV control system integrated into a sofa.

Resistive touch sensors are constructed by layering two electrodes on either side of the insulator layer[34]. Compressing these causes a change in resistance which can be measured. Yao et al. [35] created Second Skin, a resistive touch sensing that does not restrict movement, to support physical performers like aerialists and sonic artists.

Wearable Choreographer[36] is an example of a wearable technology utilising soft robotic actuators to prompt the movements of a dancer. Wearable Choreographer uses McKibben muscles, a pneumatic artificial muscle that when inflated causes contraction. These muscles are combined with fabric joints formed using the mechanical restriction caused by the combination of an inextensible woven textile and a knitted material which only bends in one direction.

2.4.2 Exploration and Movement

Robots are able to explore environments that are considered hazardous for humans and the characteristics of some soft robots make them particularly useful in exploring unfamiliar environments. The deformability of soft robots means that they are able to adapt to uneven surfaces. Hawkes et al. [37] have created can fit through small gaps by rolling out an internal spool containing additional material which, when pressurised, causes it to expand into new areas. This design means soft robots can fit through gaps much smaller than themselves, and move across terrain that is highly adhesive or contains objects that would typically cause punctures.

Soft robotics, whilst in its infancy, has significant potential to be used as part of space exploration and is being explored by organisations like NASA [38, 3]. Future applications may entail inflatable antenna systems, origami-inspired Mars rovers or collecting space debris [39, 40, 41]. On the other end of the exploration spectrum, soft robots have distinct advantages for deep sea exploration including high propulsive efficiency and “unprecedented manoeuvring skills” [42]. Despite this, deep sea exploration using soft robotics is still largely speculative and faces significant challenges to overcome[42].

2.4.3 Education

While not widely used, soft robotics have successfully been incorporated into education across various age groups. Legoons are designed to be a ready-to-play toolkit for children to incorporate into an existing LEGO play kit. This allows children to explore and create new characters in an entirely different medium [43]. At an undergraduate level, the soft robotics tool kit was developed to support engineering students’ education about soft robotics[44]. Soft robotics have been incorporated into curriculums in both computer science[45] and medicine [46] courses.

2.4.4 Manufacturing

Traditional robots are highly effective and popular parts of the modern production line workflow for manufacturing products. However, not all production lines are suitable for hard robotics use, due to the delicate or fine nature of the product. This is where soft robotics has become an effective solution. Fresh produce, protein and baked goods are all foods that must be handled with care. Soft robots now play a role in production lines transporting and packing these goods [47]. Online grocery store Ocado now use soft robots to pack their fruit and vegetables [48].

2.4.5 Surgery

The use of soft robotics in surgery is still in its infancy. They have been used in a number of different procedures including endoscopic surgery, which allows surgeons to operate while the patient is still in an MRI scanner [49], as well as support other forms of robot-assisted minimally invasive surgery with a haptic feedback system [50].

2.5 Research Field

Inflatables provide an opportunity to create robots that can occupy the high scalability area of the design space. While much literature exists on sub-metre scale robots, the creation of human-scale and above soft robots is a newly developing area of current research [6].

Much of the research on large-scale inflatables today is focused on art, architecture, and fashion. The book 'BubbleTecture: Inflatable Architecture and Design' by Sharon Francis lists over 200 inflatables being used across a range of artistic pursuits [51]. A few notable examples are Sacrilege by Jeremy Deller [52] a bouncy castle-like life-size replica of Stonehenge that was created and toured as part of the 2012 Olympic Games. Snowballing doorway by Alex Schweder is an interactive piece that moves from being open through a tight gap to inaccessible and blocked by a descending mirrored inflatable [53]. Inflatables have been used in massive architectural projects like the Eden project in Cornwall[54] or incorporated into fashion. Balenciaga released an inflatable jacket that closely resembles a life vest as part of their Spring 2017 collection[55]. That year Chromat displayed their "Inflatable Dress" which was created to represent "the idea of staying afloat in a tumultuous political environment" [56].

2.6 About the Chart Itself

A design space is a tool for representing the n-dimensional space for a particular collection of ideas, design points, or examples around a given topic. Ramírez et al. [57] demonstrates an example of this, presenting a design space of social robots with a design metaphor on the y-axis and shape level of abstraction on the x-axis. However, design spaces are not constrained to a cartesian coordinates system, Woodbury et al. [58] describes a network graph-based design space system.

My design space began as an affinity diagram of a collection of various soft robots. Affinity mapping is a technique for analysing qualitative data. In affinity mapping, extracts, sentences, and phrases from the data are transferred onto Post-it notes. Patterns are then looked for and the notes are grouped together. These groups are then named and form themes. Themes can be recombined or formed into "supergroup". During this process of affinity mapping, three major themes appeared Performance, Scale, and Trust. However, it was clear that these were more axis than they were themes.

To display these major three characteristics, I use a chart modelled on the project management triangle. The project management triangle as seen in Figure [**fig:projecttri**], states that the quality (or performance) of the project is constrained by the scope, deadlines, and cost of the project. Any particular point on the triangle represents a project's balance between these three factors.

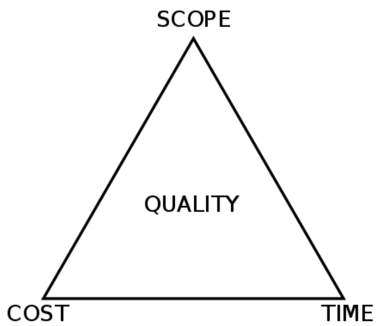

Figure 2.6: The project management triangle [59]

2.7 Discussion

2.7.1 Material

The first lens I identified and looked through was that of the material used to build the robot. The material chosen places physical constraints on the robots that limit them along the axis of Performance, Scale, and Trust. For example, silicon is often used to build soft robots for tasks like gripping and picking up objects. The density of silicon lends itself well to this task. However, when these robots are scaled up, the rigidity of these robots also needs to be increased in order to resist deformation due to gravity. The result of this is that greater energy must be applied in order to deform the robot. Consistently deforming with large amounts of energy becomes infeasible at larger scales [60]. These material constraints are closely linked to soft robots' potential applications. For example, it is not important that a robot gripper is able to scale up if the task it is needed for is picking apples. However, this does mean we are unlikely to see soft robots moving cars about in scrapyards in the future.

2.7.2 Application

The next lens I examined was the application lens. It is important to look through this because it allows us to understand the context in which soft robots are being used. For example, lots of soft robots have been developed to support animal-assisted therapy. The context for this may be similar to using soft robots to support the education of children but is vastly different from that of those used to explore earthquake-damaged buildings. While all of these may be classified as soft robots, research in one area may have varying impacts in other areas. Examining the application lens allows us to see this kind of insight.

2.7.3 Research Field

The final lens that I present below is that of the Research Field. This is the simplest of the charts and considers what type of researchers are writing about these types of soft robots. The important feature of this chart (Figure 2.4) is that very little formal scientific research is published about soft robots that are larger than human scale. Inflatables are widely used in art, architecture, and furniture. By comparison, the exploration of large-scale soft robotics is very minimal. The existing research as described in sections **??**, all explore the area from a strictly robot-centric perspective. Their research focuses on the technical development of these robots. In my work, I seek to focus on the interactions that can take place with these robots. A better understanding of how we can interact with large-scale soft robots may allow us to unlock the constraints needed to design soft robots to meet the requirement to sit in the centre of this design space. Figure 2.7 indicates where this work will fit in the design space that I have created.

2.7.4 Limitations

The nature of a design space means there are several limitations that must be understood to avoid incorrect assumptions being made. Firstly, the axes are all subjective in nature. The intention of the design space is not to classify with measurable precision, but to understand the relationships that appear within the space. Therefore rough placements were made on the chart and positions were iteratively adjusted until no new movement occurred. Secondly, both individual robots and collections of similar robots, e.g., silicon gripper robots have been placed on the chart together. This means that the density on the chart does not necessarily imply the popularity of the specific area.

Finally, while creating Figures 2.2, 2.3, and 2.4, the intention was to understand the general pattern within the charts. For example, there are different types of foam and wadding used to create soft robots and they all largely behave similarly. However, there are differences in these materials that may have more subtle effects. This is not shown on the chart. Additionally, the population within a grouping may not necessarily be completely homogeneous. Outliers are present and there are exceptions to the groupings.

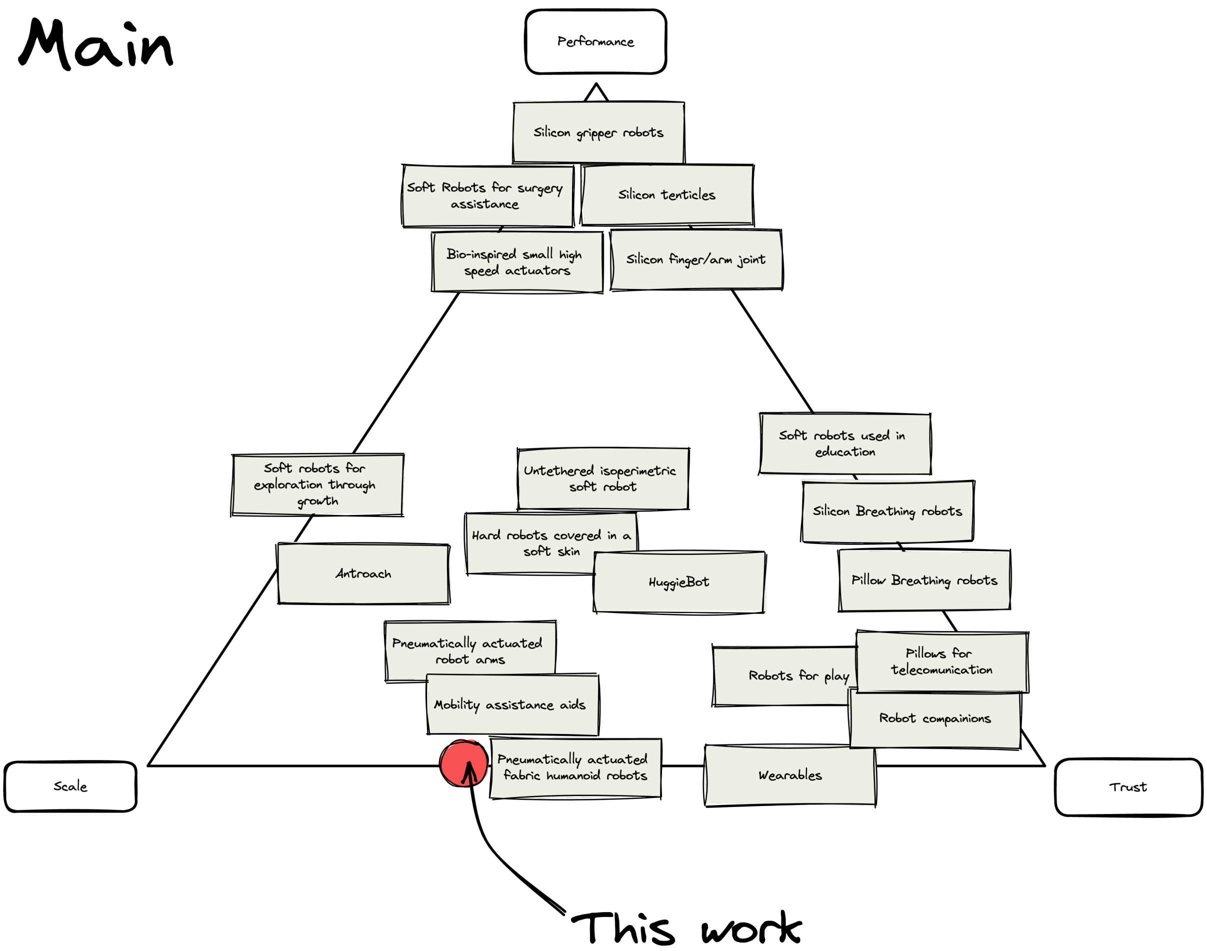

Figure 2.7: Design space with the location of this work

Chapter 3

Understanding Whole-body Interactions Through Bodystorming

3.1 Introduction

In this chapter, I present a summary and results of a bodystorming exercise completed to explore whole-body interactions with inflatables. The objective of this exercise was in two parts: firstly, to engage in an immersive experience focused on whole-body interactions with inflatables, secondly to document and analyse this experience and the insights that were generated through it.

3.2 Methodology

3.2.1 Summary

Six expert researchers engaged in a bodystorming experience at Bristol NinjaWarrior. After the exercise, the researchers were asked to complete a feedback form. Affinity mapping was then used to analyse the generated data and identify key themes.

3.2.2 Rationale Behind the Choice of Study Type

Bodystorming is a semi-structured or unstructured activity where researchers engage in a physical activity to generate ideas and insight [61].

It is not a prescriptive set of stages, but can be more generally described with a set of characteristics:

- Bodystorming focuses on play and playfulness.
- Bodystorming is activity and artefact centric.
- Participants collaborate, interact and discuss.

Bodystorming is used widely across human-centred design research [61]. There are a number of reasons why bodystorming was a good choice for this study. Firstly, bodystorming allows researchers to gain a first-hand perspective of what they are designing and provides a more accurate understanding of contextual factors [62]. Secondly, being outside of a lab environment allows researchers to understand potential threats and opportunities in a context that may be more similar to where a robot is actually used[63]. Finally, researching at NinjaWarrior allowed us to make use of the existing inflatable infrastructure rather than going through the costly and time-consuming exercise of constructing our own prototype.

3.2.3 Participants

Six researchers to part in the exercise. All have expertise in the field of large-scale soft robots. They spent an hour during the study and did not receive any compensation for their time.

3.2.4 Procedure

NinjaWarrior Bristol is an adventure park inspired by the ITV show "NinjaWarrior Uk" [64]. NinjaWarrior features a series of obstacle courses as well as a "huge inflatable". The "huge inflatable" contained a series of differently shaped inflatables arranged in a U-shape and is supported by 14 blowers. Figure 3.1 contains a series of photos taken during the experience to aid in further understanding of the context of the experiment.

Figure 3.1: Three photos from a bodystorming exercise at NinjaWarrior Bristol

The session was run as an unstructured bodystorming exercise although three tasks were prepared in case the session needed additional support to generate insights (Appendix X). The participants were simply asked to explore the types of interactions they could have with the inflatables.

The researchers were asked to fill out a feedback form after the experience. This form was completed by five out of the six researchers. This form contained the four questions shown in Table 3.1.

Table 3.1: Questions from post bodystorming feedback form

Question
Please write down any general comments about the experience here
Please write down any specific hugging experience comments here
Were there any inflatable shapes that you found particularly interesting? If yes, explain what shapes, why and what actions you did with them
Were there any inflatable shapes that you found particularly NOT interesting? If yes, explain what shapes, why and what actions you did with them

The data was then analysed using affinity mapping which is a typical method used in HCI to analyse qualitative data. See Section 2.6 for a description of affinity mapping.

3.3 Results

This section will discuss the key themes that resulted from the data analysis. Figure 3.2 shows a collection of sketches of the different inflatables discussed in this section. The key themes are:

- **Compulsion to hug** - There seemed to be a compulsion toward certain actions. Some shapes were "calling to be hugged", in particular, the cylinder with "two little arms" sticking out. One participant described these as "intended actions" that were defined by the shape of the inflatable. However, one participant said that they felt disappointed that they could not lean into the hugs with the inflatable with "two little arms" because of the lack of resistance.
- **Comfortable spaces** - Four of the five respondents mentioned that they found that certain spaces and shapes were particularly "comfortable". This experience was highlighted by all respondents.

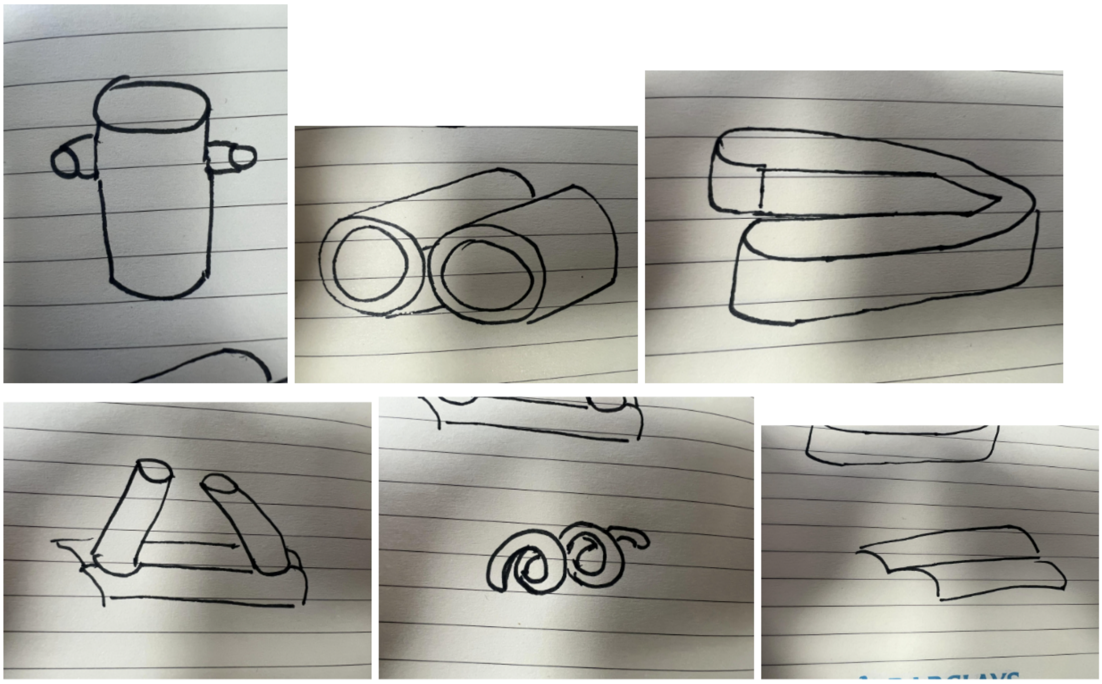

Figure 3.2: Six sketches of inflatables seen at NinjaWarrior: From left to right, Cylinder with “little arms”, Tube attached horizontally to the floor, V-shape, “inclined cylinders”, Spiral and floor recess.

Some of the shapes that caused this reaction were the insides of a tube attached horizontally to the floor with an internal diameter of approximately 1m, inside the three approximately 50 cm diameter horizontal tubes, the v-shape section (also described as boat-like), and the floor recesses.

- **Comparisons** - The descriptions used to reference the different inflatables often used comparisons to animals or objects. Despite being very simple shapes, the forms were enough for people to find a comparison to other objects they could have interactions with. Some examples of these were horses, boats, octopi, worms, and rocking chairs. All respondents made at least one comparison in their answers.
- **Movement** - All participants described enjoying the movement incurred by others or where their own movement caused the structure to actuate. This was described by all respondents, either through ”inclined cylinders” when you would bounce your feet at their bottom or two tubes that the participants shook back and forth with other participants inside.
- **Pressure** - When people complained (four participants), they discussed the amount of pressure being a key component. There was some difference in opinion, particularly around whether strong pressure was comforting or trapping:
  - **Lack of pressure** - When people complained (three participants) about the lack of pressure, they seemed to agree more. One participant described this as “alarming” because the structure couldn’t bear weight and therefore it was difficult to clamber out. Four out of five respondents complained about the spiral inflatable being negative in relation to this. One respondent described the spiral as being “too low pressure to provide any real format for play”.
  - **Too much pressure** - There were clearly some tasks where high pressure was useful, e.g., flopping over or standing on, but too much pressure was sometimes negative. This pressure was described as “trapping” or too hard when jumped on.
- **Environment** - Three of the five respondents commented on the environment that the investigation took place in. With children that “would just go around super fast” participants describe having to be aware of those around them “making sure that I didn’t accidentally go bouncing into others”. Participants also commented that they didn’t enjoy it when their vision was obscured as a result of this. There was some disagreement on the safety of the space. One person commented that you

can “hardly hurt yourself”, but another reported getting a friction burn from a slide and bouncing out of the safety enclosure.

3.4 Discussion

As explored in Chapter 2, large-scale soft robots is an under-researched area, particularly from a user-centric perspective. When undertaking research in this field I found one of the disadvantages of this is that there is little foundation to work from. It does mean that there are many exciting research avenues to explore. Part of the motivation for completing this bodystorming exercise was to generate interesting ideas that could be explored in this body of work. As must be evident from the title of this work, I settled on exploring hugging interactions with this type of soft robot. However, below are listed several other interesting areas that could be explored:

- **Game playing with soft robots -** Understanding the ludic activities of play and gaming is an important sub-field within the study of human-computer interaction (HCI). However, as indicated by the results of my design space in Chapter 2, a body of work considering how people play games with large-scale inflatable soft robots has yet to be completed. Exploring this would help support our understanding of high trust and high-scale robot interactions.
- **Naturalness of soft robots -** Jørgensen et al. [65] challenged the widely stated assumption that ‘soft robots are more “natural” than hard robots’. The authors used three robots, one made with traditional hard plastic and the other two made from silicon. Future work could explore how these results generalise to different materials like inflatable soft robots.
- **Touch sensing at scale -** A dialogue is an important feature of human-robot interactions. To achieve this sensors are required to allow a robot to perceive the world. The current generation of large-scale soft robots has not included a mechanism to interact through user touch.
- **Healthcare -** Soft robots have already been used in healthcare settings as explored in Section 2.3.2. Further works could explore the effectiveness of large inflatable soft robots as companion robots.

There were two key reasons that led me to decide to explore hugging interactions after this excises. Firstly, the ”compulsion to hug” theme identified in qualitative analysis indicates that there is a natural affordance that appears easily in inflatables that drive people to hug them. The term ”Affordance” was appropriated and popularised from the ecological works of James Gibson [66] by Donald Norman. Norman presented ”perceived affordance” as the action potentials perceived by an actor for a particular artefact in his book ”The Theory of Everyday Things” [67]. The natural affordance for inflatables to be hugged makes them a good potential technology to facilitate hugging soft robots. Secondly, hugging is an inherent nuanced social interaction, often defining the beginning or end of an interaction. By better understanding how we can hug soft robots we further understand human-robot interaction as a whole.

While the overall exercise was useful to generate ideas and qualativie research, there were two factors that negatively effected the experience. Firstly, the environment of NinjaWarrior does not necessarily align with the context that large-scale soft robots would be used. Secondly, as explored in the *Environment* theme the public nature of NinjaWarrior further exacerbated the feeling of self-consciousness that is a trait of bodystorming activities.

3.5 Conclusion

Bodystorming allowed us as researchers to interact with a wide array of different shapes of inflatables in a way that had very little cost, both in terms of time and money. The qualitative analysis of the data led to the six key themes of *Compulsion to hug* , *Comfortable spaces*, *Comparisons* , *Movement*, *Pressure* and *Environment*. The qualitative research generated from this exercise served as a foundation to understand how we interact with inflatables as well as leading to four additional areas for exploration in addition to the content explored further in this work.

Chapter 4

Toward Hugging Robots Through Focus Groups

4.1 Introduction

In this chapter, I will discuss the current state of research around hugging and hugging robots. To further explore this topic I conducted, a series of four focus groups each with three participants that explored how people hug, with a focus on hugging objects that are not typically hugged.

4.2 Background

4.2.1 The Science of Hugging

On the whole, hugs have been shown to feel good and have a large range of physical and psychological benefits [68]. In this section, I will explore what those benefits are, the role of deep touch pressure therapy, and the research around what makes a good human-to-human hug.

Hugging has been shown to increase our oxytocin levels [69] and decrease our cortisol level [70]. Cortisol is a hormone produced by the adrenal glands in the kidney. It functions as part of the body's response to stress or danger as part of the 'fight or flight' reaction [71]. Oxytocin, often called the 'love hormone', is produced by the hypothalamus in the brain and its primary functions are to facilitate childbirth and lactation[72]. Low oxytocin serum levels have been shown to be associated with symptoms of depression [73].

Hugs have also been shown to both reduce stress [74] and negative emotion as a result of interpersonal conflict [75]. The reduction in stress caused specifically by hugging someone is able to reduce the chances of getting sick from upper respiratory infections and illnesses[76].

Within romantic relationships, interpersonal touch interactions like hugs have been linked to increased perceived partner support, relationship satisfaction, intimacy, and easier conflict resolution [77, 78, 79, 80].

The benefits of hugs are not just limited to human-to-human hugs. Humans can see positive psychological effects for human-animal interactions [81] as well as benefits just from being squeezed. Deep touch pressure therapy is largely attributed to stemming from the works of Dr. Temple Grandin [82]. The 'squeeze machine' was created by Dr. Grandin, who is autistic, to help her 'overcome problems of hypersensitivity to touch'[83]. The 'squeeze machine' is constructed from two sideboards hinged to form a V shape and is able to deliver constant pressure evenly throughout the body. The 'squeeze machine' was found to be relaxing for college-aged students and five minutes of use delivered a calming effect on children with autistic disorder, attention-deficit hyperactivity disorder, or learning disabilities. More modern repeat studies [84, 85] have been performed and have reiterated the original results. Ti et al [84] were also able to demonstrate "that stimulating skin pressure sensory systems seems to benefit most of a population of young people with autism and severe intellectual disability on whom it was trialled."

Scientific research has also been carried out to understand what makes a good hug. Researchers found that hugs lasting 5 or 10 seconds were preferred compared to those lasting 1 second. They also found that for all duration the hugging style had little to no impact on the quality of the hug, but men were more likely to use a cross-arm style(where one arm goes over the other persons shoulder and the other goes under) compared to women[86].

4.2.2 Hugging Robots

In this section, I will discuss three specific robots created for the purpose of hugging. I will outline the lessons presented by the authors that we can take forward to creating inflatable soft-hugging robots.

Trovato et al. [87] used an ARMAR-IIIb humanoid robot with two variables being explored. Firstly, the researchers used clothes to cover metallic parts and wiring varying the appearance of the robots and secondly, they used a hand to toggle a noise generator on and off. The researcher found that the addition of clothes improved the appearance of the robot resulting in positive effects on anthropomorphism, familiarity, and likeability. However, the researcher also commented that "improving robot appearance is not enough in some cases to relieve the anxiety of the act of hugging a robot."

The HuggieBot was created as the first human-size hugging robot with visual and haptic perception across a series of papers [88, 89, 90]. The authors present 11 tenets for good hugging robots, the latter five of which focus on intra-hug gestures such as patting, rubbing, and squeezing. The list in full is:

"

1. Be warm.
2. Be soft.
3. Be a similar size to a human.
4. When a hugging robot is the one initiating the interaction, it should autonomously invite the user for a hug when it detects someone in its personal space. A hugging robot should wait for the user to begin walking toward it before closing its arms to ensure a consensual and synchronous hugging experience.
5. Autonomously adapt its embrace to the size and position of the user's body, rather than hug in a constant manner.
6. Reliably detect and react to a user's desire to be released from a hug regardless of their arm positions.
7. A good hugging robot should perceive the user's height and adapt its arm positions accordingly to comfortably fit around the user at appropriate body locations.
8. It is advantageous for a hugging robot to accurately detect and classify gestures applied to its torso in real-time, regardless of the user's hand placement.
9. Users like a robot that responds quickly to their intra-hug gestures.
10. To avoid appearing too robotic and to help conceal inevitable errors in gesture perception, a hugging robot should not attempt perfect reciprocation of intra-hug gestures. Rather, the robot should adopt a gesture response paradigm that blends user preferences with slight variety and spontaneity.
11. To evoke users' feelings that the robot is alive and caring, the robot should occasionally provide unprompted, proactive effective social touch to the user through intra-hug gestures.

"

'The Hug' is a telecommunicating pillow-like robot that is designed to mimic the form factor of a small child hugging a parent. The authors suggest four design suggestions for supporting intimate communication based on the work completed to develop 'The Hug'. These are:

"

1. Design physical shapes to reference a human gesture associated with a specific form of intimate communication.
2. Design physical interactions and emotive expressions to reference the qualities and actions of a specific form of intimate communication.
3. Design informative expressions and basic operations to reference existing analogous technologies. 'The Hug' uses the analogy of a telephone to decrease barriers to adoption.
4. Design the system to privilege intimate communication over information management.

"

4.3 Methodology

4.3.1 Summary

The focus groups ran as a group semi-structured interviews and were broken down into two tasks:

- **The discussion task -** participants were asked to discuss how they would approach hugging various different objects. The objects discussed moved from more typical hugging objects like people and pets to more abstract objects like shapes and concepts.
- **The design task -** participants were given a brief and asked to design a hugging robot as a group.

4.3.2 The Discussion Task

This task began with the establishment of a shared vocabulary. This was made of nine hugging types, with an accompanying description and demonstrative image. These types were selected from [91] and were:

- **A-frame hug -** a type of hug where arms are wrapped around the shoulder, but the bodies are not pressed together. This positioning forms an A-frame-like shape that the name stems from.
- **The lift and spin -** the hugging type is characterised by one participant lifting the other and rotating so that they spin together.
- **The handshake hug -** this type of hug is formed by an initial handshake and then the other arm is wrapped around the shoulder. The handshake is maintained in between the bodies of the two participants.
- **A cuddle -** in this type of hug both bodies are pressed together with arms wrapped around each other.
- **The run and jump -** this type of hug occurs when one participant remains stationary and the other runs toward and jumps into the other's arms.
- **The bear hug -** this type of hug is characterised by a tight squeeze from one or bother of the parties.
- **Carried across the threshold -** this type of hug occurs where one participant lifts the other with both arms placed underneath the liftee.
- **Arm hug -** the focus of this hug is specifically on one participant's arm. One participant may wrap their arms or body around just one of the arms of the other.
- **Group hug -** this type of hug is any hug that involves more than two participants.

The participants of the focus group were shown the different types of hugs and were allowed to ask clarifying questions. Participants were also asked to add to the vocabulary with any hugging types they felt were missing and it was made clear that this could be added to at any point in the interview.

The participants were then shown a series of images and were asked how they would approach hugging the different objects shown. The images depicted a stranger, a cat, a dog, a teddy bear, a modern building, a log cabin, a brutalist building, an old oak tree, a sampling, a circle, a triangle, a square, the word gravity, and the word time. This is also the order that these were shown. The images are shown in Appendix X.

I chose this set of objects because I wanted to include a group of objects that people might be very familiar with hugging and objects that they may never have thought about hugging at all. I wanted to understand how someone might approach hugging something that was completely novel to them. I also wanted to include a range of shapes, materials, and scales. I decided to include both gravity and time as the concepts that I focused on as I wanted to include one concept that applies a force onto people and one that does not.

4.3.3 The Design Task

Participants were given PlayDough and the following design brief:

"You are a group of NASA engineers, you have been tasked with designing an inflatable soft robot to make first contact with an Aliens. You do not know anything about the aliens, other than the fact that they communicate through hugging."

Participants were asked to explain their designs as they created them. Once they had finished their design they were asked to reflect on the design. This included questions like: "What do you like about your design?", "How would you make your design more huggable?" and "How would you make your design less huggable?"

4.3.4 Pilot Focus Group

I ran a pilot focus group involving just a singular participant in order to trial the experience. All results of this study were excluded from the data for analysis. This trial resulted in a number of changes to the procedure, which were:

- **An introduction of a shared vocabulary -** the participant found that they built up a vocabulary over the course of the trial which resulted in lots of amendments to earlier statements and they thought of new types of hugs that might apply. The shared vocabulary was also introduced to make discussions clearer as all participants would have definitions that they could all refer to.
- **Ordering the objects from least to most abstract -** In the pilot a random order of objects was used to prevent order bias. However, the participant found it very difficult to discuss hugging the more abstract objects without following this chain of abstraction. I decided that this tradeoff was justified on the basis that randomisation would not compensate for ordering bias in such a small sample size anyway.

4.4 Data Analysis

The data was coded using thematic analysis, which is a method for identifying patterns in qualitative data. It is a flexible method of analysis originally developed by Virginia Braun and Victoria Clarke[92]. There are three stages to performing this type of analysis :

- **Familiarisation -** The researcher examines the data potentially by transcribing it or reading through and making notes.
- **Coding -** Phrases or sentences are highlighted in the data and are assigned to labels called codes.
- **Theme generation -** At this stage codes are combined to form more broader themes. These themes are reviewed and appropriate names are given to them.

The process of thematic analysis is iterative so moving back and between stages is common. During this analysis codes were generated inductively, meaning there were no pre-existing codes. Additional labels were used, but only to label confirm which object type or hugging type was being referred to.

4.4.1 Participant

I used small groups of three as these are easier to organise and enabled me to focus attention on each individual and get opinions from all. These participants were students from the University of Bristol and were not paid for the approximately hour-long session.

4.5 Results

Focus groups take a long time both to complete and to analyse. This means that only small sample sizes can generally be used. My study had a total of 12 participants. To protect their anonymity participants are referred to as P followed directly by a number when quoted, e.g., P1. Following this pattern groups are referred to a G followed directly by a number, e.g., G1. Focus groups were run in groups of three until saturation was reached. Saturation is the point at which adding participants does not generate additional insights. Small amounts of new information may be added, but a large proportion of new codes have already been found [93]. A sample size of 12 is not surprising to reach saturation [94] found that 12 is the typical point at which saturation is reached with a specific group.

The key themes that my thematic analysis identified were:

- **Abstraction** - two of the groups (G2 G3) commented during the design task that the more abstract the shape the less prescriptive of how to hug the robot is. As expected the more typical things to hug like people, cats, dogs, and teddy bears were described as more huggable. However, I did not expect to find that the shape of these resulted in a greater number of different distinct types of hugs. With the more abstract objects, participants often described lots of different types of hugs that did not fit into the pre-set hugging types outlined at the start.
- **Consent and trust** - These were very common themes. Participants were very definite about some types of hugs like "from behind" being reserved for people with whom there was a clear understanding of consent. One particularly interesting discussion occurred where P12 described not having an emotional connection to their teddy bear. They said, "It's just there, so I hug it". This participant also said that they would have no issue hugging an unfamiliar teddy bear. Whereas the others in the group considered the teddy bear to be more than just an object and found this to be invasive. P11 commented, "It's a bit gross".
- **"Alive"** - An object being alive was described as being "the most important thing when you're hugging" by P4, but an exact description of what counts as "alive" couldn't easily be found. All groups rated teddy bears as the most huggable, followed by trees, and then buildings. P3 commented that "even though the teddy bear is not technically alive if it's like a childhood toy, you've still got the emotional connection to it. That, kind of, it is comparative to the tree being alive." This may be because of the malleability of the teddy bear. One group (G4) felt that they would want to hug a soft tree. The teddy bear having a head may also be an important component. Another comment (P1) was "I wouldn't feel comfortable hugging something that's headless. To me, I feel like that almost seems like it's not alive." There may also be a component where people feel that trees are not alive because "they're not conscious" (P8) or "it's not interactive" (P10).
- **Optimal for arm span** - Participants frequently commented that there is an optimal diameter for hugging. All participants made comments to this effect. While an exact measurement was not identified as it seemed to vary from person to person and was linked to their own arm span. However, it was clear that the participants felt that they needed to be able to "envelope" the object. One participant (P1) commented that they would need to span "at least over halfway" around the object. The type of hug also impacted the optimal diameter. The diameter of one of the pillars was not "thick enough to do a bear hug" said P2 and therefore an arm hug would be more suitable. Participants (G1) highlighted that for a group hug, this diameter could be the size of a building.
- **Spikes** - This was the strongest theme to appear in the analysis with every group mentioning spikes as being a clear negative that detracted from huggability. It was either the first or second comment on the topic in each group. One participant (P3) made a clear distinction between huggability and cuteness by describing a hedgehog as "very cute, but not at all huggable".
- **Gentleness** - Eight participants said they were less likely to hug something they felt like they would break and were more likely to use less intimate hugging types like a handshake, an arm hug and a side hug and definitely not bear hugging or run and jump.

4.6 Discussions

Based on the results, I am proposing five guiding principles for designing the shape of huggable soft robots. They are:

- **Animism -** Incorporate features that allude to the robot being alive in some way. Good choices for these might be including a head or arms as well as more general features like malleability akin to a human or animal. These features can stem from both Anthropomorphism and Zoomorphism and should indicate that the soft robot is able to interact with a hugger. However, when an inflatable is considered "alive" participants may feel uncomfortable if consent to hug the robot has not been established.
- **Optimal diameter -** The perfect diameter will depend both on the huggers' arm span and the type of hug that is being performed. The hugger should feel that there are clear locations where their body can dock with the robot. While fitting arms completely around the robot is not necessary, the hugger or group of huggers should be able to envelop the robot.
- **Avoid spikes -** Spikes produce a highly negative effect on huggability that may not track with other positive characteristics like cuteness.
- **Non-prescriptive -** Avoid limiting how people can hug the soft robot to specific hugging styles.
- **Robustness -** The shape (or other factors like material or construction) should convince the hugger that the soft robot will not be damaged by being hugged. Huggers will be more likely to hug these robots and deliver hugs that are tighter/firmer.

4.6.1 Limitations and Critical Evaluation

Hugging and affectionate touch differs between cultures. Wood et al.[95] conducted a study of 14,000 adults across 45 different countries. They found that more intimate types of touch such as stroking or kissing were reserved for closer personal relationships and were universal across all countries they surveyed. The amount of affectionate touch varied greatly between contact and non-contact countries [96] only 98% of participants in Spain, Estonia, Italy, Mexico, and Romania report having intimate contact with their partner in the last week whilst only 57% of participants from China report the same.

This difference can also be seen in the different ways cultures greet each other. In Japan, it is common to perform a formal bow whereas a hug and a kiss are often seen in Italy [97]. Differences can also be seen across different genders, ages, and social classes [98, 99, 100]. The implication of this is that it is likely that the results of this analysis will not generalise to populations that have different hugging cultures.

On reflection, one minor experimental design factor I would have changed, if this exercise was to be repeated would be to change the phrasing of the design task brief to specify that the alien the participants were making first contact with had friendly intentions. Some participants decided that the aliens might be unfriendly and therefore the robot needed to be designed to potentially be hostile as well. I feel that this was not conducive to generating the insight that I was interested in.

The medium of a focus group also presents several limitations that affect the internal validity of a study of this kind. Firstly, the implicit biases of the moderator. While I attempted to be as impartial as possible, some of my own biases may well have been present. Avoiding the addition of these biases is particularly difficult in a semi-structured interview setting. Secondly, focus groups have a tendency to be taken over by assertive individuals. I understood this, so encouraged all participants to have a voice as much as possible. This is also partly why I decided to run smaller focus groups. However, this will have some impact on the results. Finally, there is a gap between what participants say in a focus group and what they actually do. This is called the "attitude behaviour gap" and is often observed in environmental research[101]. This can occur for a multitude of different reasons such as societal pressure and is present in data stemming from focus groups.

The result of this is that to provide greater assurance of these guidelines' validity further research is needed to confirm these findings through the application of qualitative empirical evaluation under controlled experimental conditions.

4.7 Conclusion

In this chapter, I have identified five principles to guide the design of huggable inflatable soft robots. These were generated through thematic analysis of the transcripts of four focus groups each with three participants. These principles should be verified empirically to confirm the validity of these findings. In the next chapter, I will explore the validation of the **Avoid spikes** guideline. I decided to investigate this guideline in particular as it was the strongest theme to result from the focus groups.

Chapter 5

Low-fidelity Prototype and Controlled Experiment

5.1 Introduction

In this chapter, I explore in more depth the results from the focus group. I first describe how I designed and build low-fidelity prototypes, before explaining how I used them in a controlled study. The objective of this chapter is to evaluate the avoid spikes guideline generated through qualitative study in the previous chapter using quantitative analysis.

5.2 Apparatus

Figure 5.1: Inflatable with spikes (left), Inflatable with tubes (middle) and Inflatable with no protrusions (right)

I built three inflatables shown in Figure 5.1 to be the test subject of this experiment. All designs were built off a common platform of a cylinder with two additional cylinders that mimic arms. Two of the inflatables have protrusions spaced equidistant from each other in four rows. The total volume of each of the protrusions is consistent for both the tubes and spikes.

All three were designed entirely and sewn by myself. I made the design as simple as possible to firstly make manufacturing easier, secondly to reduce the variability between the designs and finally to draw on the conclusions of my previous work in Chapter 4. The goal of this was to increase the generalisability of the results that I would find. The designs were first mocked up using AutoDesk Maya 2022 as shown in

Figure X. The rationale for including spikes and tubes all the way around the inflatables was to prevent people from deferring to hug the back of the inflatable if they felt that that side was more huggable.

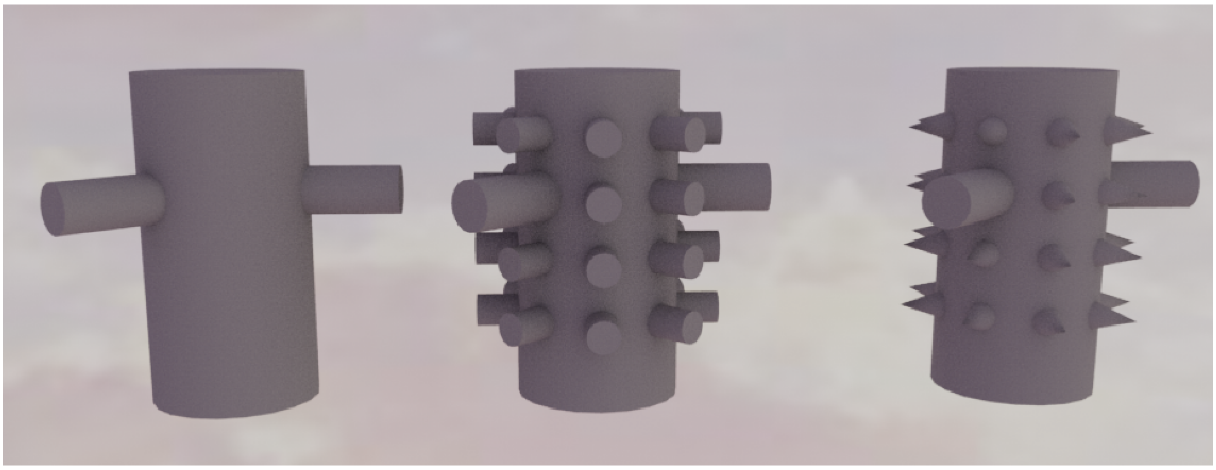

Figure 5.2: Three 3D model mock ups

The inflatables are made from RipStop Polyester. I choose this material due to the low cost and ease of working when compared to alternatives like PVC.

To inflate the inflatables I used a Kärcher WD 6 Wet and Dry Vacuum Cleaner that produces up to an airflow rate of 53 litres per second and a Bosch UniversalGardenTidy 3000 that produces up to an airflow rate of 160 litres per second. I needed to ensure that all three inflatables had a consistent deflation when hugged. However, as all three inflatables have different surface areas and seam lengths, their air loss is different. To compensate for this I found a consistent pressure for all of the inflatables. I achieved this by applying a constant weight on top of each of the inflatables and adjusting the power to the blowers until the amount that each deformed was consistent. I then hugged the inflatables myself to confirm that there was no difference in pressure that I could perceive.

5.3 Hypothesis

Hypothesis 1:

H_0: Inflatables with protrusions will receive Likert scale scores for huggability no different to those without protrusions.

H_1: Inflatables with protrusions will receive Likert scale scores for huggability less than those without protrusions.

Hypothesis 2:

H_0: The inflatables' Likert scale score for huggability ratings will not change after they have been hugged.

H_1: The inflatables' Likert scale score for huggability ratings will increase after they have been hugged.

Hypothesis 3:

H_0: There will be no correlation between the Likert scale score for huggability and appeal.

H_1: There will be a positive correlation between the Likert scale score for huggability and appeal.

Hypothesis 4:

H_0: There will be no correlation between the Likert scale of agreement with the statement "I am a hugger" and the average of the Likert scale score for huggability given by that participant.

H_1: There will be a positive between the Likert scale of agreement with the statement "I am a hugger" and the average of the Likert scale score for huggability given by that participant.

5.4 Methodology

Independent variable: Protrusion on the inflatable (spikes and tubes) or not.
Dependent variable: Change in responses to a Likert scale on huggability.

Table 5.1: Methods for Controlling Extraneous Variables

Extraneous Variable	**Control Method**
Natural Variation	Control statistically
Variation in Design (outside of independent variable)	Ensure manufacturing is accurate. Use a consistent base inflatable.
Variation in Pressure	Adjust airflow to compensate for changes in loss of air.
Ordering Bias	Vary the order that the inflatables are seen.

5.4.1 Procedures

To aid with understanding of the procedure, the investigation setup is shown in figure 5.3.

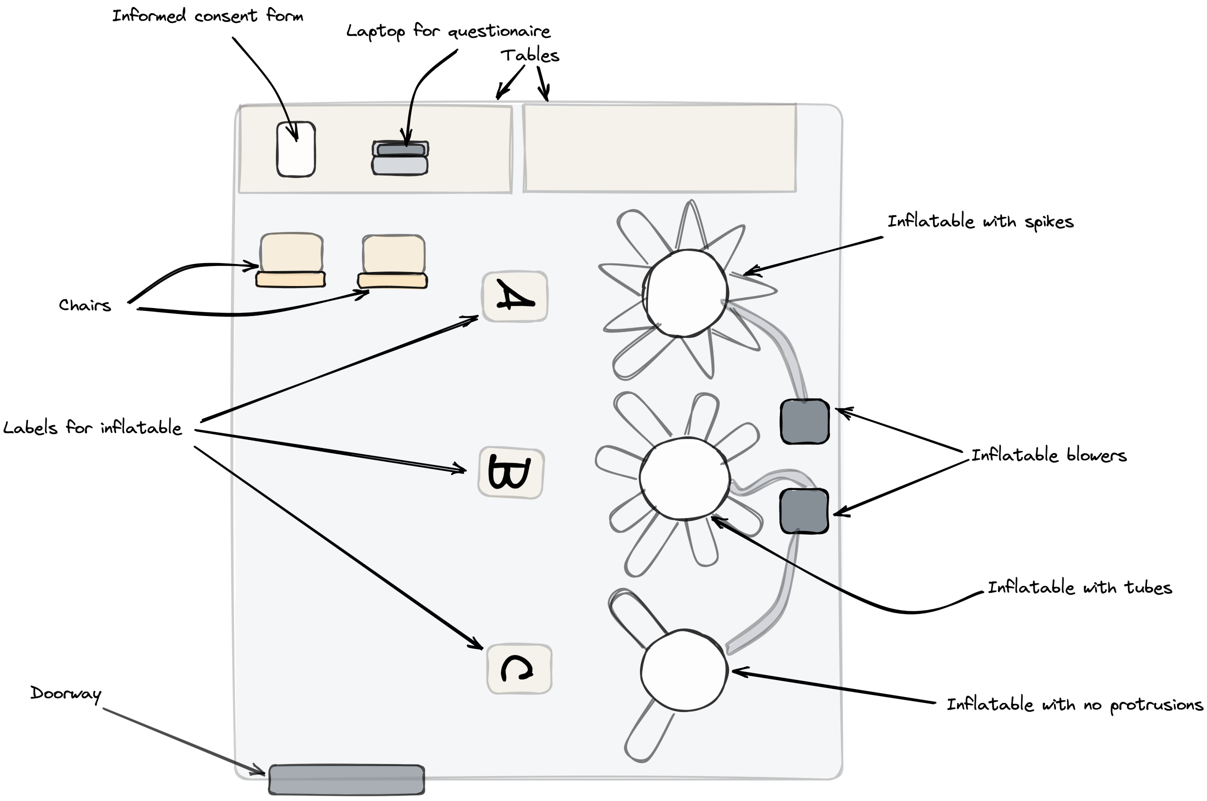

Figure 5.3: Experimental setup

The experimental procedure was as follows:

1. Participants are recruited and asked to fill in a consent and demographic form. The consent form makes clear that the participants do not have to participate or hug anything that they do not want to and can withdraw at any time without giving a reason.
2. Participants are asked not to touch any of the inflatables until they are told to. Any participants that violated this would have their data removed from the study.
3. A random order in which the inflatables are shown is generated.
4. The inflatable is inflated to the correct pressure. Participants are asked to move around and look at the robot and then fill in the corresponding stage on the questionnaire.

Table 5.2: Table showing averages for each of the inflatables

	Appeal Before	Huggablity Before	Appeal After	Huggablity After	Change in Apeal	Change in huggablity
Inflatable with spikes	3.39	2.89	4	3.89	0.61	1
Inflatable with tube	4.11	3.68	4.32	4.68	0.21	1
Inflatable with no protrusions	5.57	6.18	5.79	5.89	0.22	-0.29

Table 5.3: Table showing the results of a Mann-Whitney test that the distributions underlying Inflatables with protrusions are significantly less than those without.

	Appeal Before	Huggablity Before	Appeal After	Huggablity After
P-value	3.86E-06	2.73E-11	1.92E-06	1.13E-05

5. The participants are asked to hug the inflatable and complete the next stage of the questionnaire.
6. Stages 5 and 6 are repeated for all inflatables.
7. The participant is asked to fill out the final questions.

5.4.2 Participants

Participants were approached inside the Bristol University Queens Building. The details of the study were explained to them and they were asked if they wanted to participate. 28 non-random participants were recruited. All of which complete all parts of the study. The average age of the participant was 21.3 with a tight standard deviation of 1.8.

5.5 Results

I performed a Shapiro-Wilks test to assess if this data is normally distributed. Shapiro-Wilks is a test where the null hypothesis is that the data is drawn from a distribution that is not normally distributed. When the p-value is greater than 0.05, I conclude that the data is not normally distributed [102]. While a majority of the variables pass this test, three variables do not. As a result of this, I have used non-parametric tests across all of this analysis.

5.5.1 Hypothesis 1

Inflatables with protrusions will receive Likert scale scores for huggability less than those without protrusions.

Table 5.2 shows the average ratings of each of the inflatables for huggable and appeal from before and after they were hugged. I performed a pairwise Mann-Whitney hypothesis test with a Bonferroni correction and found that on both measurements the inflatables with protrusions were rated lower than those without. The adjusted p-values are shown in Table 5.4.

Mann-Whitney is a statical test that evaluates if the underlying distribution of one population is stochastically different, greater or less than the other, depending on if we perform a one-tailed or two-tailed version. The null hypothesis for a Mann-Whitney test is the populations both have identical distributions[103].

5.5.2 Hypothesis 2

The inflatables' Likert scale score for huggability ratings will increase after they have been hugged.

Table 5.4: Table showing the results of a Mann-Whitney testing if the huggability scores of various inflatables are greater after they are hugged.

	P-value
Inflatable with spikes	0.009
Inflatable with tube	0.011
Inflatable with no protrusions	0.844

Table 5.5: Table showing Spearman's correlation coefficients and corresponding P-values between huggability and appeal.

	Spearmans rank coerlation coeffeient	P-value
Before	0.7125496879	2.93E-14
After	0.6217115734	2.77E-10

For both the inflatable with spikes and tubes, the huggability rating increased, but the inflatable without protrusions did not change. I performed a pairwise Mann-Whitney hypothesis test with a Bonferroni correction to test the significance of the changes and found the changes in spikes and tubes to be significant; the p-values are shown in Table 5.4.

5.5.3 Hypothesis 3

There will be a positive correlation between the Likert scale score for huggability and appeal.

There is a moderate positive correlation between the huggability of my inflatables and their appeal both before and after. This was calculated using Spearman's correlation coefficient whose results are shown in table 5.5. Spearman's correlation coefficient gives a result of 1 when a positive correlation is present and a result of -1 when a negative correlation is present [104].

5.5.4 Hypothesis 4

Surprisingly, there is no evidence of a correlation between the Likert scale of agreement with the statement "I am a hugger" and the average of the Likert scale score for huggability given by that participant. A scatter chart of these is shown in Figure 5.4 and the results of Spearman's correlation coefficient was -0.0969 with a P-value of 0.6234.

5.5.5 Qualitative Results

Inductive thematic analysis was In this work I present a framework for understanding the field of soft robotics and explore the research gap of large-scale inflatable soft robotics specifically focused on hugging interactions. This led to a series of both qualitative and quantitative research. The results of my qualitative research generated five key guiding principles for designing the shape of soft robots that are huggable. These are:

- **Animism** - Incorporate features that allude to the robot being alive in some way. Good choices for these might be including a face or limbs as well as more general features like malleability akin to a human or animal. These features can stem from both anthropomorphism and zoomorphism and should indicate that the soft robot is able to interact with a hugger. However when an inflatable is considered "alive" participants may feel uncomfortable if consent to hug the robot has not been established.
- **Optimal diameter** - The perfect diameter will depend both on the person who is hugging's arm span and the type of hug that is being performed. The hugger should feel that there are clear locations where their body can dock with the robot. While fitting arms completely around the robot is not necessary, the hugger or group of huggers should be able to envelop the robot.
- **Avoid spikes** - Spikes produce a highly negative effect on huggability that may not track with other positive characteristics like cuteness.

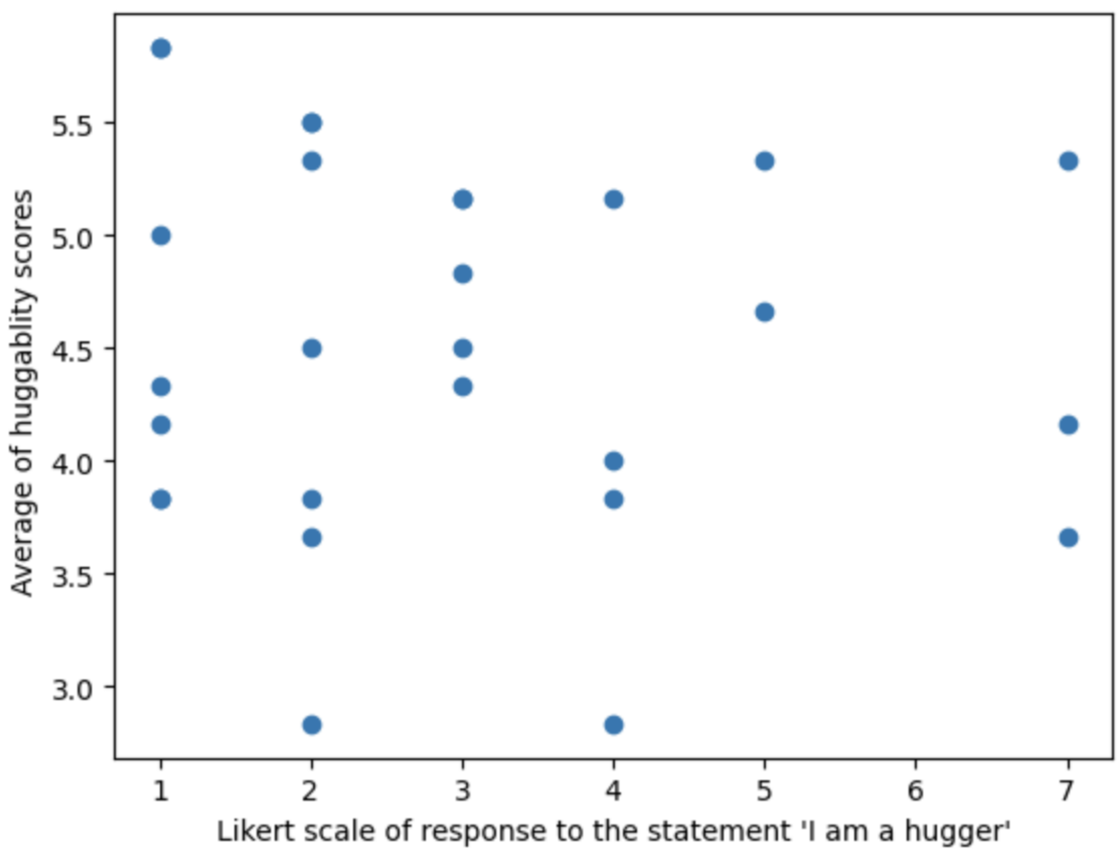

Figure 5.4: Graph of a participated average huggability score compared to their response to the question "To what degree do you agree with the statement 'I am a hugger'"

- **Non-prescriptive** - Avoid limiting how people can hug the soft robot to specific hugging styles.
- **Robustness** - The shape (or other factors like material or construction) should convince the hugger that the soft robot will not be damaged by being hugged. Huggers will be more likely to hug these robots and deliver hugs that are tighter.

Through further quantitative examination of one of the traits identified, I was able to confirm that shapes that featured protrusions in the form of either spikes or extruded tubes aligned with the expectation found in my qualitative study. This was because these shapes would be rated as less huggable and less appealing. Additionally, I was able to empirically demonstrate a negativity bias towards shapes considered unappealing. However, there is an asymmetry in the perception gap. The gap between the perception of huggability before hugging an inflatable is significantly greater than the huggability score after the participant has hugged the inflatable only when the hugging score is neutral or negative. Furthermore, the evidence indicates that the gap increases the more negative the initial huggability score. As acknowledged in my research chapter, there are variances in how people from other age groups and cultures hug. Therefore, there are limits to the generalisability of these results given the limited population and sample size that was explored. Thematic analysis was used to analyse the qualitative responses to the questionnaire. For a full description of the process see Section 4.4.

The five key themes were identified of these three matched themes found in my focus group qualitative analysis. These themes were:

- **Optimal diameter** - The focus of this was primarily on the width of the inflatables. These suggested that the shape could be improved if it was "slightly less wide" than ideal. Both the responses that mentioned the height of the inflatable indicated that the height was "ideal".
- **Animism** - A repeated suggestion was that to improve huggability would be by "adding a face" or making the inflatable more "humanoid". These are both characteristics of being alive.

- **Pressure -** Five of the respondent mentioned that either the inflatable should be ”more solid” in some way or that it should “lose less pressure when hugged”.

The two additional new key themes were:

- **Hugging back -** Five participants used the phrase “hugged you back”, three more gave responses that meant the same thing. These responses referred to two distinct sub-themes. Firstly, the phenomenon where the self-actuation caused by the participant hugging the inflatable caused by the ”arms” to move and ”hug back”. Secondly, the participants desire for the inflatable to actively squeeze back.
- **Changing opinions -** The nature of the experiment presented clear priming for this theme, but many of the responses concerned the difference between the expectation of hugging a shape and the reality of this. Participants were asked, “Did your opinion about the huggability of the inflatables change? If so, what caused that opinion to change?”. Of the response to this question, 13 indicated positive change and 3 indicated negative change for the spiked inflatable. The inflatable with extruded tubes also had 13 responses that indicated a change in opinion that was positive and 4 that indicated a negative change. However, for the inflatable, only 4 indicated positive change and 3 indicated negative change.

5.6 Discussion

As air pressure applies a constant force to all external panels of an inflatable they have a tendency away from hard edges, where corners will become at least slightly bevelled. In order to confirm that participants were actually perceiving the spiked inflatable as such, I included a question asking the subjects to assign a name to each of the inflatables either ”Bouba” or ”Kiki”. The Bouba Kiki effect [105] is a cross-cultural example of sound symbolism. The nonsense word ”Bouba” is associated with round shapes whereas ”Kiki” is associated with spiky shapes. I am able to verify that participants did perceive the spikiness of the spike inflatable as 83% of respondents assign the spiky inflatable the name ”Kiki”. Whereas 67% and 100% of respondents assigned the inflatable with tubes and no protrusions respectively the name ”Bouba”.

The results from the test for *Hypothesis 1* indicate that shapes that have protrusions such as spikes and tubes as less huggable than those without.

The results from *Hypothesis 2* provide evidence that there exists a negativity bias [7] that occurs when the shape produces a negative expected huggability. Negative dominance is one of the four manifestations of negativity bias. This means that when an experience/event/item has both negative and positive aspects when considered in summation the negative components will dominate. This may be what is occurring when participants were perceiving the negative qualities of the spiky inflatable. This may explain why there is a significantly greater change in huggability score in the inflatable perceived as negative than the change in those that are perceived as positive.

The results from the qualitative analysis further indicate this point as there was a much greater amount of positive change in opinion seen for the inflatables with protrusions compared to those without.

The results from the analysis of *Hypothesis 3* indicate that there is a correlation between huggability and appeal. Given this, these results may indicate more general shapes that have positive appeal will also be rated more huggable. However, as the nature of this study was focused narrowly on the comparison of protrusion compared to non-protrusions, further research may be needed to confirm the generalisability of this result.

The results from the analysis of *Hypothesis 4* were surprising to me as I had predicted that participants the perceived themselves as ”huggers” would be more likely to rate the huggability of all inflatables more greatly. There was no evidence to suggest that this was the case. I performed two one-sided t-tests (TOST) at an equivalence interval of ± 0.1 to evaluate if there was significant evidence of no correlation. However, the result of this has also non-significant. This is not surprising as TOST typically requires sample sizes much larger than 28.

During the preparation for running the experiment, I identified ordering bias as a potential extraneous variable. I felt that, as the initial experience of hugging an inflatable may have been novel to many of the participants, there would likely be a significant change to the huggability score produced on the first

Table 5.6: Table showing the results of a Kruskal-Wallis hypothesis test between the order that the inflatables were seen.

	P-value
Appeal Before	0.5673
Huggablity Before	0.7461
Appeal After	0.8465
Huggablity After	0.1734

inflatable. I evaluated this using a Kruskal-Wallis hypothesis test and found that there was evidence of no significant difference in the change in huggability score between the distribution of the inflatables hugged first, second or third. This is shown in Table 5.6.

Three themes identified in the qualitative analysis match those generated from the focus groups I completed. This further indicates that they are worthy of further investigation to establish if they can be proven to be affected empirically.

The theme of "hugging back" is present in the thematic analysis. In order to achieve this some form of controlled actuation is necessary. A method of achieving this is explored in Chapter 6.

5.6.1 Limitations and Critical Evaluation

There are several factors that must be considered in relation to the internal and external validity of the experiment and analysis presented in this Chapter. Firstly, internal validity, these are factors that limit the extent that a cause-and-effect relationship is clear. While pressure differences were accounted for by marking positions dials on the inflation equipment. No precise mechanism was used to ensure that these were constant both between inflatables, and participants, and within each individual test.

Secondly external validity, these are factors that limit the generalisability of the results to a more broad context. Only three models were used in this experiment. This was limited by the manufacturing time producing the inflatables took. This process could be sped up by using a computerised numerical control fabric cutter and a Seger machine to provide tighter seems and reduce time re-threading and refiling the bobbin. The bobbin is a spool that holds the bottom thread that is caught by the needle. Further shapes could be explored to provide greater generalisability as well a greater variety of spike and tube dimensions. Additionally, a greater sample size could be used to provide weight to the evidence shown in the report. Thirdly, the participant recruitment method was inherently limiting because it heavily targeted students that were likely to be studying a STEM subject as they were recruited inside an Engineering building, in the University of Bristol. As explored in Section 4.6.1 the impact of this is important as cultures of hugging vary greatly.

Finally, two or more researchers could have been used to generate the themes. While this is not essential [106] recommend this approach to increase the reliability and trustworthiness of the results.

5.7 Conclusion

In this chapter, I have shown that inflatable soft robots that have protrusions are significantly less huggable than those without protrusions. There also exists a negativity bias that exists towards inflatables that are perceived as less huggable. This indicates that the negative components of the design dominate such that the expectation of huggability is significantly less than the reality, causing significant opinion change after hugging.

The qualitative results presented in this chapter are also in agreement with the results from the focus groups discussed in Chapter 4. I have developed a supporting technology for future research addressing these results which is expanded upon in Chapter 6.

Chapter 6

Pneumatic Joint

6.1 Introduction

Although the goal of this project was to principally contribute to understanding users through three empirical evaluations, I wanted to push my objective further by embedding the knowledge learned within a functional prototype. In this chapter, I present a prototype pneumatic joint system for actuating metre-scale inflatable soft robots. The goal of this is to support future work into creating hugging robots by allowing them to move, thereby developing an understanding of the differences that result from giving a soft robot a hug and the soft robot giving a hug back.

6.2 Description

Figure 6.1: Prototype pneumatic joint in 180-degree position (left) and 90-degree position (right)

I have created a low-cost low-pressure pneumatic joint system and demonstrated this in a one-degree-of-freedom prototype. Figure 6.2 shows a diagram of how this system functions. When air enters the system through the opening denoted with an arrow. When Valve A is open and Valve B is closed the pressure chamber is field causing the joint to rotate to the 90-degree position. When Valve A is closed and Valve B is open the pressure difference between causes the internal chamber and the outside world caused the air to equalise and the joint to rotate to the 180-degree position.

The valve system is manufactured using a single SG90 servo motor and three PLA 3D-printed components that I designed and built. These 3D printed components can be seen in Figure 6.3 and are denoted the:

- **Top** - This serves as a mounting point for the servo motor.
- **Guard** - This panel will be rotated by the servo motor and prevents air from moving through the valve.

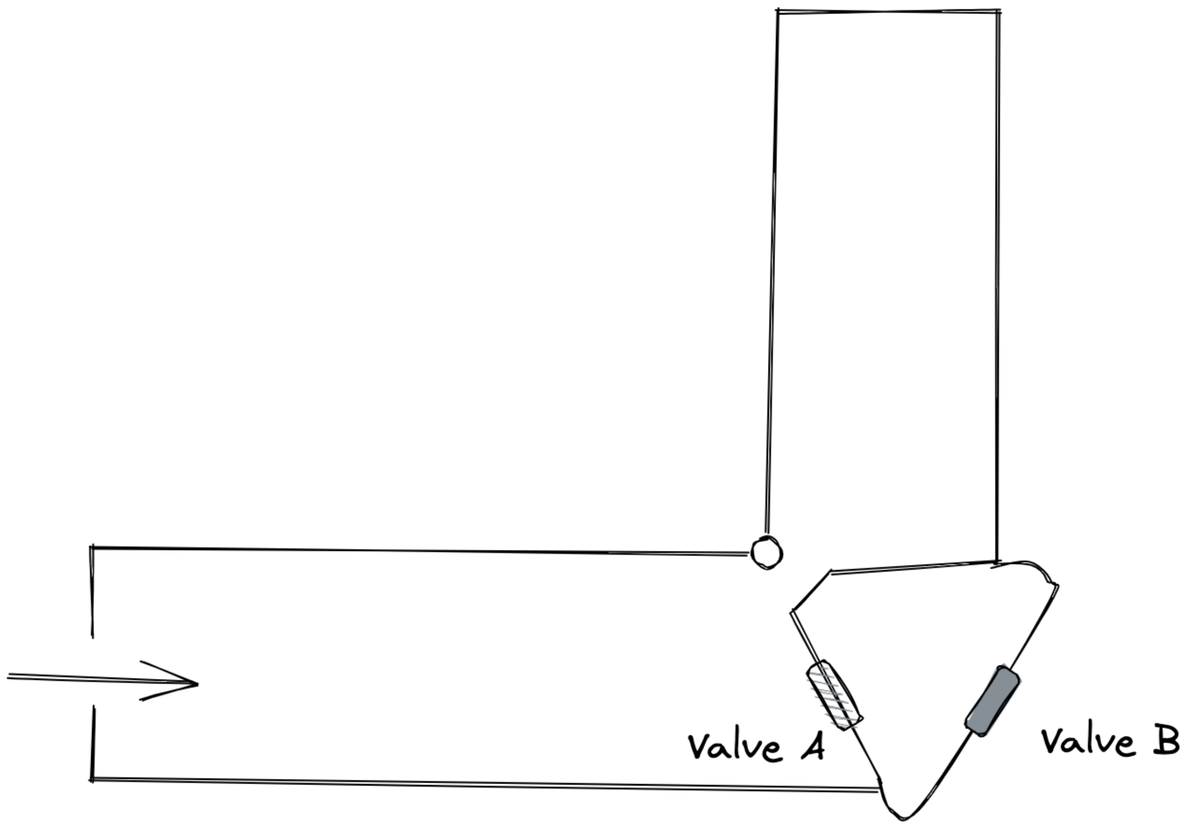

Figure 6.2: Pnuematic joint diagram

- **Base** - This forms the counterpart to the Guard and is mounted to the other side of the fabric to the Top.

The servo motors are attached to the Top using a two-part epoxy glue. The 3D-printed components are attached to the fabric using a fabric-to-plastic contact adhesive.

The servo motors are driven by a PCA9865 servo controller attached to a RasberryPi v4.

6.3 Rationale Behind the Type of Actuation

As large-scale soft robotics is a very new field, a defacto standard approach for achieving actuation has not yet appeared. Currently, four methods for achieving motion are present in the literature. These are:

1. Ant-roach from Otherlab[29] uses a traditional pneumatic valve system that allows compressed air to flow into a muscular system that contracts when inflated. Ant-Roach is able to achieve tethered walking and support at least 454kg [4].

   Li et al.

2. [107] demonstrate a modular soft robot that can bend in eight directions. These operate by using a vacuum pump to create a contraction in a foam skeleton surrounded by a nylon skin. The result of this is a musculature system that can operate untethered and at scale.

3. Both King Lousie[5] and Park et al.[30] use a similar system, where highly compressed air is released into pressure chambers that expand causing actuation. Park et al.[30] presents a simple to assemble method for creating bi-direction soft joints. King Lousie is a humanoid robot with a pair of four degrees of freedom arms.

4. Niiyama et al.[8] presents a system of tendons that, when with leaf-shaped patches in the fabric, are able to achieve controlled deformation causing the robot to actuate.

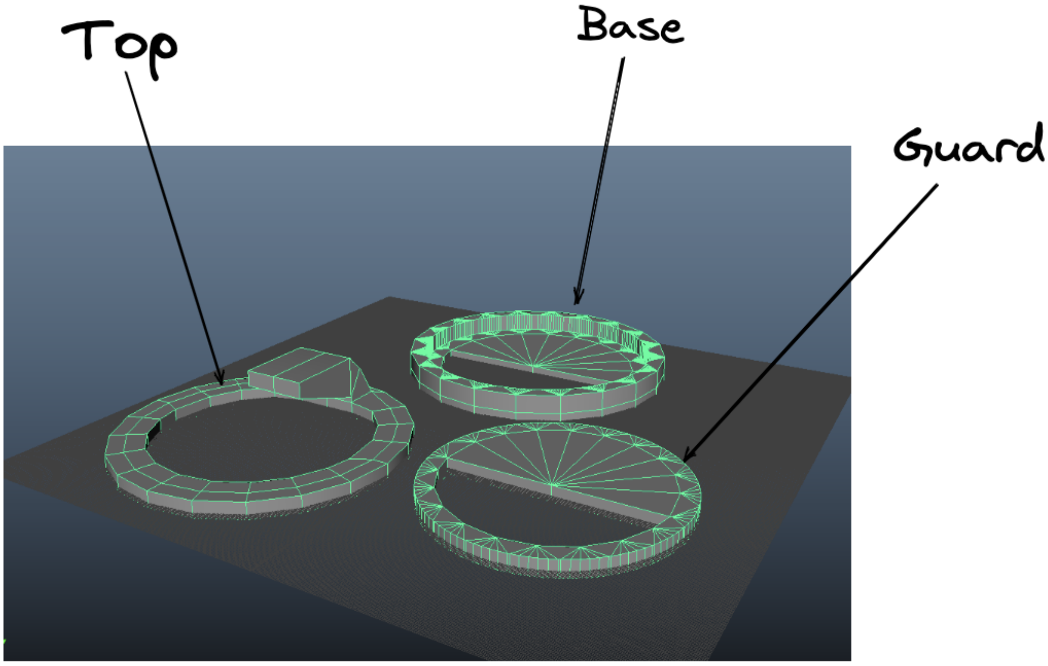

Figure 6.3: Valve model

The system I have developed has several advantages over the existing methodologies. Firstly, this system is very low cost. All of the materials and components to replicate the prototype I have built could be purchased for under £50. Secondly, my system exclusively uses low-pressure air which avoids the scaling issue presented in Park et al. [30]. Thirdly, the system is not limited in shape in the ways seen in a tendon-actuated system like Niiyama et al. [8] because they require either an attachment point to a fixed surface inside of the robot or a line of sight path from the attachment point to the motor.

6.4 Design Evaluation

The system I have designed represents an early prototype. As such there are some simple further improvements that could have been added to the next version. Firstly, develop a jig to allow for accurate positioning of the 3D-printed components for glueing. This would prevent off-centre attachment and make the assembly process easier. Secondly, develop a non-permanent method of attaching the valves to the fabric to prevent wastage. This could be as simple as three mounting brackets on the side of the components that would allow the pieces to be pinned in place. Thirdly, modify the mounting system so that the servo motors can be replaced in case of damage. Finally, using a single pressure chamber instead of a pair of pressure chambers, heavily limits functionality. It means that counter pressure cannot be used to provide stiffness and precision. It also means that the current system has asymmetric actuation speeds as filling the pressure chamber is much faster than depressurising it.

6.5 Conclusion

In conclusion, the pneumatic joint system I have created can act as a stepping stone toward the development of bi-directional hugging with large-scale soft robots. This method is both low-cost and simple to assemble but requires further development to make it feasible.

Chapter 7

Conclusion

In this work, I presented a framework for understanding the field of soft robotics and explored the research gap for large-scale inflatable soft robotics and delve specifically into hugging interactions. This led to a series of both qualitative and quantitative research.

The results of my qualitative research generated five key guiding principles for designing the shape of soft robots that are huggable. These are:

- **Animism** - Incorporate features that allude to the robot being alive in some way. Good choices for these might be including a face or limbs as well as more general features like malleability akin to a human or animal. These features stem from both anthropomorphism or zoomorphism and help indicate that the soft robot is able to interact with a hugger. However, when an inflatable is considered "alive" participants may feel uncomfortable if consent to hug the robot has not been established first.
- **Optimal diameter** - The perfect diameter will depend both on the person who is hugging's arm span and the type of hug that is being performed. The hugger should feel that there are clear locations where their body can dock with the robot. While fitting arms completely around the robot is not necessary, the hugger or group of huggers should be able to envelop the robot.
- **Avoid spikes** - Spikes produce a highly negative effect on huggability that may outweigh other positive characteristics like cuteness.
- **Non-prescriptive** - Avoid limiting how people can hug the soft robot to specific hugging styles.
- **Robustness** - The shape (or other factors like material or construction) should convince the hugger that the soft robot will not be damaged by being hugged. Huggers will be more likely to hug these robots and deliver hugs that are tighter.

In the qualitative study, participants expected that shapes which featured protrusions in the form of either spikes or extruded tubes would be rated less huggable and less appealing than shapes without such protrusions. Further quantitative examination confirmed this expectation with participants scoring shapes with protrusions lower than those without both before and after hugging. Additionally, I was able to empirically demonstrate a negativity bias towards shapes considered unappealing. Interestingly, participants rated the huggability of the inflatable more negatively before they hugged it than they did after hugging it, but only when the initial perception of huggability was neutral or negative, i.e., for the inflatables that featured spikes or extruded tubes. Furthermore, the evidence indicates that this asymmetry in the perception gap increased the more negative the initial huggability score.

As acknowledged in my research chapter, there are variations in how people from other age groups and cultures hug. This limits the generalisability of these results given the limited population and sample size that was explored.

Finally, I was able to lay the groundwork for exploring bi-directional hugging in inflatable soft robots through the development of a low-cost, 3D printable valve system and a one-degree-of-freedom pneumatic joint. This foundation could be used to explore to what extent results from hugging studies that used traditional internal robotic skeletons, such as in Block et al.[90], generalise to inflatable soft robotics.

This could also be extended to build a novel actuation method suitable for metre-scale modular soft robots.

Overall, I have explored how shape impacts the huggability of large-scale inflatable soft robots and established some guiding principles for this. Further development of this has the potential to enhance our knowledge of the design of robots for use in situations where performance, trust, and scale are important. We should embrace the potential that soft robotics has through future exploration and research.

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