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Adaptation of soft robotics technologies for use in the industrial design of medical products

by

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DECLARATION

I, Adrian Ingemar Wilton, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed: ____________________ Date: 1st July 2022

ABSTRACT

In the field of medical product design, available technologies and materials limit the extent to which a product can be developed to best suit the end-users' needs. Certain parameters restrict the design of soft, intelligent devices that require actuation or the need to adapt to the user during use. Conventional designs for medical devices which are in direct contact with the user, predominantly involve rigid plastic or metal components that may be padded with foams or rubber. In order to drive motion in such devices, the options available are either motors (servo, mechanical, etc.) or piston-type drivers that are either pneumatic or hydraulic. This results in complex mechanical designs that are often heavy and costly to manufacture. If designers and engineers are to develop lightweight and more ergonomic products, alternative technologies should be explored, understood and tested.

This research project outlines soft robotics technologies (SRTs) in the robotics industry that could be adapted for use by industrial designers to develop soft, lightweight, intelligent and adaptable medical products. One group of SRTs, namely, electro-active polymers (EAPs), has been chosen for in-depth investigation in this study. The features of this SRT are outlined in detail and potential applications explored and discussed. A practical study was conducted with a group of Industrial Design students from the School of Design, Hunan University, China. The results of this focus group are presented and discussed, to show how the use of SRTs is not only feasible, but also allows for novel and innovative designs to be generated.

A multi-method qualitative research methodology was followed, making use of two real-world medical design case studies to define the research scope. Data collection methods included document analysis, interviews, questionnaires and a participatory design focus group. The findings demonstrate the viability for the use of SRTs, specifically EAPs, to actuate elements of a device/product and allow for solutions that are compact, lightweight and superior to available alternatives.

The limitations of this study are contained to the SRTs discussed, with a focus on actuation, in the context of industrial design. Although the technology has broad applications, this study focuses specifically on the use of SRTs in medical product design.

Keywords

Soft robotics, artificial muscle, biomimetic motion, dielectric elastomers, elastomeric actuators, electro-active polymers, soft actuated material, soft products, soft medical devices.

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LIST OF ABBREVIATIONS AND DEFINITION OF TERMS

ABBREVIATION	TERM	DESCRIPTION AND REFERENCE
AM	Artificial Muscle	Synthetic actuator that replicates the function of organic muscles (Rossiter et al., 2016).
BM	Biomimetic Motion	Relates to the imitation of complex movement systems found in nature, i.e., plants and animals (Must et al., 2015).
CAD	Computer-Aided Design	Software programmes used in design of various media and products.
CE	Contractile Elements	Segments of a soft robot that are actuated to contract (Roche et al., 2014:1).
DE	Dielectric Elastomers	Electrically conductive and stimulated elastic polymers (Trivedi et al., 2008:104).
DOF	Degree of Freedom	Range of motion and movement that a robotic device can use to perform functional tasks (Trivedi et al., 2008:99).
EAP	Electroactive Polymer	Polymer material that changes shape or volume when stimulated by electric current (Bar-Cohen et al., 2004).
EI	Embodied Intelligence	Physical properties incorporated into the physical structure of a robot or device that can be exploited to drive certain desired outcomes (Rus et al., 2015).
IPMC	Ionic Polymer Metallic Composites	Polymers combined with metallic micro particles to allow for the composite to transmit electricity (Trivedi et al., 2008:104).
MC	Morphological Computation	Control is devolved to the body itself, completely bypassing the brain or control system (Hauser et al., 2011).
PAM	Pneumatic Artificial Muscle	Artificial muscle that is actuated through the compression and decompression of air in chamber(s) within the physical structure (Trivedi et al., 2008:103).
PCB	Printed Circuit Board	Baseboard onto which electronics are installed to allow for control and operation of devices and robotics by means of firmware.
RK	Robot Kinematics	The range of motion and inherent motion and dynamics within a robotic structure/system (Laschi et al., 2009:2).
SA	Soft Actuators	Similar to artificial muscle but focused on specific soft polymers and soft materials that can be actuated (Bar-Cohen et al., 2004).
SM	Smart Materials	Materials that can be used in complex electronic systems to have more than one function – e.g., actuation and sensing properties (Laschi et al., 2017).
SMA	Shape Memory Alloy	Metallic materials with the ability to return to a predetermined shape, after a severe deformation produced by a thermal stimulus (Hernan & Cuellar, 2015:50).
SRT	Soft Robotics Technology	Soft robotics primarily involves construction from soft materials and intentionally compliant structures (Laschi et al., 2016).

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CHAPTER ONE
Introduction

1.1 Introduction

With the well-funded development that occurs in the military and robotics industry, there are advances in robotics technologies that now allow for soft design solutions to replace historically rigid mechanical designs, including in the field of industrial design. These advances explore the use of soft materials such as rubbers and polymers that are flexible and adopt alternative methods to drive movement. These soft materials offer comfort and increased mobility in joint movement which improves the functionality of the rigid mechanical designs (Rossiter & Hauser, 2016).

There is a gap however, between the development of such soft design technologies and their adaptation for use in medical products for the mass market. This thesis is a focused investigation into these technologies and their adaptation for use in the industrial design of medical products, to better meet the needs of the intended user.

1.2 Research study

Adaptation of soft robotics technologies for use in the industrial design of medical products.

1.3 Role of the researcher

The researcher is well positioned to conduct this research as he has experience in product design within South Africa as well as abroad. Through this experience, it has become clear that there is a gap between what is being developed as “the best solution” and what is accessible to the mass production market for use by the majority of people.

Having worked in the medical field to develop a number of functional medical products, the requirement for softer alternatives to conventional materials and mechanical components became clear to the researcher. From the researcher’s perspective, the opportunities that such soft solutions could allow for in terms of innovative design and problem solving are endless, new and exciting. It could, therefore, be of great value and importance if such alternatives were explored, understood and adapted for use in accessible product design to improve user experiences, improve product functionality and reduce product cost.

The researcher is well-placed to conduct this research, as he worked for a medical company that explored the latest available trends and cutting-edge technologies. This exposure to innovative thinking and the experience gained through developing such advanced medical devices formed a solid base from which to conduct such a study.

The researcher included two real-world medical design projects in the study, with the purpose of guiding the research. These are, namely, the FIT and Medi-dot projects that are described in detail in Appendices A and B. By working with the real-world requirements of these two projects, the overall aim of investigating SRTs in the context of medical product development was further aligned.

The researcher has also gained experience, through working in China, of mass production and the efficiencies associated with production speed, material cost, production processes and functional engineering. By applying this understanding during the research process, practical and achievable outcomes were pursued, where the conclusions are not only feasible in principle, but also viable for mass production.

Having grown up in South Africa and having developed a low-cost wheelchair as part of his bachelor’s degree in Industrial Design, the researcher is strongly aware of the limited access to medical devices that exists in the middle and lower-income groups. The need for cost-effective and functional solutions is undeniable, and therefore this soft robotics research would contribute to a knowledge pool to support such thinking as well as product development. In simple terms, by exposing designers to the alternatives offered through using soft technologies, it may be possible to influence a way of thinking and encourage product development in a direction that will benefit the majority of people in South Africa in the long term.

1.4 Statement of the research problem

In the medical consumer product market, there is a limitation to design solutions that employ materials and technologies currently available. Conventional materials and manufacturing processes are driving product design towards more rigid end products. Technologies and materials have been developed in other fields, specifically the robotics industry, which could allow for new design solutions, but these have not been adapted for use in consumer or medical products for the mass market (Rossiter et al., 2016). This is the gap that appears in most of the research and studies on soft robotics, where the technologies and innovations are developed in laboratory environments and the focus is on those interested in the field of robotics (Li et al., 2021). There is a clear need to analyse these SRTs from an industrial design point of view and provide potential applications or uses in this context.

For example, a soft robotics actuator, instead of showing the possible robotics applications for grippers or limb movements (Shian, Bertoldi & Clarke, 2015), might rather show how such an actuator could be used in an everyday device (Polygerinos, Wang, Gallowaya, Wood & Walsha, 2015). The stigma and resistance to such “complex” mechanisms is thereby removed and they are reduced to their most basic function. The understanding that such a soft actuator is able to drive basic movement can then be incorporated as required to explore all the benefits of this alternative technology (Yao et al., 2013). It is this gap then between the development of soft design technologies and their adaptation for use in the design of medical products for the mass market that this thesis has focused on.

1.5 Description and background to the research problem

In conventional robotics, the mechanical structure of the robots is rigid which makes them task-specific. These rigid robots are characteristically used to perform repetitive tasks with a predefined motion that can be repeated indefinitely to a high level of precision (Trivedi, Rahn, Kierb & Walker, 2008:99). The rigid structure ensures that the limited degrees of freedom (DOF) are exploited to reduce the effects of mechanical vibration and the resultant deformation in order to enhance the accuracy of movement and function/task performance (Trivedi et al., 2008:99). This, in simple terms, makes the rigid robots ideal for repetitive tasks in industrial mass production systems, as the components being handled in industrial mass production are in most cases resilient and suited to this production environment.

With the increased demand for automation and the move from manual labour to machine-driven production lines, the need for robots that can handle soft, fragile and even organic items has increased. This has led to focused development of soft grippers and robots that have increased degrees of freedom and movement. In contrast to conventional mechanical robots, soft robots have the ability to deform or change shape throughout the structure, referred to as distributed deformation, which provides in theory, unlimited degrees of freedom to the robotic system (Trivedi et al., 2008:99). This ‘freedom’ is being explored by companies such as Festo and Soft Robotics Inc., among others to develop appropriate solutions for the handling of soft goods, and for closer interaction with people. Figure 1.1 shows a bio-inspired robot developed by Festo to mimic the look and movement of the Australian kangaroo. Exploring inherent flex in the structural-lattice design of the legs using polymers, has allowed for the Festo designers to create a robot that can hop in a natural way mimicking the live animal in nature.

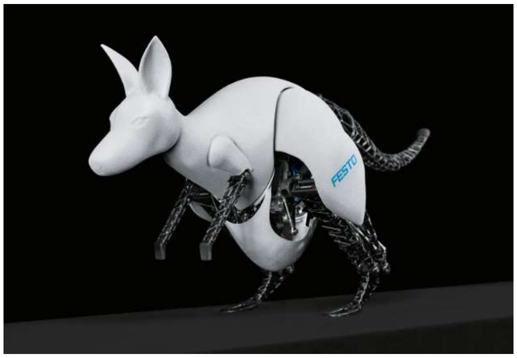


Figure 1.1: FESTO kangaroo robot (FESTO, 2017)

In the same way that historically rigid robotics solutions are being adapted to better meet the needs and requirements of industry, users and applications, so too is there a need for this evolution in other fields. This is specifically required in the medical products market, where design solutions have been limited to only the readily available materials and production methods. Should softer alternatives become available, it would allow for a shift to occur, where products could be better designed and engineered to meet the user’s needs improving function, ergonomics and comfortability of the overall user experience.

The researcher has noted compromises on materials and technologies selected during the design phase that have resulted in end products with inherent properties and functionality that are not ideal. It is this experience and need for softer alternatives that impelled the researcher to conduct this research.

In the same way that soft materials allow for the automation of processes beyond the capacity of conventional rigid robotics (Pfeifer, Lungarella & Iida, 2012:76), so too might SRTs enable design solutions that are unachievable with currently used conventional materials and technologies (Kanaan, Pinho & Pedade, 2021).

1.6 Research questions

Main research question	How can SRTs be used in the industrial design of medical products to improve inherent properties and functionality in order to enhance the user experience?
Sub-question 1	What SRTs exist that could be adapted for use in the industrial design of medical products?
Sub-question 2	How can SRTs be adapted for use in the industrial design of medical products?

1.7 Objectives of the research

1. Explore the current status of research and development in the field of soft robotics, by identifying and defining existing and emerging SRTs for use in medical products.
2. Identify the most appropriate SRTs that can best be integrated into medical product design.
3. Explore potential applications for these SRTs in consumer medical products to improve the user experience.

1.8 Research design and methodology

1.8.1 Mixed method design: qualitative analysis of quantitative and qualitative data

The research study employed qualitative methods as the researcher evaluated the potential of SRTs by comparing and discussing their intended applications and how these could be adapted for use in medical product design. Thus, all analyses were done through the lens of industrial design, in order to determine the appropriateness of SRTs for improving the user experience. By displaying, coding and analysing various reports, studies and data sources, the researcher sought to identify themes and patterns that could direct further research in this study (Miles & Huberman, 2014).

Some qualitative testing was done in the field through practical experiments and design focus groups where the collected data were applied to conceptual examples and applications. The purpose of these “practical experiments” was to test feasibility for use in product design. By keeping the research theoretical and conceptual, the cost for conducting research through prototyping was avoided as no specialised facilities were required.

A focus group, conducted with industrial design students, made use of co-design methods to ensure a participatory approach was followed (Schuler & Namioka, 1993). Specialists such as Harvard Biodesign Lab, involve the end-user during their development process to ensure their products are functional and ergonomically sound, and so follow a similar co-design research method.

Selected experts in the fields of industrial design and the medical industry were interviewed and open-ended questionnaires were used to guide the interviews. By involving such specialists in advance of the “conceptual design phase” of the research, the researcher was able to ensure that co-design principles were considered when discussing applications for SRTs. This input was split into two phases: the discussion and “planning phase” where applications were identified, and the “practical phase” where those potential applications were put to the test and applied to creative design concepts. Although the focus was on the use of SRTs, core functional concepts were required into which these SRTs could be integrated, and so the specialist's experience was leveraged to ensure that these conceptual designs were also feasible in principle.

The conceptual design focus groups were arranged so that the participants could be engaged in an open type of discussion. The intention was to discuss viable and practical applications for SRTs and give the participants a starting point from which to explore these SRTs further. Co-design methods were used in the design focus groups, where the main aim was to conceptualise products/designs incorporating SRTs that could be reviewed and discussed collectively to gauge feasibility. With the real-world projects being conducted by the University of Hunan, it was possible to make use of their user-centred experience and keep the focus on appropriate product ideas. Triangulation has been used to analyse the various data inputs into this study, in order to show where there is corroborating evidence or support for the various themes identified.

1.9 Research methodology flow

- **Stage One: Qualitative analysis of metadata (secondary research)**

  a) Analysis of secondary data, reports, studies and relevant literature.
  b) Coding of data to highlight common themes and patterns.

- **Stage Two: Interviews with medical, design and 3D printing experts**

  a) Interviews with specialist companies and individual experts.
  b) Analysis of the interview data in a structured way to identify themes.

- **Stage Three: Focus groups, practical testing and digital simulation**

  a) Focus groups with design students to discuss potential applications for SRTs.
  b) Practical testing through focus group "conceptual products/designs".
  c) Digital simulations in Solidworks.

- **Stage Four: Analysis through triangulation**

a) Triangulation was used to compare findings from the literature review, focus groups and discussions with experts in the field of product design to find commonality and identify clear outcomes that are feasible for the development of medical products using SRT's to improve the users' experience.
b) Final analysis and outcomes described.

1.10 Research philosophy

Pragmatism: Design is subjective, and most design solutions could be executed in many different ways. Therefore, in order to describe appropriate technologies that may be used in the design process, a broad view needs to be adopted with the understanding that no single viewpoint can be comprehensive. The research conducted allowed for the practical application of these learnings, providing a baseline that could be incorporated, advanced, exploited or used in many different ways to address the practical problem under investigation.

Ontology: The researcher's worldview has been shaped by a deep understanding of the South African context as illustrated in the investigation and design of a low-cost wheelchair for the mass market. The barriers of introducing such an industrial design to the South African market led the researcher to contact companies in China where products are quickly scaled to reach the intended population. In this case, the researcher's worldview, shaped by the previous development of a socially conscious product design, instigated further research into the application of SRTs. By grouping and describing the various technologies to create a comprehensive picture of the current research landscape, the researcher has aimed to show how this might allow for a broader base of potential users to benefit from these technological advances.

Epistemology: The foundation of knowledge in this research study is to understand how this study will construct a "truth" that is not only perceived and believed by those who read it, but also by those who will ultimately benefit from the research. All discussions and conclusions should therefore be justified by rational, empirical data, with the underpinning that reality is co-constructed and many role-players' input informed the process of research.

Axiology: An understanding of how ethics and the researcher's value system affected the research being done is critical. The research methodologies used helped counter the researcher's inherent bias and have a direct impact on the research process. To mitigate bias and ensure a balanced view is presented, academic rigour, a comprehensive study of the relevant literature and complete immersion in the fieldwork and domain of soft robotics provided the axiological basis for the study.

1.11 Ethical considerations

The researcher completed all prescribed Ethics Approval forms prior to proceeding with any interviews or focus groups. In addition to the general Corporate Ethics agreement, an individual consent form was supplied to each participant in the research, to ensure a clear understanding of the boundaries of this research study. All participants were required to sign the CPUT's *Individual Consent for Research Participation* (FID/REC/iCv0.1) form.

No coercion or incentives were used to encourage participation in any interviews or focus groups. Participants had the option to remain anonymous if they so preferred. All data gathered were kept in an encrypted file on a Dropbox Server and remained so for the duration of the study after which they have been, and will remain, archived for five calendar years for audit purposes as required by the Cape Peninsula University of Technology (CPUT). There is no risk of compromising the data and participants' identity.

The researcher has abided by all ethical guidelines and requirements as set out by the CPUT. The researcher has respected the wishes of all participants in the study and protected their right to anonymity. The researcher has not and will not compromise any participants' intellectual property or make public any information that could be deemed confidential or pending formal protection such as copyright, design registration or patent.

1.12 Delineation of research

The area of study is specifically related to the industrial design of medical products, focusing on incorporating SRTs, and the advances in technologies within this field of study. The researcher has aimed to understand advancements in SRTs in order to ring-fence those technologies which could be applicable for use in products designed for the average person. The researcher has identified and described these applicable SRTs and shown how these may be applied for use in the industrial design of medical products.

The focus area has covered materials development in soft robotics, the methods used to drive motion/movement (actuation) and 3D printing production methods that can be used to create support structures, frames and complex systems in an integrated single process. Manufacturing techniques have been considered throughout this study, and the feasibility for mass production has been key to justifying commercial viability. This was a quintessential factor when coding and grouping the metadata, as well as reviewing the various design concepts created in the focus groups. This ensured that the thread of “feasibility” was followed from start to finish in this study to further add support and credibility to the findings.

The researcher has not repeated existing research or conducted materials development research. The nucleus of the study has not been to hypothesise regarding future materials, but rather to build on existing technologies currently being used. This research is not for the purpose of expanding on robotics technology or the existing knowledge base in robotics. This study is not a study of robots in general and the intention is not to be able to design robots with the information gathered through this research.

1.13 Significance of the research

How will this make the world a better place?

Industrial design with SRTs opens up huge opportunities for the production of low cost and advanced products that can have inherent customisability and adaptation as required. This could lead to an advancement in the way products are designed, especially where a product is worn or is in direct contact with a person, such as those used in the medical industry.

By reducing the cost to produce certain medical products, it is possible to make these devices accessible to a broader segment of the population. In turn, this could lead to an advancement in the product experience and form part of “human augmentation” whereby one’s abilities and quality of life are improved through the use of such devices.

Why/How will this information be useful to other people?

This research could encourage the development of a framework or system that could be used by designers to incorporate SRTs into their designs and develop “soft” alternatives to products that may have featured rigid mechanical parts in the past. This could create a base for designers to work from and allow them to think differently when developing products that involve direct human interaction. The research provides an overview for the field of industrial design and identifies opportunities for further research and development in terms of applications, materials development, motion design, medical product design and others not yet defined.

1.14 Outline of chapters

- **Chapter One – Introduction to the study**

This chapter outlines the background to SRTs, the problem statement, research questions and introduces the research study. The relevance and direction of the study is set out, from a broad perspective, allowing for a basic understanding of the entire body of research contained herein.

- **Chapter Two – Literature review**

The second chapter reviews studies and meta-data in the field of SRTs to outline the current state of the art and bring the primary technologies into focus. Extensive materials research, developments in soft robotics research and applications for SRTs are discussed.

- **Chapter Three – Research design / methodology**

Qualitative methods have been the primary tools used in gathering data for this study, including participatory design focus groups, questionnaires, interviews with expert industrial designers and discussions with additive manufacturing specialists. Fieldwork has been conducted through practical design exercises with industrial design students, where the learnings were applied to conceptual examples and applications. This chapter clarifies and validates the research design choices. The methodologies used within the data collection and analysis chapters are also explained.

- **Chapter Four – Data collection and presentation of findings**

In this chapter, the data collected from questionnaires, interviews, discussions with experts and the focus group outcomes are clarified and presented.

- **Chapter Five – Discussion and analysis of findings**

This chapter focuses on and analyses the findings delineated in Chapter Four. To determine whether the literature supports what the researcher discovered and whether it refutes the findings, triangulation is used to bring into alignment the literature, focus groups and expert opinions. This chapter revisits the research problem set out in Chapter One and shows the outcome of the research in line with the initial problem statement and questions in order to corroborate the findings and define areas for further study.

- **Chapter Six – Conclusion and recommendations for future study**

Here, a summary of the research is presented, and the most important lessons learned are highlighted, indicating possibilities for further research in the field of industrial design and the use of soft robotics technologies.

1.15 Expected outcomes, results and contributions of the research

1. To show the potential for the use of soft robotics technologies in the industrial design of *specialised* medical products.
2. To show the advances in soft robotics and to identify/define practical alternative applications for this technology for the mass market.
3. To show the potential for a design shift from hard mechanical designs towards softer, more organic design solutions with improved ergonomics that better meet the end-user's needs and improve the user's experience.

1.16 Chapter summary

In the medical and consumer products markets, there is a limitation on design solutions as a result of the materials and technologies currently available. Conventional materials and manufacturing processes are driving product design towards more rigid end products. Technologies and materials have been developed in the robotics industry that could allow for new design solutions and advanced products that have inherent customisability and adapt to the user as required (Rossiter et al., 2016). Adapting these technologies for use in industrial design could lead to an advancement in the way we design products, especially when the product is worn or in direct contact with the user.

These technologies cost less to mass produce than the rigid alternatives, thereby reducing the total cost and making the end products more accessible to a broader segment of the population. By looking to new materials and methods of production "…we might in fact be on the way to a new industrial revolution" (Pfeifer et al., 2012:78).

The current research study employed qualitative research methods. The researcher evaluated SRTs in order to identify unique properties that could justify adapting these SRTs for use in medical product design. These were then tested through focus groups and simulation and the findings presented. The findings were discussed and recommendations for further study and research on this topic were described.

CHAPTER TWO

Literature Review

2.1 General overview

For the researcher to get an understanding of the various SRTs, and to describe the "state of the art" holistically, it was necessary to do an extensive study of the available literature. This literature is comprised of independent studies, journal articles and metadata available through institutions such as SoRo and RoboSoft, among others. Google Scholar was used as the primary sourcing tool for these data, which were then input into both Mendeley software and Atlas TI software in order to code the data, group them according to themes and identify keywords that could assist in driving further research with a narrower focus. The literature was reviewed through the lens of industrial design of medical product development, to see how SRTs could be used to develop improved medical products and focus on defining the SRT attributes most likely to be of use to an industrial designer.

There are many networks and organisations that have been established to provide a structure in which soft robotics development can happen and be directed. Organisations such as RoboSoft, have helped link scientists, industries and research facilities across the world. Some areas of interest are soft robot-legged locomotion, soft robot manipulation, underwater soft robotics, biomimetic soft robotic platforms, plant-inspired soft robots, flying soft robots and soft robotics in surgery. There is also a large focus on the methods of controlling these soft robots (Laschi, Lida, Rossiter, Cianchetti & Margheri, 2017:10). Studies such as these have been conducted to explore how soft actuators can be used to drive motion and be manipulated to perform specific intended actions.

Conventional robots are described appropriately by the term "robot", derived from the Czech word "robota", which is generally translated as "drudgery" or "hard work" (Pfeifer, Lungarella & Iida, 2012:76). However, robots of the future are likely to be present in all areas of human life, and not only those functions of the past where they have largely replaced humans in the performing of mundane, repetitive tasks.

Currently soft robotics is at the forefront of robotics research and technological innovation, according to Laschi et al. (2017:8). Soft robotics will influence society and industries in areas ranging from manufacturing and consumer devices to medical applications and wearable technology (Rossiter & Hauser, 2016:18). The research being conducted in the field of soft robotics is extensive and varied, which alone demonstrates the perceived potential.

One of the key areas of SRT research is in the development of new smart materials to drive actuation which has created opportunities for improvements such as simplifying a design, reducing weight and making the design smaller. New materials such as piezoelectric composites, electroactive polymers (EAPs) and shape memory alloys (SMAs) are being explored as promising alternatives to conventional mechanical motors (Hernan & Cuellar, 2015:30).

In many cases, soft robotics researchers attempt to mimic the movement or muscle function of an animal or human. By first studying the natural movement and biology, the researcher gains insight into how each muscle functions in isolation and how they work together to perform a desired action (Trivedi, Rahn, Kierb & Walker, 2008). This is an important point to understand as an artificial muscle or actuator is designed not only to work in isolation but also as part of a system, whereby complex movement and control can be achieved. The complexity involved in coordinating multiple muscles will not be discussed here, but it should be noted that to program such complex movement control manually is almost impossible. Artificial intelligence and machine learning may become essential in developing the software code/algorithms that will eventually drive such complex “assemblies”.

For the purposes of this research, the individual components will be studied in order to manage them at their most basic level. In cases where artificial muscles are used to drive movement, there are multiple materials and solutions that have been explored. In each case, the focus is on a specific application with a practical element being pivotal to demonstrate the feasibility of the proposed “soft robot”. These case studies number in the hundreds, so a sample set of the most successful will be used in this research analysis.

One of the main characteristics of soft robots is their compliance under an applied force, allowing them to deform with potentially unlimited degrees of freedom (Calisti, Giorelli, Levy, Mazzolai, Hochner, Laschi & Dario, 2011:2). This will be shown in the assessment of the various case studies and used as one of the key areas of comparison. While increased degrees of freedom on the surface may appear to be a great advantage, there may be compromises to the overall structure and mechanical design which need to be understood. Selecting the most appropriate SRT becomes key in the successful implementation and use thereof as an alternative.

In industry there are many different kinds of robots, such as those used for factory automation systems, car assembly lines and food packing lines. In other specialised fields there are robotic devices that support surgeons during surgeries where high-precision manipulation is required, robotic vehicles for exploration on other planets, and devices for dangerous inspections such as those on a powerline or oil platform. In the commercial sector, there are toys and educational toolkits, service robots that clean floors or mow lawns and even companion robots (Pfeifer et al., 2012:76). There are so many places where robots are already present, that it is logical that these will evolve over time as they receive further focus and development.

It is clear from research being conducted, that engineers and scientists are continuously working to overcome the limitations of conventional robotics and manufacturing in order to move forward and evolve the technologies to allow for better solutions (Sanders, Elangeswaran & Wulfsberg, 2016). This would allow for robots to have even closer interactions with humans in their daily lives. Soft robots present a significant advantage over rigid mechanical robots in that they are able conform to the obstacles they are handling, allowing for delicate handling of fragile goods without causing damage (Trivedi et al., 2008:99).

However, this is only one of the ways in which SRTs have opened up opportunities for further development and adaptation (Rossiter et al., 2016). To fully understand the spectrum of solutions and innovative thinking, one needs to investigate not only the technology being developed, but also the thinking behind this development. To understand the direction current development is being pushed in, one needs to see the main players in a global context. High-end robotics companies such as Boston Dynamics and Festo are developing advanced robots that push the boundaries of what has been possible and have focused on complex applications (Hussain, Omar, Wang & Adewale, 2021).

2.1.1 Soft robotics and industrial design: a suite of soft suits

Research facilities, such as Harvard University, have made advances in applying SRTs to devices and products intended for direct interaction with people. Development at the Harvard Biodesign Lab (2017) has focused on assistive devices such as the soft exosuit that make use of soft alternatives to meet their functional requirements. This is one example of the real-world applications for SRTs and how they could be adapted for use in consumer and medical products. The team at Harvard Biodesign Lab, use participatory design in their process of development, to ensure that the devices they develop meet the functional needs of the end-user. “We are developing next-generation soft, wearable robots… to provide a more conformal, unobtrusive and compliant means to interface to the human body. Our soft robotics research focuses on new design, fabrication, modelling, and control approaches for… robotic systems” (Harvard Biodesign Lab, 2017).

Figure 2.1: Soft exosuit (Harvard Biodesign Lab, 2017)

If one compares conventional rigid exoskeletons to the softer “exosuits” now being developed, the contrast is striking. The leap forward in design thinking and engineering shows how much such technologies are able to improve what we have come to take for granted. The development by Harvard Biodesign Lab of a soft exosuit (Figure 2.1) is a good example of this change in thinking and design approach. In the past, exosuits were rigid mechanical structures intended to aid or assist the user to perform repetitive tasks, increase the user's ability to lift load, or aid walking. These rigid exosuits were bulky, heavy and cumbersome. The intention behind the soft exosuit is to assist the user, without the need for a bulky mechanical structure.

Another good example of this type of soft exosuit is the one being developed by Seismic (Seismic, 2018) depicted in Figure 2.2. Extensive resources have been allocated to the implementation and use of soft alternatives to drive the assistive bands in their design, with the aim of the suit to be worn by the elderly underneath their clothing and to provide a 20 to 30 per cent assist in daily movement. The clear difference between such a soft suit and the historic mechanical exosuit is plain to see. In addition to the functional benefits, the suit is less costly to produce and can be customised to suit different body types and shape.

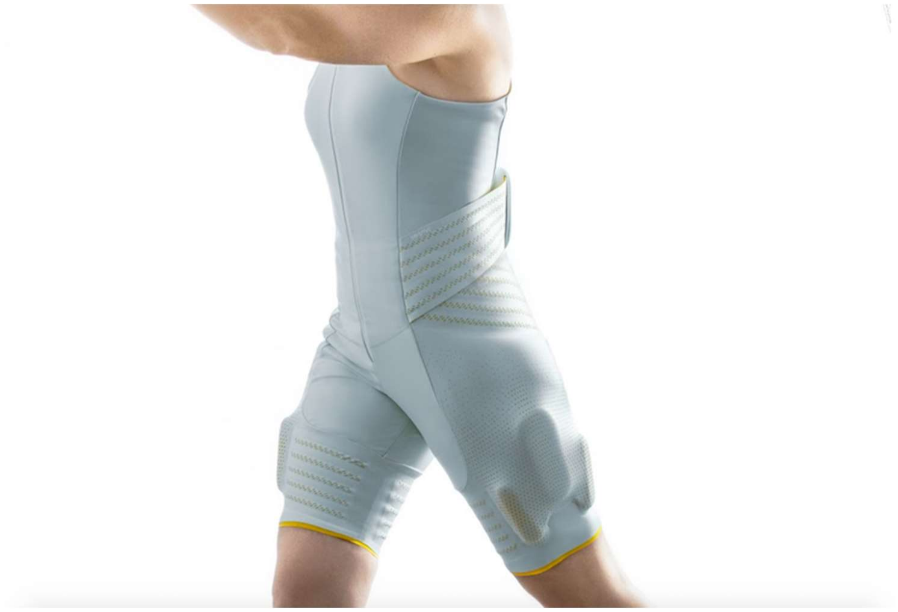


Figure 2.2: Seismic soft suit (Seismic, 2018)

In addition to the simplified function of the suit's "assist" bands (Figure 2.3), the power supply has been addressed along with the drivers of the bands resulting in the overall unit being unobtrusive and far more ergonomic than previous exosuits.

Figure 2.3: Seismic soft suit integrated power pack (Seismic, 2018)

Figure 2.4: Superflex Aura powered suit (Fuse Project, 2018)

Another example of a soft suit is the concept developed by Superflex. The Aura powered suit follows the same line of thinking as the Seismic soft suit, where assistance is supplied to the user wearing the suit by means of bands that contract. These concepts demonstrate the shift in thinking that soft alternatives can allow, and how such alternatives might change the way we design for the future.

It follows that if the building blocks of a design are geared towards ergonomic design solutions and allow for adaptation to each unique user, then the end product is more likely to provide a good user experience**.** The work done by Soft Robotics Toolkit, demonstrates the way in which these technologies can be broken down into the base elements for use by designers and engineers as required (Holland, Park, Polygerinos, Bennett & Walsh, 2014).

Next, the various robotics technologies will be assessed, to show the intended and potential applications for the various SRTs and focus the research on the most appropriate and feasible of these.

2.2 Conventional robot technologies

In conventional robotics, actuation or motion is driven most commonly by either electric motors/servo motors or a pneumatic/hydraulic action (Hernan & Cuellar, 2015:1). The mechanical process of motion follows the path of transmission through the use of gearboxes, bearings belts and other mechanical mechanisms to support linear motion. Although successful in many devices, these systems are complex and unwieldy (Hernan & Cuellar, 2015:1). This is the common thread among all conventional robots and the result of using these conventional methods to drive motion is a rigid, complex and usually heavy system.

Linear motion makes the actual functional area of the robot specific and limited and does not allow for any form of adaptation to the environment or object that might enter the working area. Although this constrained degree of freedom can be optimised, it does tend to limit the applications to those described above. To think of such mechanical robots in direct contact with humans, raises immediate concerns for safety and the potential for injury (Calisti et al., 2011:2).

Even micro mechanical robots have these limitations since they too are composed of rigid elements. These rigid parts cannot flex or deform to the environment and so they become difficult to integrate into systems where the user has direct contact with the device, often requiring excessive padding or coverings. (Kim, Laschi & Trimmer, 2013:287).

In short, it is the rigid actuation of conventional robots that is their greatest strength and weakness. Such rigid structures are highly efficient for repetitive tasks and can be optimised for single task functions. However, they are not adaptable to the degree where they can be used effectively or efficiently in soft product design. For this, one needs to explore alternative actuation technologies, commonly referred to as soft actuators.

2.3 Soft actuators

In the case of soft actuators, there has been extensive research and development done to discover the “holy grail” of synthetic materials that can replicate the function and properties of organic tissue/muscle. This has led to many laboratory-based experiments which are investigations into potential solutions. However due to the unique nature of such robotics studies, the actuators and elements used in the laboratory based experiments are largely custom made by the researchers and so are not widely available standard parts (Pfeifer et al., 2012:83). Such development is not only time consuming, but also costly and covers material science, biomechanics and engineering to name a few. The principles behind soft robotics will now be looked at from the perspective of bio-inspired robots and artificial muscles.

2.4 Artificial muscles

In the development of synthetic muscle, researchers attempt to replicate the functionality of organic muscles. In general, this consists of “...agonist-antagonist muscle pairs. It is well known that during the contraction of biceps to bend the arm at the elbow, triceps are relaxed, and vice versa. This feature may be used to significantly reduce the de-actuation time of the proposed actuator” (Miriyev, Stack & Lipson, 2017:6). Accordingly, to manage the activation and deactivation of a synthetic muscle, it is often considered as a pair, where the opposing muscles can be used to deactivate each other as required. This type of muscle pairing can be seen in the arrangement of muscles in the synthetic human heart (Figure 2.5), which describes: (a) “Heart with opposing rotation of counter clockwise at apex and clockwise at the base, (b) Sub-epicardial and sub-endocardial fibres are arranged in opposing helices” (Roche, Wohlfarth, Overvelde, Vasilyev, Pigula, Mooney, Bertoldi & Walsh, 2014:5).

Images of the physical prototype are shown in Figure 2.5: (c) at various pressure increments, displaying how the synthetic heart is designed to contract (Roche et al., 2014:5). In this case, the artificial pneumatic muscles are moulded into the outer wall of the heart in a helical arrangement. When air pressure is supplied to the individual muscles, they expand and cause overall contraction to occur. This example demonstrates how the integration of soft actuators into the main soft body, in this case, pneumatically driven, can be used to drive a shape change and thereby replicate the pumping action of an organic system, like the human heart. The muscle material for the body and general principles are relatively simple and yet they can be used to create a complex arrangement.

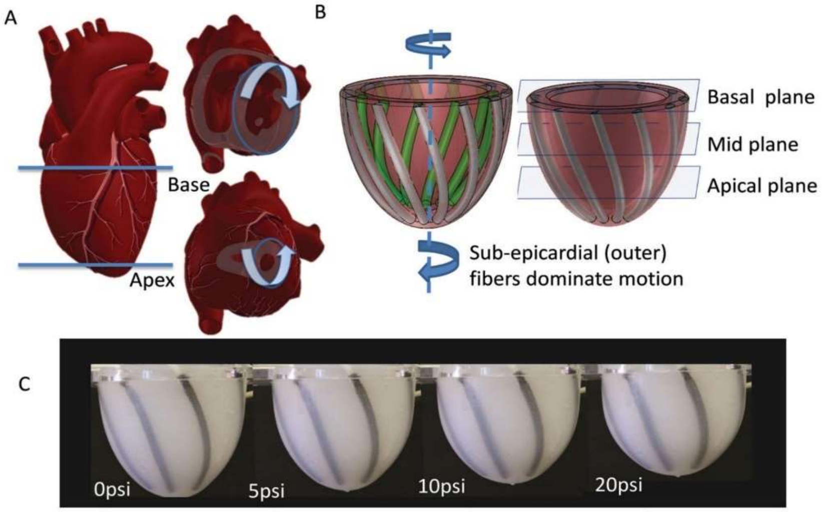


Figure 2.5: Artificial heart (Roche et al., 2014:5)

This artificial heart is comprised of linear contractile elements (pneumatic-driven bladders in braided sheaths) completely embedded in an elastomeric rubber matrix (Roche et al., 2014:5). Although it is integrated here for a specific purpose to follow desired geometry, this has inherent properties that would allow it to be adapted to suit many other applications. By changing the properties of the rubber matrix, the number and spacing of actuators, it is possible to fine tune the overall action and motion of the system (Roche et al., 2014:6). In “c” of Figure 2.5, it is shown how a change in air pressure can be used to alter the shape/morphology, but this can also be fine-tuned through adjusting the size and shape of the artificial muscles and overall matrix. In this way such soft solutions are very flexible in their design, as they can be refined through iteration until the overall movement action meets the exact desired requirements.

In order to closely replicate organic tissue and muscle, researchers assess properties of such materials. The soft rubber-like flexible materials used in the creation of these synthetic systems have a modulus on the order of 125 kPa, which is a close match to that of biological tissue. This ensures that the synthetic replica is inherently safer for interfacing with people (Roche et al., 2014:6). In this way too, the synthetic muscle resembles, as closely as possible, the feel and function of the organic muscle.

Researchers understand that organic muscles embody desirable properties such as a “high contraction ratio, they are energy efficient, they are intrinsically compliant, and their stiffness can be varied smoothly and dynamically” (Pfeifer et al., 2012:82). It is for these reasons that many robotics engineers have sought to develop bio-inspired robots and attempted to replicate natural movement and muscle function.

2.5 Bio-inspired soft robots

Many cases of soft robotics development involve replicating the movement of the human hand or that of an octopus tentacle, as these provide small-scale, real-world examples that can be simulated in a controlled environment. The mechanisms used vary from wired limbs that are driven by pneumatics, to artificial muscles of electroactive polymer (EAP). EAPs are soft, smart, electroactive materials that can change state or volume when electrically stimulated. EAPs are able to transfer the volumetric change into energy in the form of expansion or contraction force and so have great potential for use in artificial muscles design (Rossiter et al., 2016:18).

One of the most challenging tasks in soft robotics is to develop soft robots able to exert effective forces that can be controlled. “In recent years, biology has inspired several solutions to such complex problems” (Calisti et al., 2011:2). Whereas with rigid robotics, the motion can be limited to the degrees of freedom allowed between joints, in soft robots there is often no structure that can set this. So, the natural ability of the material and soft muscles to flex makes it difficult to finely control such robots.

There is a good understanding of this limitation, so that such complex robots more often than not include some internal support structure similar to a spine. “The following generation of robots are classified as continuum robots, able to bend constantly along their length and to produce smooth curves; they show no rigid links or evident rotational joints. A further step is an innovative generation of robots widening and completing the skills of continuum robots: the soft robots" (Calisti et al., 2011:2; Zhong, Hu & Xu, 2020). Such development is being actively driven for use in minimally invasive surgeries.

Progress in bio-inspired robotics can only occur when various components are integrated and operate seamlessly to yield the desired result. These components include computation, sensors, actuators and appropriate materials (Pfeifer et al., 2012:76). It could be argued that this is application specific. However, the complex nature of such systems is undeniable. To effectively achieve this, bio-inspired soft robots will require the development of complex control systems for detailed manipulation and safe interaction with humans (Pfeifer et al., 2012:76). A new way of thinking is required to make such soft robots feasible for mass production, and cutting-edge manufacturing technologies such as additive manufacturing might play a role in their commercial realisation.

The goal of using biological inspiration is to understand the underlying principles of human and animal behaviour and transfer these to the development of the robots. (Pfeifer et al., 2012:77). Changes in stiffness during motion is not possible with conventional robotics but can be achieved in soft robotics through the combination and control of material properties, actuation and morphology design. By understanding the intended action or motion, the overall shape and material properties are adjusted to suit the need, i.e., form follows function (Pfeifer et al., 2012:77).

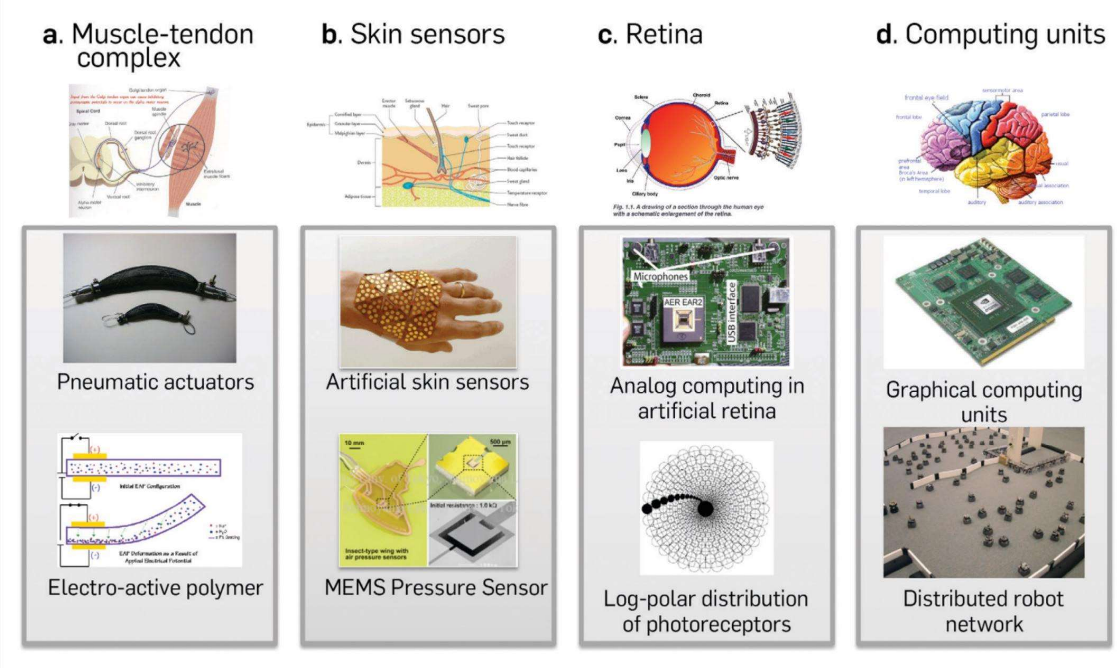


Figure 2.6: Bio-inspiration and enabling technologies (Pfeifer et al., 2012:81)

In Figure 2.6, various SRTs are shown, from pneumatic actuators to soft skin sensors. By mimicking the function of the organic inspiration, researchers are developing technologies that not only have desirable properties for simpler soft robots, but for other more complex robotics applications as well. For example, inspiration derived from biology and self-organising units can advance the design of autonomous robots greatly (Pfeifer, Lungarella & Iida, 2007:1088).

Taking concepts from the biological world and transferring them to the development of robotics, which may ensure at least "some of the desirable properties of the biological organisms, such as adaptivity, robustness, versatility, and agility" (Pfeifer et al., 2007:1088), will be present in these robots.

2.6 A comparison of various octopus bio-inspired soft robots

Some examples of complex arrangements of organic muscles include "the arms of octopuses, the arms and tentacles of squid, many tongues, the elephant trunk and a variety of invertebrate structures", which support tissue to allow for the required functionality and control (Trivedi et al., 2008:102).

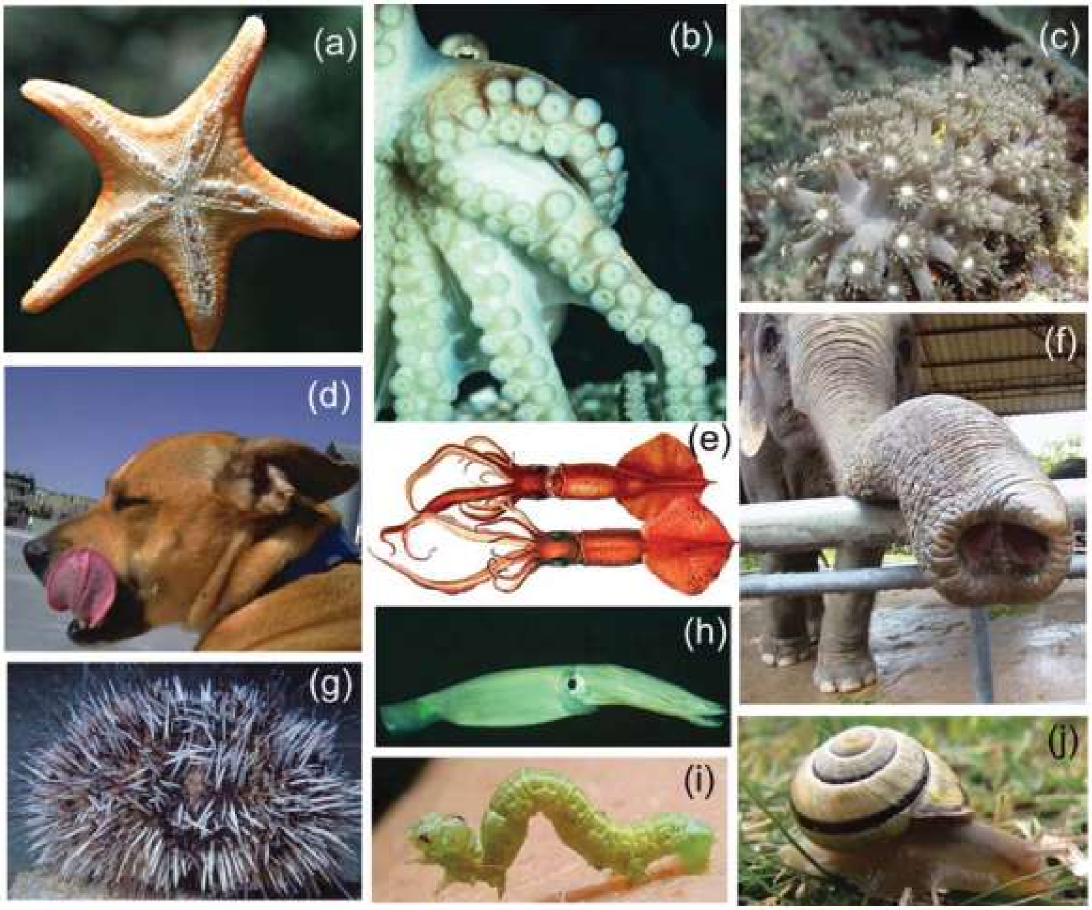


Figure 2.7: Bio-inspiration and enabling technologies (Trivedi et al., 2008:102)

See Figure 2.7 showing complex arrangements of organic muscles known as muscular hydrostats: (a) tube feet in starfish, (b) octopus' tentacles, (c) colonial anemone, (d) mammalian tongue, (e) squid, (f) elephant trunk, (g) echinoid, (h) squid, (i) inchworm, and (j) snail feet. (Trivedi et al., 2008:102).

An octopus tentacle (b), and the various soft robots developed to mimic the octopus tentacle will be discussed in the subsequent section. There are a number of octopus-inspired robots that have been developed using the broad concept of "compartmentalised deformation to produce limbed locomotion" (Kim et al., 2013:291). The following section will look at some of the most prominent examples and assess how SRTs were used to control the arm movement and overall actuation.

The researcher has chosen this example for comparison, as the "…octopus" arm (tentacle) presents peculiar features, like the capability of bending in all directions, of producing fast elongations, and of varying the stiffness" (Laschi, Mazzolai, Cianchetti, Mattoli, Bassi-Luciani & Dario, 2009:2). In terms of SRTs this will give a good baseline for what has been tested and which attempts have been the most successful.

In the case of the movement in the octopus tentacle, the embodied intelligence in the tentacle allows for autonomous movement and deformation without the need for conscious control (Calisti et al., 2011:3). Embodied intelligence here allows the octopus tentacle to change shape and react based on the direct reaction of sensors along the arm. By incorporating this action of adaptability into the arm itself, the octopus is able to conform to the surrounding surface automatically. This is a complex interaction between sensors and muscles, and so all attempts to mimic the octopus tentacle have been far more simplistic. In most cases it has been an attempt to drive the overall shape and dexterity of the arm with the ability to coil around an object in a gripping action.

In the first example of a robotic octopus tentacle (Figure 2.8), the researchers used a cable to control the overall shape of the tentacle and allow for it to wrap around and grip objects. This action was not easily controlled, as the accuracy level was low. An additional flexible steel cable allows for the tentacle to shorten or extend in length. An additional nylon cable increases the bending and grasping capabilities, this is all encased in a soft silicone cone (Calisti et al., 2011:9). In this case, the arm morphology is controlled by pulling central cables to actuate the shape change. Fine control of the arm is not possible, as the number of actuators is few, and distribute the shape change across the length of the tentacle. Simply speaking, this method of manipulation or actuation is not intended to allow for focused and controlled deformation at one point. This arm shown in Figure 2.8, demonstrates the issues of finer control and grasping strength. The central cables drive the arm’s contraction, and although simple to operate, they do not allow for fine motor control. In the living octopus, this ability to manipulate the tentacle with a high degree of control is thanks to the hydrostatic characteristics of the muscles that are arranged all along the tentacle (Laschi et al., 2009:2).

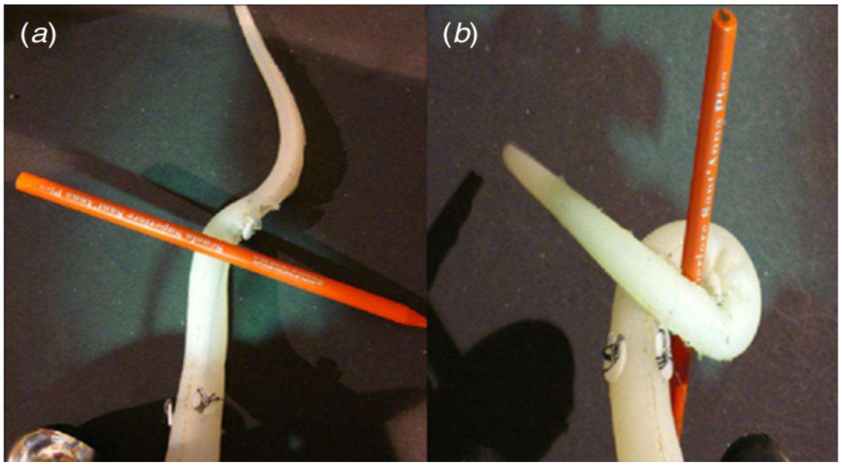


Figure 2.8: Octopus tentacle (Calisti et al., 2011:10)

Whereas this type of application, where pull wires are embedded within a soft casing, has limitations in terms of fine motor control, there are certainly applications where more subtle "contraction" could be achieved by embedding a lattice of wires into a more complex soft structure to achieve compression, squeezing or other similar actions.

In another example, researchers designed a robot arm that was "…completely soft and compliant, composed of muscles that can contract and that are arranged according to the geometry of the octopus tentacle, so as to reproduce the tentacle motor performance" (Laschi et al., 2009:2). For the muscle actuators they chose "…an electro-active polymer (EAP), based on dielectric elastomers because it allows one to achieve, in theory, the performances required in terms of force and power density even if lower than other non-polymeric actuators" (Laschi et al., 2009:3). To understand the potential for such EAP actuators to be used and achieve an effective result that mimics that actual movement, a basic understanding of the octopus tentacle muscle arrangement is required.

The muscle action of an octopus tentacle can be described as follows: "…activating the longitudinal and transverse muscle fibres along the length and around the circumference of the arm causes the arm to bend in complex shapes. Activation of the CW and CCW oblique muscle fibre layers twists the arm in the CCW and CW directions, respectively. This complex structure of soft active material and connective tissue can produce large and convoluted extension, bending and twisting motions" (Trivedi et al., 2008:103).

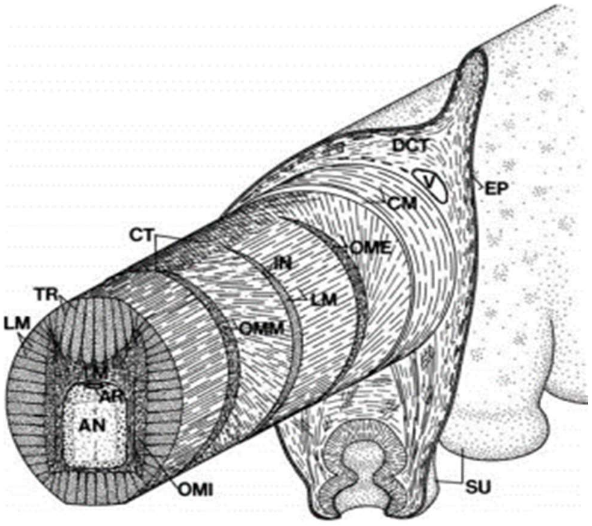


Figure 2.9: Octopus tentacle muscular structure (Trivedi et al., 2008:103)

“Diagram of the arm of an octopus, showing the three-dimensional arrangement of muscle fibres and connective tissue fibres. AN, axial nerve cord; AR, artery; CM, circumferential muscle layer; CT, connective tissue; DCT, dermal connective tissue; EP, epidermis; IN, intramuscular nerve; LM, longitudinal muscle fibres; OME; external oblique muscle layer; OMI, internal oblique muscle layer; OMM, median oblique muscle layer; SU, sucker; TM, transverse muscle fibres; TR, trabeculae; and V, vein” (Trivedi et al., 2008:103).

Here it can be clearly seen why organic muscle fibre is viewed as the benchmark for soft actuator development. Not only does it allow for quick movements with considerable force, but the way in which the tentacle is able to move with the DOF makes this complex arrangement functional and useful. (Roche et al., 2014:1).

In order to properly replicate such a complex arrangement of muscles, one would need to replicate a similar arrangement with synthetic muscle or actuators. Some interesting relationships can be seen in the way in which the arm is able to move, due to the specific arrangement of muscles along the length and around the circumference of the tentacle, which does allow for certain coordinated movements to be more natural than others due to some movement constraints that present when the tentacle “folds”. Such constrained movement effected through the design of the segments, may allow for precise point-to-point movements (Trivedi et al., 2008:109). In principle, this leads design towards a semi-rigid support structure on which the artificial muscles can be applied and reduces the overall degrees of freedom (DOF) of the robot to simplify the means of control.

In the case of EAPs, by selectively arranging synthetic actuators, a range of motions can be achieved quite easily (Roche et al., 2014:1). This has great potential to simulate the normal motion of animals and people (Roche et al., 2014:1). Thus, an extraordinarily complex set of motions could be programmed and managed through the stimulation of artificial muscles. The arrangement of EAP muscles in such a way, where the biological arrangement is replicated to some degree, could further allow for the focused control and desired actuation of a soft robot tentacle.

2.7 Shape memory alloys

Another area of SRT research is the use of shape memory alloys (SMAs) that make it possible to build robots that are lightweight, small, quiet, have no motor, no gears and no joints (Hernan & Cuellar, 2015:3). These materials are usually used in the wire form and have the ability to return to a predetermined shape after deformation caused through the application of heat (Hernan & Cuellar, 2015:50). These wires are most commonly referred to as NiTi wires.

Although low in cost, the lengthy time it takes to cool the wire limits the speed at which the actuator can operate. NiTi wires commonly have the following characteristics: a diameter of 127µm, require an electrical current input of approximately 320mA, when heat is applied will contract in about 1s and will return to original shape while cooling in 1.4s. This gives a cycle time between heating and cooling of 2.4s which is quite slow (Hernan & Cuellar, 2015:52). Even though there are functional limitations, SMAs are used extensively in robotics design, including in micro robots. (Hernan & Cuellar, 2015:54). It is for this widespread use that they are included in the body of research, and form part of the SRT assessment and comparison.

The following “Octopus Project” demonstrates how SMAs were used to drive the actuation of a tentacle structure. Figures 2.10 and 2.11 show the overall structure, which consists of an external plastic braid that provides some mechanical structure to the arm. An internal spine allows for support segments to be fitted to add additional shape control to the structure. Also shown in Figure 2.11 are the SMA springs that can expand or contract to effect local changes to the diameter (Kim et al., 2013:291). By supplying current to the SMA wires it is possible to change the shape and so control deformation and movement of the arm. The soft actuators, SMA springs, are arranged so that the operator can individually control these local deformations, and so change the shape of the tentacle at all points along its length.

Figure 2.10: Octopus project SMA tentacle (Laschi et al., 2014)

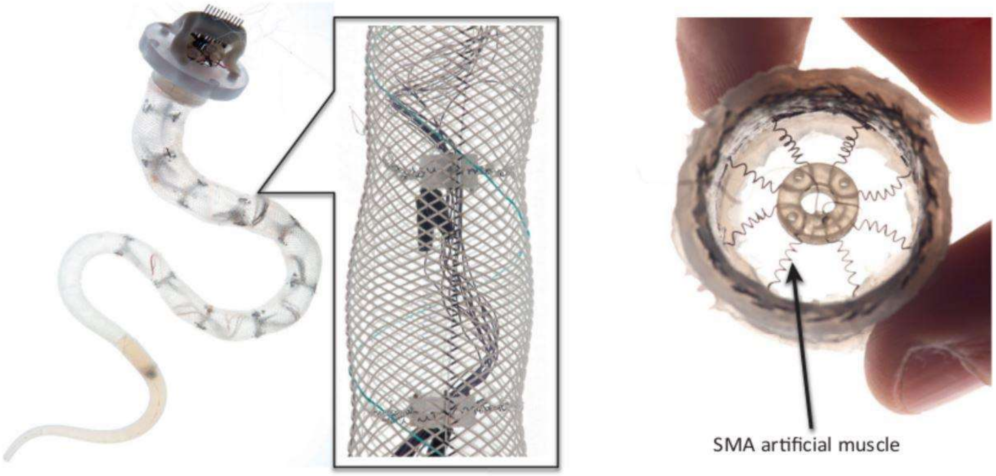


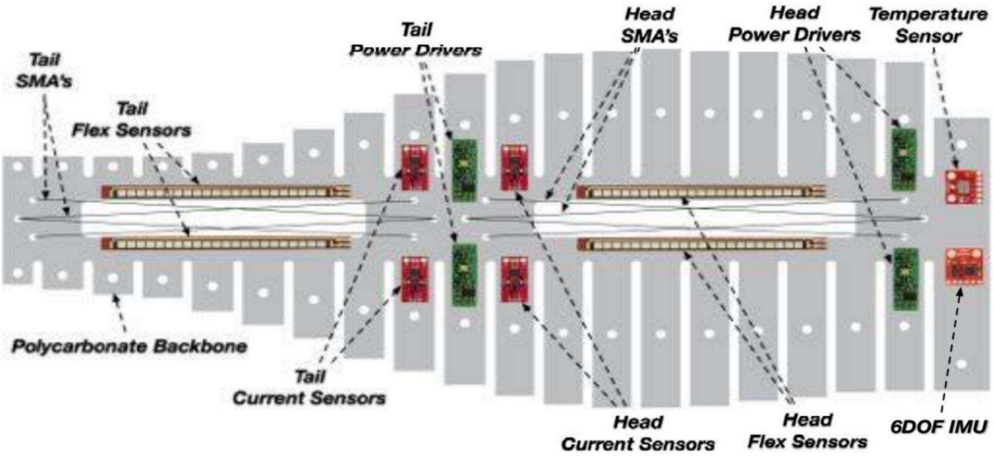
Figure 2.11: Octopus tentacle - SMA actuators (Kim et al., 2013:291)

Although this type of actuator is easy to integrate, the "…force generation in SMAs depends on temperature change, so robust temperature control in various thermal conditions is a challenge" (Kim et al., 2013:292). As the environment cannot be easily controlled outside of a laboratory, real-world mass implementation of this technology in large robots, seems unlikely. However, for small scale applications, there is certainly potential where the SMA can be enclosed and thereby insulated from major temperature changes.

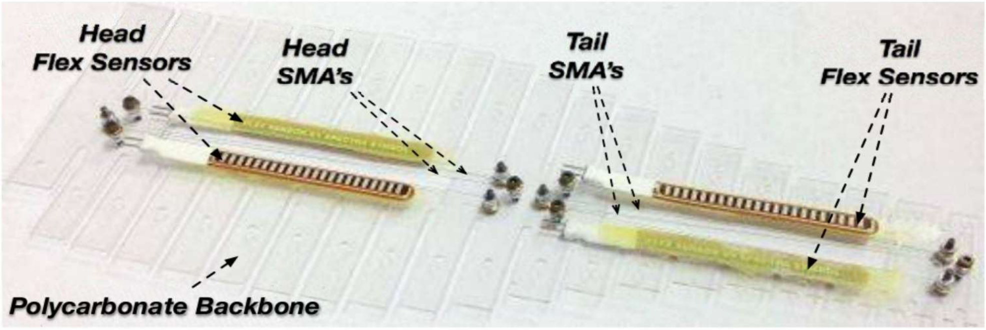
Another drawback of SMAs is that energy efficiency is extremely poor (approximately 1 per cent), so 99 per cent of the input energy is lost. Also, the repeated heating and cooling of the wire causes it to degrade, resulting in part breakage and failure (Kim et al., 2013:292). Therefore, it follows that for effective use in mass-production of consumer goods, these issues would need to be resolved.

In a project to replicate the swimming motion of a fish, see Figures 2.12 and 2.13, the researchers used SMAs to cause the bending of a flexible structure and so mimic the various swimming actions of a fish (Hernan & Cuellar, 2015:4). SMAs were used here due to their low cost and low current/voltage requirements to function (Hernan & Cuellar, 2015:31). This allows for the reduction in size, weight and complexity of the robotic systems. It is the view of Hernan and Cuellar that this technology is well suited for developing devices that require actuation, in a new way. As with the case of the octopus tentacle, the outcomes of this research ring-fenced the technology for use in rather specific applications.

As seen in Figure 2.12, the robot fish functions as follows: the main structure is a single flexible sheet that has vertical cuts to create segments that allow flex of the overall structure. SMA wire is then attached to either side of the sheet in length, so that they can be made to flex towards either side. This is subsequently timed in such a way as to create a wave action, where the structure is flexed in a sequence to ultimately drive the soft robot forward in water in a natural way, as referenced in Figure 2.13 (Hernan & Cuellar, 2015:110).



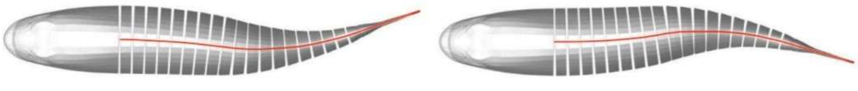
(a) Backbone and electronic components



(b) Backbone with attached flex sensors

Figure 2.12: Fish robot with SMAs to drive motion (Hernan & Cuellar, 2015:110)

(a) Thunniform Up (b) Thunniform Down



(c) Caranguiform Up (d) Caranguiform Down

(e) Subcaranguiform Up (f) Subcaranguiform Down

Figure 2.13: Fish robot swim patterns (Hernan & Cuellar, 2015:110)

On the whole, it was found that combining the effect and properties of the materials being used together with the SMAs provided a system that allowed for the most efficient application of SMAs (Hernan & Cuellar, 2015:49). This involved complex mechatronic design and applications where repetitive and minimal range of movement is desired. SMAs may be a good solution for applications where a wave pattern or linear drive is required, and the repetition is smooth and slow.

Another example of where SMAs were tested is the soft robotic worm, where the worm moved by means of a rolling action. An SMA is incorporated inside a moulded elastic rubber body. When the SMA is activated by electric current, it contracts, causing the worm to change shape and roll forward. When current is removed from the SMA, it cools and the stored elastic energy in the rubber body aids in flexing the worm open into the original shape (Kim et al., 2013:290). Although this is certainly an example of simplistic actuation using SMA, the lack of control and potential for randomised motion, does not make this application ideal.

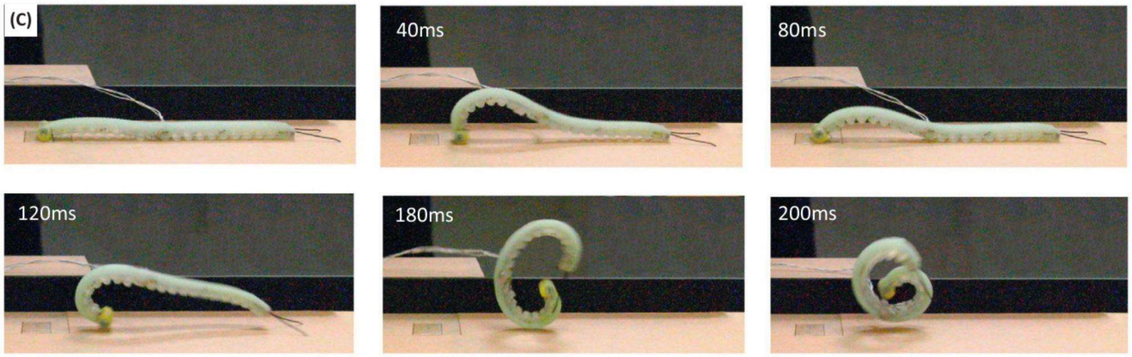


Figure 2.14: Soft robotic worm with SMA actuators (Kim et al., 2013:290)

The idea of combining actuation within an elastic body does have potential and is worth considering for further investigation. If one considers this worm design then as an element in a larger system, in the same way that the segments along the fish body work together in a system to drive motion, it is clear that combining two elements with flexion and contraction properties makes sense. It would be interesting to explore how a lattice of these worms might work together in a coordinated way. This may then be viewed as a study of an SMA composite artificial muscle, more than merely a robotic worm that moves in an interesting way.

Figure 2.15: Elephant trunk robot incorporating SMA (Trivedi et al., 2008:104)

Figure 2.15 depicts an elephant trunk structure with an articulated skeleton and SMA actuators around each segment. This example shows how SMAs can be further integrated into complex structures where multiple points of control are provided. However, the lack of efficiency and requirement for environmental control make this sort of application in the real-world unlikely, as was shown in the previous examples.

2.7.1 Benefit of SMAs

Size and weight: SMAs are well suited for use as linear actuators, in applications that require small robotic devices, are lightweight and have a negligible volume allowing for extremely light robots to be produced.

Noise-free operation: SMAs do not produce dust particles or sparks during use and make no sound. This makes them well suited for use in microelectronics and where biomimicry is desired.

Sensing properties: SMAs also have sensing capabilities and so can function as part of a larger sensory network built into the robotic system (Hernan & Cuellar, 2015:68).

2.7.2 Drawbacks of SMAs

Slow speed: Due to the inherent thermal hysteresis (shape memory at different temperatures), SMA actuators are considered to be slow actuators, and so are better suited to applications that do not require a quick action or motion.

Fatigue: SMAs can degrade over time as a result of the continued change in shape and temperature. This can lead to total part failure.

Low energy efficiency: The energy efficiency of SMAs is extremely low, only 1 per cent is converted into mechanical energy as most of the energy is lost as radiant heat. (Hernan & Cuellar, 2015:68).

2.8 Electro-active polymers

EAPs have been the focus of research and development for over a century. However, the technology is only now becoming viable for commercial applications. Organisations such as NDEAA and even NASA have been working on applications for EAPs with a view to using them as artificial muscles in robotics and space applications (Bar-Cohen, 2017). This research has typically been focused on high-end applications. However, soft robots can be manufactured inexpensively using EAPs, and so facilitate access to the mass market through affordability. This could broaden the general impact of robotics as a result (Rossiter et al., 2016:19). Therefore, once proven and refined, these technologies may be adapted for use elsewhere.

Figure 2.16: FESTO manta ray (FESTO, 2017)

Companies such as Boston Dynamics (2017) and Festo (2017) have done extensive research and development of robots by making use of EAP muscles. With the floating inflatables by Festo being excellent examples of how the natural movement of fish such as the manta ray (Figures 2.16 and 2.17) can be reproduced and used to move the floating “robot manta ray” through the air.

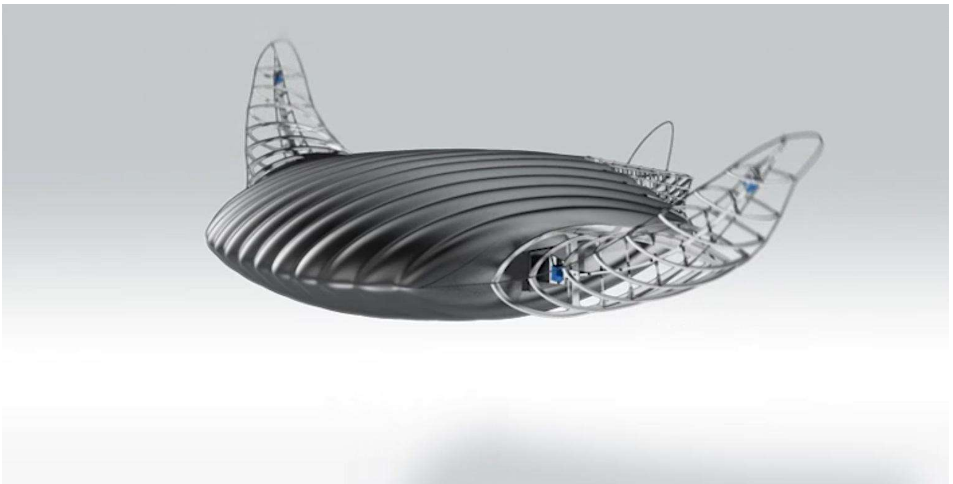


Figure 2.17: FESTO manta ray in flight (FESTO, 2017)

An example of a layered EAP muscle presented in Figure 2.18, has a specific folded geometry that allows for increased contraction range and greater resultant force of the artificial muscle (Laschi et al., 2009:4). By layering the EAP material with a gold conductive layer, it was possible to create a relatively strong and simplistic actuator.

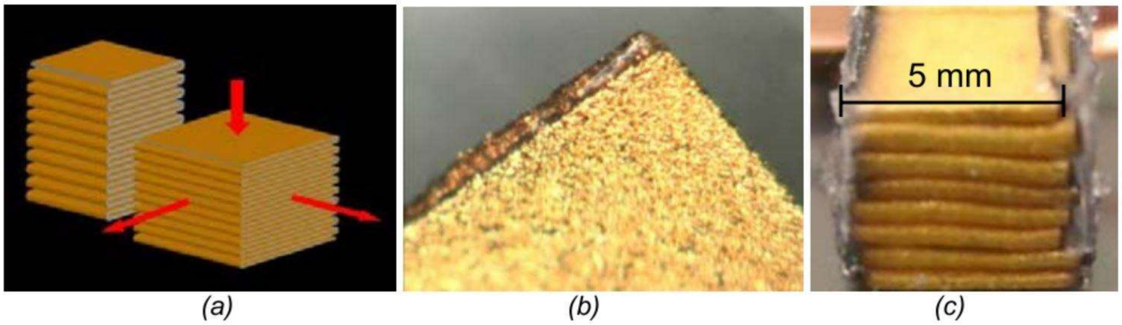


Figure 2.18: Layered EAP muscle geometry (Laschi et al., 2009:5)

Apart from the standard EAP materials being developed, which respond to electric stimulus, there are materials which change phase during activation which allows for additional properties and certain desirable actions. These are referred to as “phase change EAPs” and make use of the energy created when a liquid changes phase into a gas and visa-versa (Miriyev et al., 2017:2). As these are more complex and involve control of the environment around and within the EAP, they will not be investigated further in this study. However, it should be noted that this technology was shown to have a large area of expansion within the EAP, and so has a high return on energy transferred into the system. Such devices are challenging to manufacture as it is difficult to directly cast or 3D-print this technology. It is, however, a valid area of SRT study worth exploring further (Miriyev et al., 2017:2).

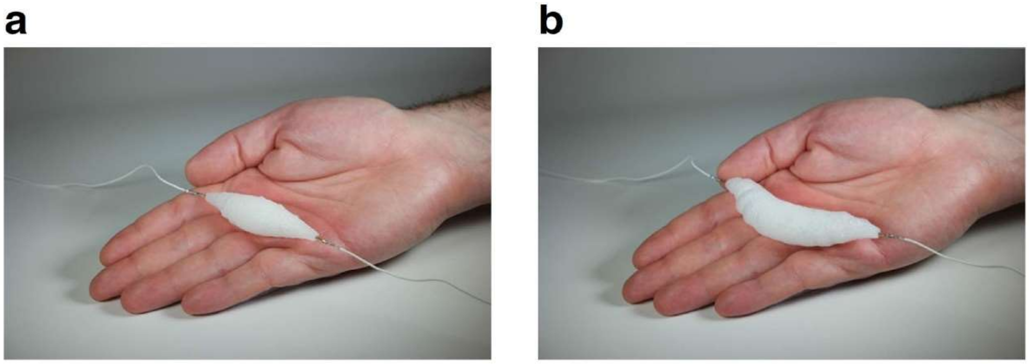


Figure 2.19: Soft artificial muscle (Miriyev et al., 2017:1)

As seen in Figure 2.19, the ideal form of an EAP is one that is able to function similarly to natural muscle and change volume or shape through simple electrical stimulation. (Miriyev et al., 2017:1). It is the high resultant force for the minimum amount of electrical current that is required to make EAPs a more applicable technology. The on-going research and development in this area and ease of integration makes this one of the most attractive solutions in soft robotics actuation. One of the greatest challenges for soft robotics engineers has been the lack of strong, soft actuators that are easy to manufacture for customised designs and can be stimulated by simple electric current to change forms (Miriyev et al., 2017:2).

In Figure 2.19, the sample tested was a soft silicone elastomer with micro-bubbles of ethanol distributed through the matrix (Miriyev et al., 2017:2). The passing of electric current through the polymer causes the ethanol bubbles to expand and thereby increases the overall volume of the artificial muscle. It is possible to produce significant forces in this way. The ethanol-infused silicone is in principle simple to produce and mould to a desired shape, so this type of EAP is of particular interest to this study.

It is generally understood that soft robotics actuation is based on either EAPs, SMAs, pneumatics (compressed air) or hydraulics (pressurised fluid) (Miriyev et al., 2017:2). However, it is possible to combine these technologies to form hybrids, for example, to use the McKibben-type artificial muscle as shown in Figure 2.20, in combination with an EAP to fill the interior void instead of relying on hydraulic or pneumatic pressure.

Here it can clearly be seen that as the volume is increased, the limitation constraints of the exterior braid cause the two ends to contract. This type of application has been tested broadly in many studies using fluids or air to drive this motion. The potential for a simpler solution making use of an EAP inside a braided sheath to drive the kinematic motion is clear and has many potential benefits, such as omitting the need for external motors or pumps, omitting the need for complex control of fluid/air pressure and ultimately allowing for more discrete integration into a robot or device.

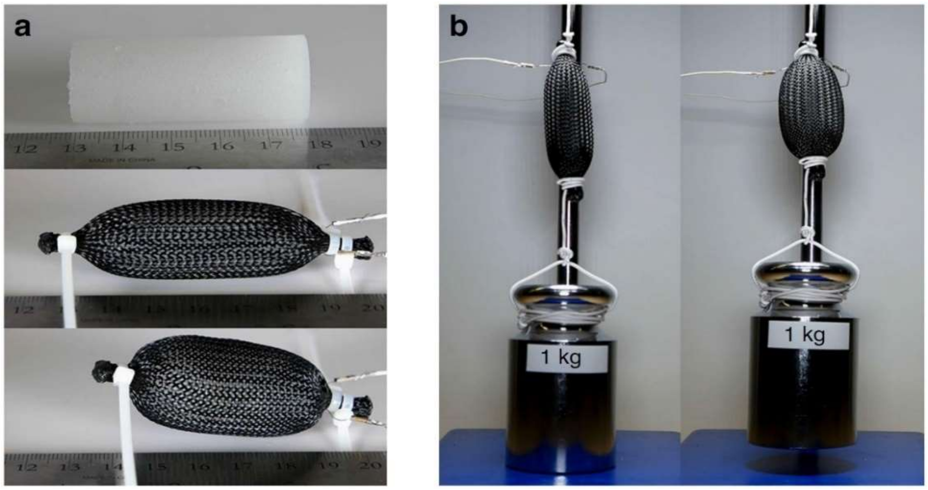


Figure 2.20: McKibben-type artificial muscle (Miriyev et al., 2017:5)

If we assume that such EAP materials will function as demonstrated in Figure 2.19, then it is certainly a feasible SRT for use in actuation, as the EAP material can be cast or 3D printed easily, making mass production of these synthetic muscles viable (Miriyev et al., 2017:2).

As shown by Miriyev in Figure 2.20(a), the artificial muscle can be electrically actuated using a thin resistive wire plus low power to cause significant expansion/contraction and has the ability to repeatedly lift the weight (Miriyev et al., 2017:2). This demonstrates the capacity of the artificial muscle based on EAPs to replace conventional motor-driven actuators in robots (Miriyev et al., 2017:4). This is an excellent example of what EAP muscles could become and their potential for use in robotics and other design as an alternative source of actuation. EAPs can easily be integrated into the manufacture of soft products through a multi-stage moulding process, or through additive manufacturing as will be demonstrated further in this research study (Roche et al., 2014:1).

2.9 Pneumatic artificial muscle

A pneumatic artificial muscle is powered by air pressure. The contractible actuator consists of an internal bladder surrounded by a braided mesh, under pressure the expanding bladder causes the actuator to shorten and stiffen (Pfeifer et al., 2012:82). Although simple to fabricate, this form of muscle requires pneumatic pumps or motors to drive the flow of air and regulate pressure. These are generally referred to as the McKibben actuators as previously described and can be seen in a more complex arrangement in the OctArm in Figure 2.21. McKibben-type actuators can be made to produce extreme force and lift heavy loads, but require high power and large, complex air/fluid supply and control (Kim et al., 2013:292). It is for this reason that they are better suited for use in industrial applications. Although useful in certain industrial applications, they are not well suited for use in soft robotics due to the requirement for the additional mechanisms needed to drive the flow of air/fluid. These mechanisms are large, heavy and restrict movement (Trivedi et al., 2008:108).

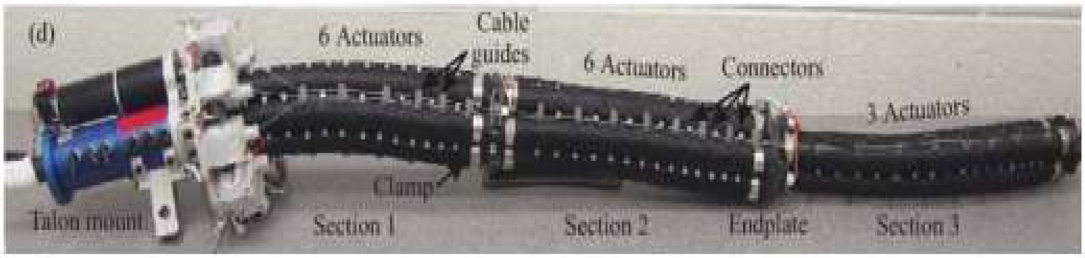


Figure 2.21: OctArm VI (Trivedi et al., 2008:107)

As shown in Figure 2.22, the OctArm can be manipulated to high precision due to the arrangement of six artificial muscles at each of the three segments. The segments can bend on two axes and extend in length (Trivedi et al., 2008:107). This allows for dextrous control, but also requires complex and bulky mechanics to move and operate the arm. This is therefore not a viable solution to incorporate into medical products to drive motion, since weight and scale are critical factors in the design.

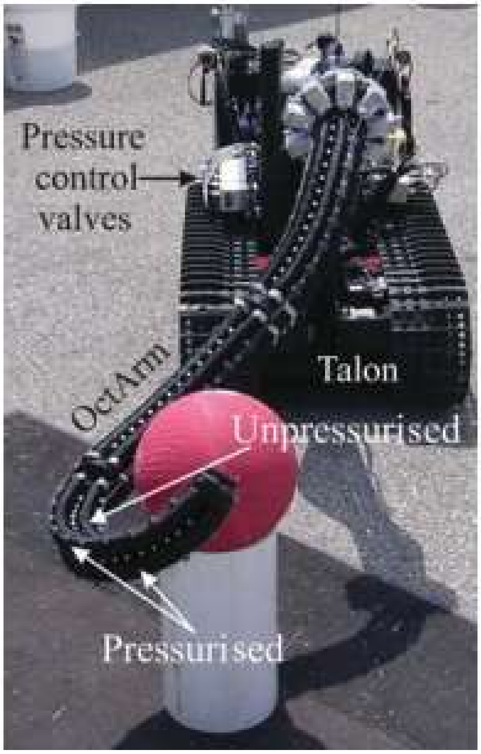


Figure 2.22: OctArm VI (Trivedi et al., 2008:108)

In addition to the conventional McKibben-type pneumatic actuator, there has been extensive research on smaller soft robots that make use of regulated air pressure to cause a shape change to the rubber or silicone matrix that embodies the robot. These, have in general been designed to include single or interconnected voids within the soft robot, which are filled with air, causing the robot to deform as pressure increases.

This morphological change can be used to simulate many actions, such as a caterpillar crawling, or similar. An example is the caterpillar robot where pneumatic pressure is used to drive a shape change in the silicone robot (Kim et al., 2013:291). Using this method of moulding the soft robot structure to include a network of air cavities, it is possible to design soft robots with detailed levels of control and pre-determined deformation patterns (Kim et al., 2013:291). However, this form of artificial muscle still requires an external source of pressurised air and means of controlling the air flow, so again it becomes more complicated to integrate into a lightweight product where weight and size are important factors.

2.10 Elastomeric electrodes and electronics

Another area within soft robotics that has direct impact on the flexibility and control of the robot is the conduction of electricity via flexible electrodes. There are various elastomeric electrodes under development with the main focus of having a fully integrated network of electrodes that are able to flex and stretch as the soft robot changes shape. This also allows for the development of flexible circuit boards and reduces the number of rigid parts and connections within the robot that might restrict free movement or a desired action. One example of a soft robot makes use of such “dielectric elastomers” and incorporates them inside a silicone skin to allow the soft robot to move in worm-like action (Kim et al., 2013:287). As this area of soft robotics, termed “flexible electronics”, is vast and exhibits continuous innovation, the current status will be considered feasible with the understanding that improvements to the technology are ongoing. It can be noted that once artificial muscles are developed to the point where fabrication can be done cheaply, at high speed and with the integration of flexible electrical circuits and electronics, soft robotics design will be virtually unlimited to experiment with shape, movement, function and reducing size.

2.11 Soft sensors

In addition to artificial muscles and flexible electronics, soft sensors are being developed that are able to flex and deform. This too is a vital part of soft robotics innovation, “…because of the central importance of tactile sensing for learning, manipulation, and tool use, improvements in skin technology are likely to lead to a quantum leap in soft robotics” (Pfeifer et al., 2012:82). The ability to integrate multiple sensors into a soft robot, allows for the increase in the robots’ complexity of movement and function. Current developments in robotics aim to equip robots further by integrating sensors into pressure-sensitive artificial skins. These sensors can be force sensitive, pressure sensitive and temperature sensitive among others (Pfeifer et al., 2012:81). The advances in sensor function, flexibility and reduction in size are allowing for ever more complex soft robots to be developed, with the potential for the medical industry, among others, being immense.

As an example, simulating pressure sensors in the skin on the fingertips as shown previously in Figure 2.6(b) is done using force-sensitive resistors built into the flexible fabric. The sensors' function is not impeded when the flexible fabric is deformed (Pfeifer et al., 2012:82). The ability to have localised sensors within a robot or device and to programme the robot to react when sensors are triggered, will allow for not only intuitive-type robots to be developed, but also devices that adjust as the environment changes.

In this way, it is possible to imagine wearable devices that adapt to changes in the human body and provide a desired action or function, whether it be the application of pressure, pulsation, vibration or similar. This would allow for intelligent devices to be developed, for example, which respond as needed in real time to assist patients or the elderly. Again, as this is a broad area of development, and there are working solutions available, it will be regarded as a feasible technology and not expanded on further here.

2.12 Soft robotics toolkit

A study was done at Harvard University which sought to create a soft robotics toolkit (Holland et al., 2014). This was conducted with students from science and engineering and the requirement was to develop a range of functional medical devices. The aim was to compile a basic toolkit from these devices that could then be used in other ways. The results of these test projects were then uploaded to a website and the Soft Robotics Toolkit was expanded from there. The current database is a good overview of what has been achieved in SRT and covers not only the actuators but also the controls and sensors required in robotics. This database has been built up, by and for, robotics engineers, to use freely and encourage further development. However, it is driven from the viewpoint of soft robotics and so the applications do not drive innovative product design, but rather innovative functional robotics design (Holland et al., 2014).

2.13 Soft robotics applications

There are many examples of soft robotics applications, where rigid alternatives would not be appropriate. A large portion of these is within the group termed "grippers" where a mechanical arm is fitted with a flexible gripper. Companies like Soft Robotics Inc. in the USA manufacture such grippers for use in the food handling and pick-and-pack industries. Figure 2.23 shows an example of a soft gripper that is able to hold a fragile item, in this example, an egg, and lift and replace the item on a surface (Miriyev et al., 2017:4).

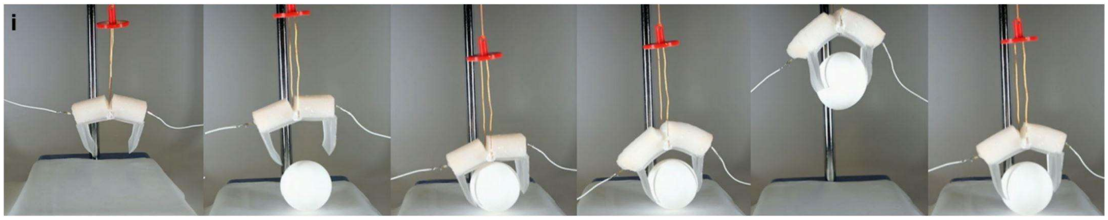


Figure 2.23: Soft gripper (Miriyev et al., 2017:5)

It is easy to see the value in a gripper that would be able to handle fragile items, and so it is plausible that there are applications for soft robotics that conventional rigid solutions on their own fail to satisfy. To put this in perspective, Table 2.1 helps to show the overall differences between rigid and soft robots in general terms.

Table 2.1: Comparison of rigid robotics technologies and SRTs (Trivedi et al., 2008:100)

Properties	Rigid	Discrete hyper-redundant	Hard Continuum	Soft
Degrees of freedom	Few	Large	Infinite	Infinite
Actuators	Few, Discrete	Many, Discrete	Continuous	Continuous
Material strain	None	None	Small	Large
Materials	Metals, plastics	Metals, plastics	Shape memory alloys	Rubbers, Electro-active polymers
Capabilities				
Accuracy	Very high	High	High	Low
Load capacity	High	Lower	Lower	Lowest
Safety	Dangerous	Dangerous	Dangerous	Safe
Dexterity	Low	High	High	High
Working environment	Structured only	Structured and unstructured	Structured and unstructured	Structured and unstructured
Manipulable objects	Fixed size	Variable size	Variable size	Variable size
Conformability to obstacles	None	Good	Fair	Highest
Design				
Controllability	Easy	Medium	Difficult	Difficult

Path planning	Easy	Harder	Difficult	Difficult
Position sensing	Easy	Harder	Difficult	Difficult
Inspiration	Mammalian limbs	Snakes, fish		Muscular hydrostats

2.14 Cost and viability

As the focus on SRTs moves from the specialised laboratories and heavily funded companies to the smaller research and development environments, accessibility and cost become necessary factors to consider, and designs are influenced by what is financially viable. This shift in understanding of “what is possible” is inevitable, when the technologies being developed are also commercially viable. So, with the potential of industrialising these technologies, the need for a common understanding and standardisation of SRTs will become necessary. Researchers will need to align their efforts in some way to this overriding aim, to make technologies proven on a small scale, accessible to the world (Laschi et al., 2017:9).

SRTs are, in general, extremely low cost by comparison, easier to manufacture and better for the environment as they require less energy to operate. This allows for the development of new, entirely soft robots to perform tasks that are currently either too costly or can only be managed through manual labour (Miriyev et al., 2017:1). The future could very well include soft robots in many aspects of daily life, where it would be assumed that advanced rigid robots were the inevitable next step.

As the properties and benefits of SRTs are better understood, there is certainly merit for further study and investigation to improve overall efficiency (Miriyev et al., 2017:5). SRTs are ideal for adaptation to replicate biomimetic motions, as they have the ability to bend, twist, extend and flex (Roche et al., 2014:1). This, coupled with commercial viability, makes the opportunity to innovate and engineer in new ways possible.

2.15 Bionics and human augmentation

SRTs that are suitable for adaptation in medical applications are ones which incorporate suitable mimicking of biological movement and efficient application in contextual situations. Where this is done successfully, the soft robot will replicate the form and movement through the use of well-designed structure and morphology and exploit the physical properties of the materials used (Pfeifer et al., 2007:1088).

Through the combination of sensors and actuators, it is possible to not only replicate a natural motion or action, but also support or assist in the performing of such an action when used in a hybrid-type system such as tissue engineering for the medical industry.

Such advanced integration is not hard to imagine, when one compares the use of a mechanical pacemaker to a potentially lifelike artificial heart (Kim et al., 2013:287). The potential for human augmentation, the replacement of organs with synthetic organs and the many ways in which artificial muscles could be used in medical applications within the human body, makes this an exciting area of research. What may seem impossible today, could very well be the inevitable and accepted norm of tomorrow.

2.16 Design for soft robotics

The field of soft robotics has experienced advances that have allowed for simplification and increased functionality. One such advance is referred to as "embodied intelligence" whereby the shape of the soft robot is specifically engineered to drive a certain action or motion and limit others. This shape or morphological design, then requires less complicated means of control and so allows for a simplification of the control system, programming and other systems involved, such as a network of sensors. The use of functional materials or combining different densities of soft materials together, is an example of this, where certain motion or degrees of freedom are controlled by the physical geometry itself (Pfeifer et al., 2012:79).

There are times when the approach using morphological design and material properties is required to develop soft robots that are lighter and less complex to actuate (Pfeifer et al., 2012:79). For example, embedding soft actuators into a silicone sheet will cause the entire sheet to deform resulting in an action on the entire body simply by driving motion in one area. Certain functions of the soft robot can be physically embedded in its structure and the control of the robot is not reliant on the control system but also aided through the material characteristics, properties and geometry.

This can be combined with another characteristic referred to as **“**self-organisation and emergence**”** whereby the soft robot performs the correct motion even though it is not fully controlled through that action. This can be seen in the example of the flying manta robot developed by Festo, see Figure 2.17, which is under-actuated and not fully manipulated during the flying action. The wings self-organise into the proper movement and the resultant action is fluid and natural (Pfeifer et al., 2012:84). This morphological change in soft robotics has been coined as the term “morpho-functional machines” to describe devices that can change their functionality not only by a change in actuator control but by modifying their base structure and form as well (Pfeifer et al., 2007:1092).

When designing soft robots, one must consider that the item being designed is going to be set in motion, so the structure will adapt or change in the same way an organic or biological example would. This “complex dynamical system” (Pfeifer et al., 2007:1088) is the key aspect and difference between soft robotics and rigid alternatives, where the structure itself can change. In applying this technology to real-world products, it is a factor that must be understood as it could be used as a benefit, to allow for products that adapt to the user and change as required during their use. In the field of medical devices, a range of soft products that are customisable to the patient’s needs and are safe, would certainly be worth investigating and essential to the advancement of assistive and other medical devices. One of the drivers behind the development of these forms of assistive technologies is the belief that individuals should be able to live independently as long as possible. Examples of these include service robots, assistive devices and medical monitoring devices (Pfeifer et al., 2012:86).

It can be understood that in general soft robotics, engineers work at developing better geometries that exploit the innate properties of soft materials (Kim et al., 2013:287). Through experimentation with functional forms and the refinement of the base structure there is the potential to greatly reduce the mechanical and algorithmic complexity commonly associated with robot design (Kim et al., 2013:287).

2.17 Chapter summary

It is widely believed that the robots of the future will have soft bodies and will be capable of safe interaction with humans (Pfeifer et al., 2012:76). The unique characteristics that are found in soft robotics, namely embodied intelligence, self-organisation, soft morphology and materials allow for novel designs to be developed. This requires a new set of design principles to be used when developing soft robots that are useful and functional. In terms of robot design this will help support the move from a hard to a soft engineering approach, which appears from the research covered to be vastly different (Pfeifer et al., 2012:78).

With advances in manufacturing techniques such as additive manufacturing it may be possible to integrate sensors, actuators and conductive networks into a single body through multilayer printing (Pfeifer et al., 2012:83). For the purpose of prototyping and rapid design evolution this will have a major impact on the speed at which this technology becomes proven and accessible.

The development of effective and functional soft robots will allow for safer interactions with humans and other fragile systems, adaptive machines with inherent mechanical intelligence and a broader level of access to such machines due to the reduced cost to manufacture (Kim et al., 2013:293).

In the same way that many organisms incorporate a skeleton or semi-rigid structure, we may see the construction of soft robotics and other soft structures incorporating this in their design. This combination of a partial substructure or internal framework would allow for the use of soft actuators and materials without compromising the need for a stable body that still allows for changes in morphology.

The further development and use of smart and electro-active materials will continue to be of interest to soft robotics researchers and developers. This will be one of the key factors that determines feasibility and the rate at which this technology can be refined and adapted for use elsewhere.

CHAPTER THREE

Research Design and Methodology

3.1 Introduction

This chapter will explain the approach taken for this research and why this was necessary to ensure a clear understanding and investigation of the research problem. By planning the research design effectively, it was possible to follow through with the actual research methodology to get a view of how SRTs are perceived in the design industry through the lens of industrial design.

A thorough review of the current state of SRTs needed to be combined with the requirements of real-world design projects in order to direct the method of exploration and data capture in the most appropriate way. This was used as the base to interact with professionals in the medical design industry and guide further investigation. This staged approach formed the basis for the research design and allowed for a logical and efficient collection of useful, relevant data. Various tools were used in the course of each aspect of this data capture and will be discussed further in this chapter.

3.2 The importance of the research design

3.2.1 Research philosophy: epistemology, axiology and ontology

An appropriate research design was essential to ensure the subjective influence of the researcher was minimised, as design is subjective, and most design problems could be solved in many different ways. Therefore, in order to research and describe appropriate technologies that may be used in the design process, a broad pragmatic view needed to be adopted with the understanding that no single viewpoint can be comprehensive. Pragmatism was used to underpin all stages of the research, and this was key to ensure the research flow was logical, efficient and would provide for sufficient data to evaluate the research question and provide insight.

The epistemological grounding of this research through participatory design helped construct a view that can be perceived and believed by those who read it. All discussions and conclusions are therefore supported by rational, empirical data, with the underpinning that reality is co-constructed, and many role-players' input informed the process of research. The unique ontology of the researcher has been shaped by a deep understanding of the South African context as illustrated in the investigation and design of a low-cost wheelchair for the mass market. Such social-design product development encouraged further research into the application of SRTs in order for a broader base of potential users to benefit from these technological advances.

The research design was planned in such a way as to allow for triangulation and comparison during the evaluation phase. Metadata were collected from the literature review, as well as input from product design experts and medical experts. Theoretical applications of these learnings were applied in the form of concept development in design focus groups, which provided a closed loop of data for review and analysis.

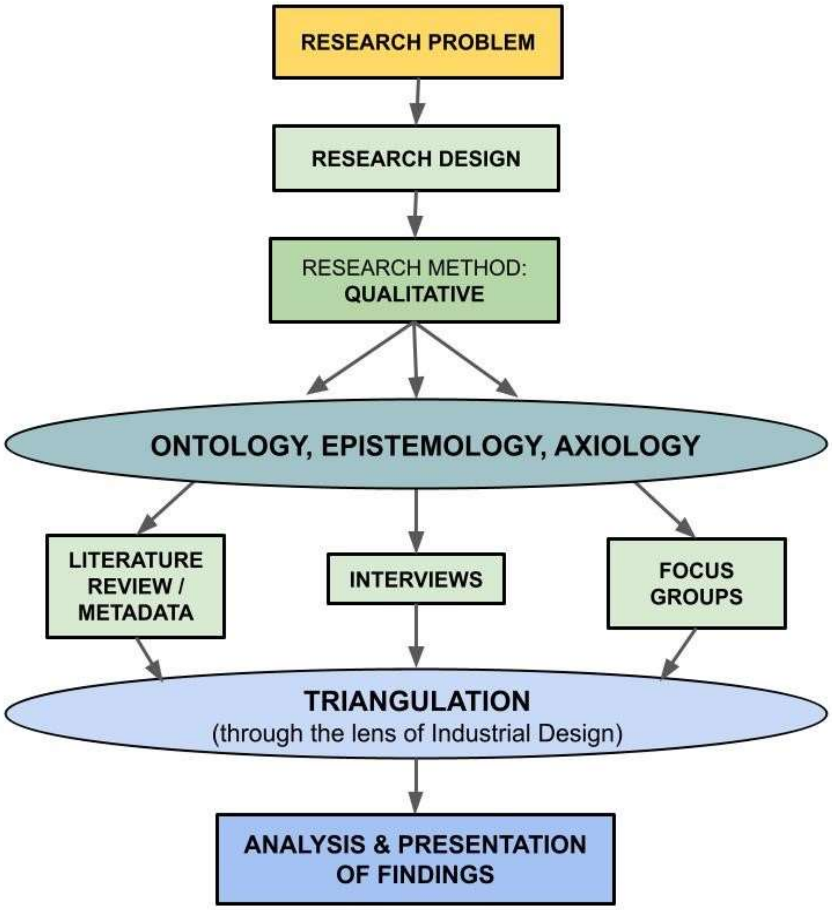


Figure 3.1: Research design overview (Author's construct, 2021)

3.2.2 Rationale for using qualitative research methods and analysis

This study has made use of the qualitative research methodology to create meaning for all research collected and presented. Various research tools, as described by Miles and Huberman (2014), were used by the researcher during the study, to ensure efficient gathering of data that would allow for the research questions to be addressed. By displaying, clustering, coding and analysing various design briefs, interviews, focus group studies and metadata sources, the researcher sought to identify themes and patterns in order to evaluate the research questions and draw inferred conclusions.

The researcher gathered all data in order to evaluate the main research question:

How can SRTs be used in the industrial design of medical products to improve inherent properties and functionality in order to enhance the user experience?

Matrices were used to compare and discuss the intended applications and unique properties of the various SRTs and identify overriding themes that could be used to drive further, more focused research. The researcher aimed to determine if these could be adapted and used by designers in novel ways to develop new products. As this relied on the researcher to extrapolate throughout this study and follow multiple branches of thought, the best process for evaluation and consideration was to focus on the positive attributes of the various SRTs and how these could drive improvements in the design/features of medical products. In addition, all analysis was done through the lens of industrial design, in order to determine the appropriateness of these SRTs for improving the user experience, and if they could realistically be integrated or incorporated in medical product designs in a meaningful way.

Qualitative testing was done through practical design exercises and a focus group where the collected data were applied to conceptual examples and applications. These practical exercises made it possible to test, in theory, the feasibility for the use of SRTs in product design. By keeping the research theoretical and conceptual, the cost of conducting research to prototype was avoided as no specialised facilities were required.

3.2.3 Qualitative research as a meaning-making methodology

Throughout the study, the researcher has used multiple sources for metadata collection. This was intended to provide a stable, reliable base from which to expand the research further. By first examining the field of soft robotics, the researcher was able to familiarise with the various SRTs, and so made it possible to have more focused and meaningful interviews with the various participants.

The first interviews were arranged with expert in the medical field and allowed for the researcher to get detailed design briefs for two real-world medical design projects. This allowed for comparing of the requirements and categorising these into broader themes that required further research and understanding. By discussing the requirements directly with the project experts, it was possible for the researcher to pinpoint the key attributes that would not only make these products succeed in meeting the users' needs, but also understand which aspects of the design could be improved by a "softer" design solution or approach.

After the first two interviews were completed and the two design briefs reduced to core requirements, the researcher was able to conduct more detailed research on SRTs to try to understand, and if possible, identify SRTs that might be of use in solving such design requirements. Again, multiple sources were used in this phase to ensure a good understanding of the research landscape. These sources were then coded and analysed using Atlas Ti software to identify patterns in the data and overriding themes that could be useful for the next phase of the research. The researcher also tabulated the various technologies in order to compare their attributes in the context of design, and this assisted further in identifying the most appropriate SRTs for further study and exploration.

Subsequently, from this extended metadata analysis, the researcher arranged interviews with two industrial design agencies in Shanghai. Both of these agencies had extensive experience in developing medical products and had exposure to the latest technological trends for manufacturing, materials development and improved user experience. By meeting with and interviewing expert industrial designers at these two agencies, it was possible to get supporting views from two leading companies. The interviews focused on clarifying the level of understanding the agencies had of the design process, their focus on medical design and whether they had any previous exposure to SRTs at all. The themes defined during the metadata analysis and general literature review helped guide these interviews. The potential applications for SRTs were discussed with these industrial design experts, in order to get their opinion on feasibility and whether such technologies might realistically be adopted in the future by medical product designers.

After the design experts were interviewed, it was possible to meet with a 3D printing specialist. Two representatives from the company Stratasys were interviewed, in order to get an understanding of the current forerunners in rapid prototyping and additive manufacturing. The interviews were conducted at their head office in Shanghai, and covered the latest trends in 3D printing, new materials being developed for 3D printing by their material research division in Israel and the viability of using 3D printing as a production method in the future. This interview was illuminating, as the researcher was able to witness cutting-edge machinery in the process of 3D printing. The researcher was also able to handle samples of the latest composite material prints, where multi-density rubbers were printing at the same time on the same machine. This aligned with certain key points discovered during the metadata analysis, where the morphology of the end design could be used to assist in simplifying the operation and control. In simple terms, by being able to print soft and hard rubbers together in one part, it is possible to design the object to flex where it is soft and be more resistant to deformation where the rubber is more rigid. The researcher was able to discuss the potential for printing with EAPs and was guided to further discussions with the research facility in Israel. This will be expanded on under the analysis of findings section in Chapter Five.

After the design agencies and 3D printing specialist interviews were completed, the researcher was able to transcribe the interviews for further analysis. By using a thematic analysis of these interviews, it was possible to highlight the views of “experts in the field” in terms of SRTs and their attractiveness, feasibility for use in industrial design of medical products, and ultimately manufacturability.

The researcher was at this point in the study well-positioned to organise and conduct a design focus group with eight industrial design students from the School of Design in Hunan, China. This was handled in three steps, firstly, a pre-focus group questionnaire was filled in by the participants in order to gauge the level of understanding and exposure to SRTs. This helped guide the researcher on how best to manage the focus group in order to extract the most from the students and overall experience. A presentation on SRTs was given by the researcher to the students, so as to inform them of the technologies in the field of soft robotics. Secondly, a focus group was conducted as a series of two design workshops in which the participants were asked to generate conceptual designs using one SRT, in this case EAP, to drive movement in some way. The concepts generated in the first design workshop were discussed as a group and then the students were asked to repeat the exercise again, having gained more insight into how the EAP might be used in product design. These more advanced concepts were at that juncture discussed as a group and presented to a larger forum. Thirdly, after the focus group was completed, the researcher asked the students to complete a post-focus group questionnaire in order to demonstrate the students' change in understanding and perception of SRTs. These designs and the findings from the questionnaires will be presented in Chapter Four.

As can be seen from this outline, there were various research tools adopted to ensure reliable credible data were sourced and used in the study. Triangulation was ongoing within each phase of the research, as multiple sources and participants were used at each point, to make cross-referencing possible. This has allowed for a meaningful analysis to be done using triangulation, to bring plausible themes to the surface for discussion.

The researcher's inherent bias has been intentionally limited through the use of transparent research methods, by ensuring the interviews conducted were a fair representation of the various specialised fields, using co-design methods during the focus groups and ensuring that the feedback from the participants was open and honest.

The research method laid out here was effective as it followed a logical flow from start to finish. The researcher began by defining the problem and then researching the landscape of SRTs. The participant samples were selectively chosen to be appropriately representative. The tools used to conduct the research were carefully planned and thought through, from the interview questions to the questionnaires and focus group agenda. The researcher was diligent in the collection of the data, as well as in the condensing of the data through coding and thematic analysis in order to allow for the data to be presented in a clean, logical and structured way to the reader. This method flow is meticulously outlined by Miles and Huberman (2014), where the research progression is described and was used by the researcher in structuring this study.

Figure 3.2 shows the detailed research design and flow from one stage to the next. The left side sets out the data collection and fieldwork that was conducted, whereas the right side shows how that information was processed or used by the researcher. There are a number of inter-dependencies that are illustrated in this flow chart, which provides the overview and understanding of why the researcher chose to proceed in the order described. Triangulation of the themed and coded research was possible, in order to condense the large number of metadata sources, notes, interviews and designs into a clean set of criteria as shown in the analysis and presentation of findings. This qualitative study has employed a qualitative methodology at every point along the way, with the aim of producing a view on SRTs that has meaning and value to industrial design.

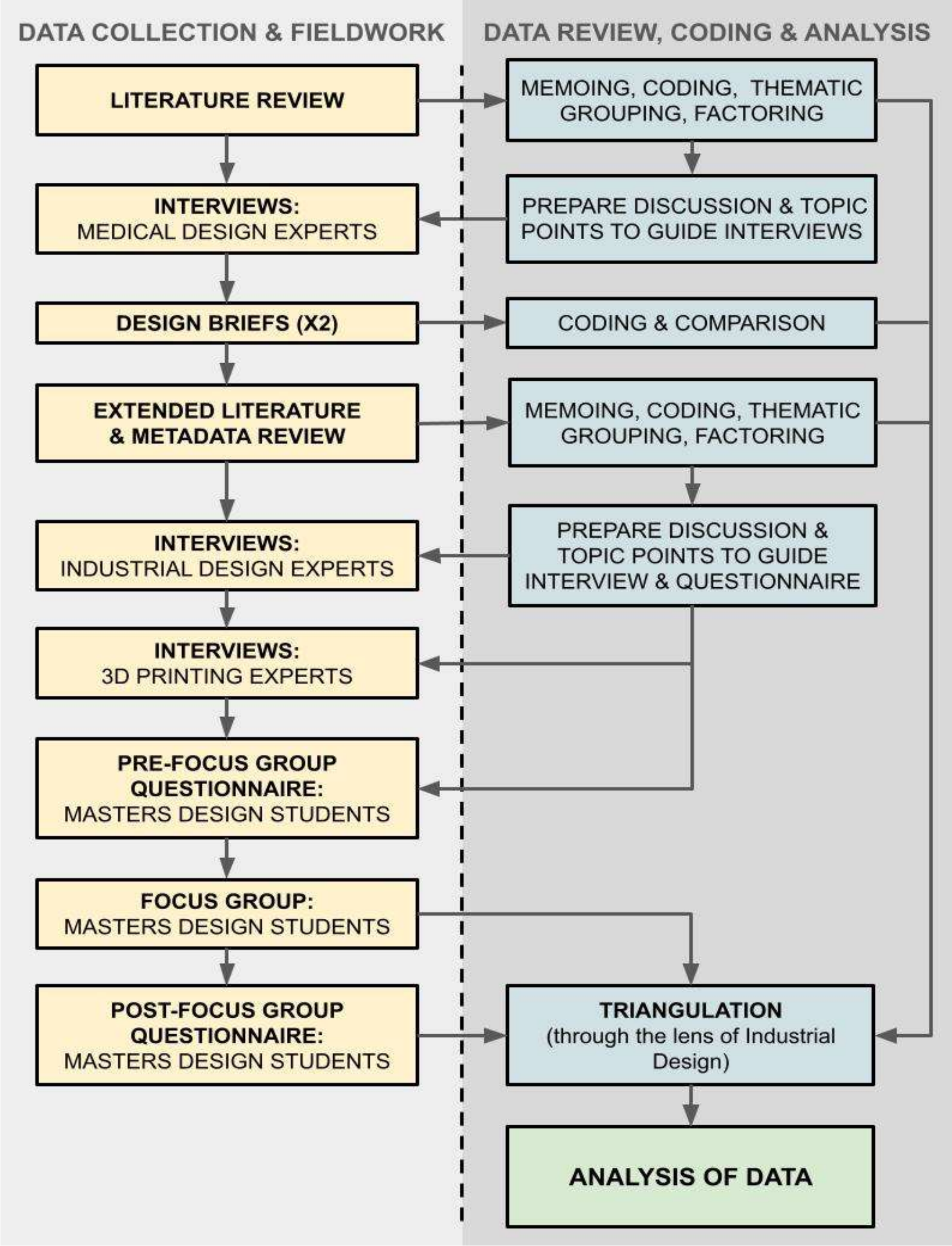


Figure 3.2: Research design detailed view (Author's construct, 2021)

3.2.4 Participatory co-design

In this study, the researcher made use of participatory co-design methods as a way of making meaning of the research together with the participants. Through the approach of co-creation and involving participants at specific stages of the research, it was possible to guide the research in a structured way. This was first demonstrated through the interaction and interviews with medical design experts in order to formulate real-world project briefs that could help direct further research. By engaging with these experts at an early stage in the research, the key factors that might guide design and engineering of medical products were discussed as they related to their specific projects (see Appendices A and B). Through discussions around the focus of this study into the adaptation of SRTs, it was possible to design the project briefs in such a way as to allow for exploration of new methods, materials and techniques to solve the project requirements. This collaboration between the researcher and the medical design experts shows the effectiveness of working in a participatory framework, where multiple inputs can inform and construct the overriding guidelines of a design project or research study.

The next stage at which the researcher made use of co-design methods was during the focus group workshops. Participatory design was the base from which the students were asked to develop conceptual industrially designed products that explored the use of SRTs in some way. The researcher established a safe environment where the students were relaxed and willing to participate in this design exploration work. The intention behind the workshop was explained so that the participants would feel free to be as creative as possible. The researcher also demonstrated, by means of an example sketch, the freedom with which the students could explore using SRTs. This ensured that the exercise was understood, and that the concept designs developed by the students would be aligned to the overall project aim and research questions.

By involving medical design experts early, the researcher was able to direct the entire study with certain key parameters in mind. These parameters were refined through discussion and iteration of the project design briefs. This participatory approach allowed for the various metadata to be gathered, filtered and analysed with a clear focus in mind: The adaptation of soft robotics technologies for use in the industrial design of medical products. The learnings from this metadata research were then applied and tested in the participatory co-design focus group, where the researcher leveraged the creativity of the industrial design students. The concept designs generated can be seen as an initial exploration and a more advanced development of these concepts came about after they were discussed in a group setting.

Ultimately, it was through the group discussions and participatory approach that these advanced designs were possible to create, as the collective input from the focus group helped the individual designers to evaluate their first-level concepts, recognise areas for improvement and then implement the changes in the second stage of concept development.

3.2.5 Clustering and factoring

As explained by Miles and Huberman (2014), clustering can be seen as the process of forming categories that allow for the sorting of data. This method has been used extensively during the metadata research gathering, where the numerous studies and journal articles needed to be grouped in a logical way. The initial approach to this was to simply try to identify different SRTs, but it became clear after reading the literature, that there are overriding themes that could assist in categorising these studies to better explain their origins of development and usefulness. For example, a number of SRTs have been developed as a result of the intention by researchers to mimic the movement of animals and people. This biomimetic influence was useful in grouping various studies that sought to emulate the movement of an octopus tentacle, for example, and so highlight the strengths and weaknesses of these different approaches.

This initial clustering made it possible to implement high-level factoring, where the overriding properties of the various SRTs were identified. The pattern that emerged clearly showed that the underlying properties of the SRTs were essential to their adoption and use in soft robotics. These are described in Chapter Four in detail, but cover characteristics such as flexibility, durability, ease of fabrication, mass producibility, low cost, ease of use, among others.

3.2.6 Coding

Coding was used extensively in this study to order information that would be of value to not only understanding the research landscape, but also to identify paths for the researcher to explore. The various codes used are described in the list of abbreviations and definition of terms on page “v”. It made it easy for the researcher to do broad reading and mark up areas of interest in each study quickly. These could then be extracted from the metadata sources and viewed collectively through the use of matrices. The coding was grouped in the matrices, and this allowed for a consolidated view to be created as shown in Figure 3.3. By relating the various SRTs back to three core guiding factors, namely, suitability for use in industrial design, suitability for use in medical product design, and suitability for mass production, the researcher was able to identify the most appropriate SRTs for further exploration. This type of descriptive coding also allowed for a coherent write-up of the literature review, as well as a clear presentation of the findings in Chapter Four. The various points of view of the researchers could be aligned and compared in a methodical way to create the snapshot described in this study.

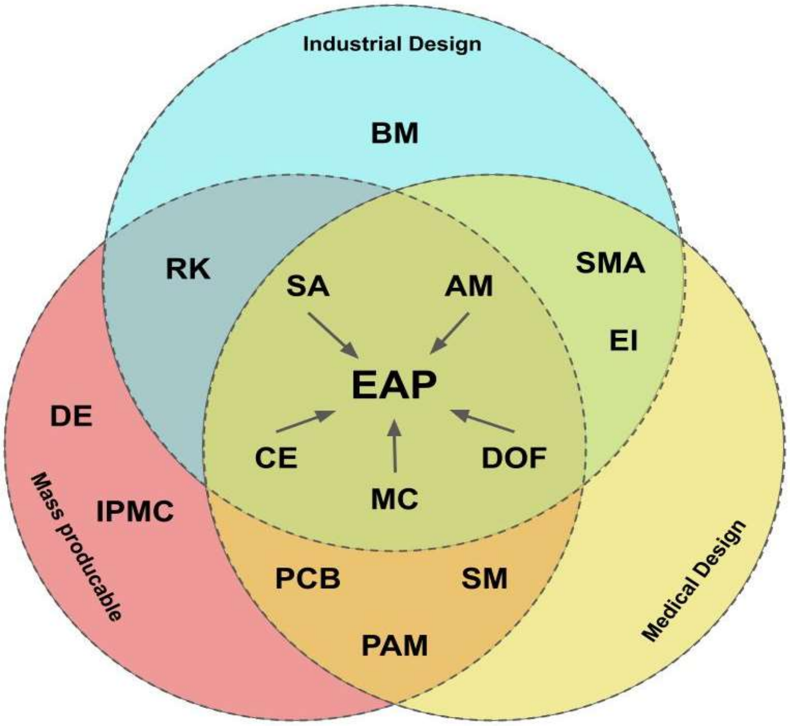


Figure 3.3: Coding used to group SRTs (Author's construct, 2021)

To a certain degree, topic coding was used in order to group data by a broader subject. The coding conducted in this study was mostly clustering and then factoring. There was also the use of analytic coding, where conceptual implementations for the various SRTs were considered and theorised. This extrapolation of "what might be possible" was restricted mainly for use in the focus groups in order to stimulate and direct the students' conceptual design work. Some development on the conceptual implementations is discussed in the recommendations for further study in Chapter Five.

3.2.7 Memos

In order to keep track of spontaneous thoughts and ideas during the data collection phase of this study, the researcher made use of memos. This was a useful tool to record ideas and thought paths so that they could be reflected on and explored further at a later time, if found worthwhile. The template used for this is shown in Table 3.1 with a single line filled in as an example. This also allowed for the use of coding and to relate ideas to specific coded groups. In some cases, this was used to bring relevant reference material into the literature review, but for the most part it was a tool to expose overriding links between different studies and provided the researcher with sufficient structure to be able to discuss these in a logical, coherent way. Although a number of these thoughts involved conceptual content and ideas, they did provide much of the inspiration for what might be explored in the focus groups in the form of conceptual design sketches. These ideas that started as recorded memos, were explored in the focus group and the concept designs developed made it possible for the researcher to formulate propositions that would aim to answer the research questions.

Table 3.1 Memo template (Author's construct, 2018)

Data Source	Type	Code	Concept / idea	Where to discuss
Miriyev, A., Stack, K. & Lipson, H. 2017. Soft material for soft actuators. *Nature Communications,* 8(1): pp. 1-8.	Journal	EAP	Could EAPs be used to actuate a mechanism or strap in a soft garment device?	SRT applications and during focus group activities.

3.2.8 Comparison

Another key tool used during the metadata review, interview review, questionnaire review and focus group review was that of comparison. It was found to be essential during the review of metadata to create matrices that could be used to cross analyse and compare various research studies, technologies, materials and robotic systems. The same matrices used to collate coded references and sources, were used to compare the sources in order to bring to the surface anything that might help direct the study. As an example, when looking at the various SRTs, it was necessary to compare these to conventional rigid robotics technologies in order to show the differences and potential benefits within the group of SRTs. However, it was possible to go further with this method of comparison and focus on the differences between the various SRTs in order to identify which of these might be best suited to further exploration in this study.

This, in turn, allowed the researcher to narrow the focus to EAPs and make these the core technology to be tested in the focus groups. This provided support for the practical significance of the study, with tangible evidence to support the answering of the research questions. This progression of focus through the use of comparisons, is referred to as enumerative induction, where the research is able to develop along a logical, intentional path that concludes in a compounding of the evidence to prove or disprove the hypothesis. This is also a good method to adopt in order to make a conceptual idea coherent, as the process follows the following "bottom-up" steps as described by Miles and Huberman (2014). Firstly, the researcher establishes clear findings, in this case, the literature review. Secondly, the findings are related to one another through coding, comparison and thematic analysis. Thirdly, any patterns or themes are highlighted and described. Finally, the condensed data are used to describe a broader conceptual idea, in this case, that SRTs can be used by industrial designers to develop better medical products. This progression has allowed for the researcher to build the argument that this research study will be of use to others.

3.2.9 Partitioning or subdividing variables

When creating matrices for thematic analysis and comparison, it became clear that there was a need for partitioning or subdividing the variables. As there are a number of SRTs with similar attributes and applications, it was necessary to break these down into subcategories in order to ring-fence those technologies that appeared to have higher potential for use in the design of medical products. For example, it was not enough to describe a soft actuator as being stimulated by an electric current, as this was applicable to both SMAs and EAPs with quite different results. In this case, the researcher needed to show that electric stimulation caused a local volumetric change to EAPs, whereas it caused deformation to SMAs with a negligible volumetric change. The difference in this case was extreme, as has been shown in the literature review, since the volumetric change in EAPs produces substantial force compared to the energy supplied to the system, whereas in SMAs the energy use was poor. By partitioning the characteristics in this way, it was possible to eliminate SMAs from further study and focus only on the potential of EAPs when doing the focus group design workshops.

3.2.10 Abstraction

The researcher used abstraction in order to test the hypothesis that SRTs might be useful in the industrial design of medical products. By working from the data gathered during the metadata review, interviews and focus groups it was possible to build a logical chain of evidence. This allowed for the use of “if/then” tests to be used to answer the research questions. By this logic, the researcher is able to test the presupposition: *If* it is possible for industrial design students to generate feasible concept designs that make use of SRTs, *then* the main research question has been answered. So, we can show that for each concept design that *if* it was successfully implemented, *then* that was a logical claim in support of the hypothesis. This use of abstraction forms the basis for the conclusions in this research study, where the theoretical data gathered, analysed and displayed is supported by practical, rational, and believable evidence.

3.2.11 Triangulation

Triangulation has been used in each stage of the research design, to ensure that multiple sources inform the study. During the collation and analysis of metadata, multiple resources were sourced to build reliability into the findings. This allowed for the double checking of findings and ensured robust groundwork was done from which the next stages could develop. Interviews were handled with multiple sources, again to ensure that any guiding data, themes or requirements were supported by multiple participants. The focus group and questionnaires were conducted with a class of design students so as to provide many viewpoints and interpretations of the practical portion of this study.

By ensuring the three main areas of research, those being, metadata, interviews and focus groups, were managed in this way, it was then also possible to use triangulation to analyse and discuss the overriding themes and to show overlaps or discrepancies in the outcomes. This formed a control step in the research method, to ensure the final conclusions of the research are logical and supported. Figure 3.3 shows how triangulation was used in this study. First within each focus area, next so the three focus areas could be compared, and finally, the central themes could be identified and presented.

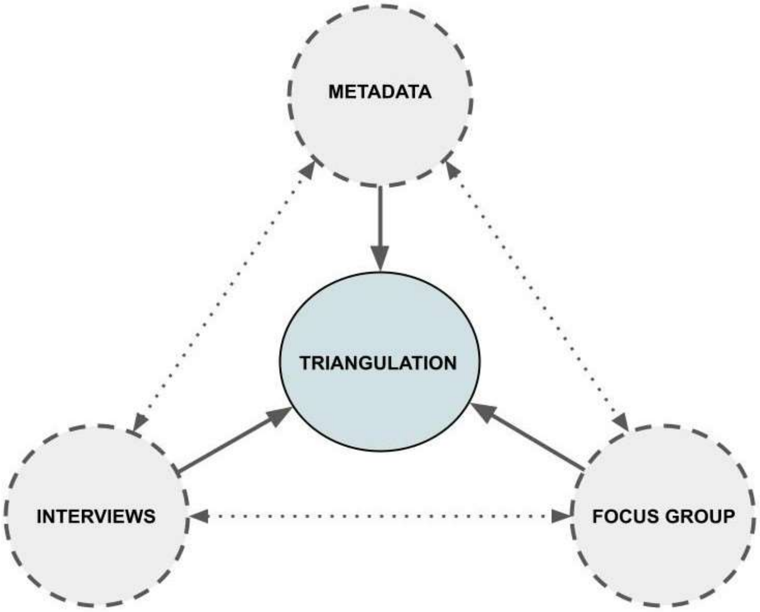


Figure 3.4: Triangulation in this study (Author's construct, 2021)

3.2.12 Replicating a finding

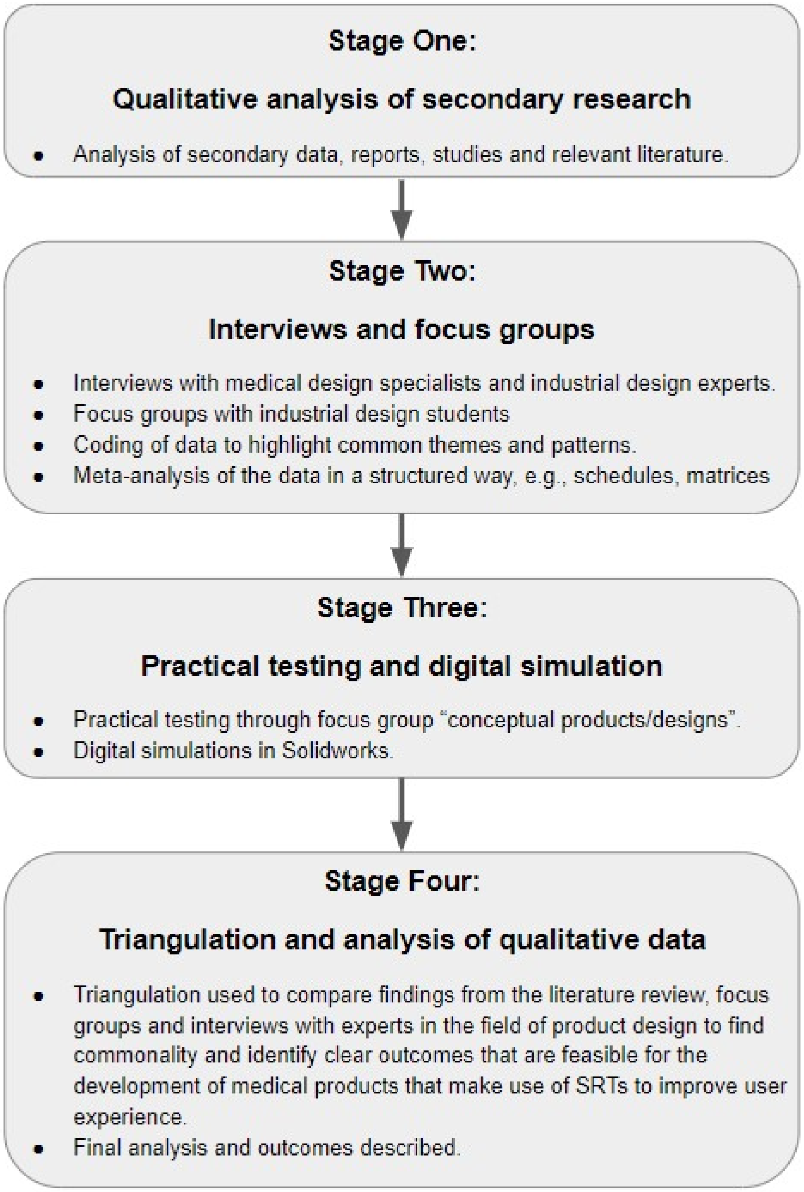
As described in triangulation, the research findings are more reliable when supported by multiple sources (Miles & Huberman, 2014). The principal of "replicating a finding" has been used in the planning of the focus group workshops with the intention of treating the various concepts developed as independent investigations by each participant. In this way the various design concepts can be viewed as multiple "tests of the hypothesis" being carried out in parallel. Based on the *if/then* logic, *if* multiple concepts were successful in making use of an SRT in some novel way, *then* it would lend strong support to the claim that SRTs can be adapted for use in the industrial design of medical products (Miles & Huberman, 2014). The researcher has also aimed to describe the research design and methodology used, to ensure it is easy to understand and repeat, in order for others to replicate this study and potentially come to the same conclusions.

3.2.13 Research method – implementation of the research design

The research method followed all steps set out in the research design, was conducted diligently and according to all ethics requirements and expectations of such a master's study as set out by the CPUT. As described in Figure 3.1, the overview of the research method involved defining the research problem in order to develop the research design. This then informed what type of study would be conducted, in this case a qualitative analysis of qualitative and quantitative data. This was to be effected through a deeper understanding of how ontology, epistemology and axiology affect research, in order to ensure correct research practices were used with the appropriate intention. The various stages of research were then conducted, and these covered the metadata research, interviews and focus groups. The detailed research design for this portion of the study is described in Figure 3.2. Each step of the detailed research design was planned carefully and with intention by the researcher, to ensure a building of evidence to address the research questions. These stages were linked in such a way so as to ensure the separate parts combined to form a holistic study. That is, the relevant literature gives rise to the research methodology, which, in turn, is used to guide the collection of the data and the subsequent analysis of the data. The conclusion succinctly recaps the study and points to further research (Lankshear, 2001).

The researcher has implemented the research design through the use of appropriate participants, which include experts in the medical design industry, expert industrial designers in the medical field, the leading experts in the 3D printing industry and a class of industrial design students for the focus groups. The study has made use of triangulation and multiple sources at each stage of data capture, for example, multiple metadata sources, multiple interviewees, multiple design briefs and multiple students.

The research methodology flow can also be viewed in four stages, as shown in Figure 3.5. Stage One focused on the early qualitative analysis of the literature on SRTs. Stage Two is the fieldwork phase where all interviews were conducted, focus groups were arranged, and the data gathered were formatted for analysis. Stage Three covered further practical testing, through additional focus group concept development, as well as simulations of SRT applications by the researcher using Solidworks software. Stage Four covered all triangulation and analysis of the data gathered, in order to present them. This grouping of activities into stages was useful to the researcher in respect of time management, as a large portion of the fieldwork was conducted on a one-month research trip to China in October 2018.



- Analysis of secondary data, reports, studies and relevant literature.

- Interviews with medical design specialists and industrial design experts.
- Focus groups with industrial design students
- Coding of data to highlight common themes and patterns.
- Meta-analysis of the data in a structured way, e.g., schedules, matrices

- Practical testing through focus group “conceptual products/designs”.
- Digital simulations in Solidworks.

- Triangulation used to compare findings from the literature review, focus groups and interviews with experts in the field of product design to find commonality and identify clear outcomes that are feasible for the development of medical products that make use of SRTs to improve user experience.
- Final analysis and outcomes described.

Figure 3.5: Research methodology flow (Author’s construct, 2021)

3.2.14 Data collection methods

The researcher made use of various data collection methods, namely: individual interviews, questionnaires, co-design participatory workshops and an extensive literature review. Various research tools were used to support these activities including coding, clustering and factoring, memos, partitioning, abstraction, comparing, replicating a finding and triangulation. By coding the various reports, studies and data sources, the researcher sought to identify overriding themes and describe these themes in detail as they relate to the use of SRTs for the industrial design of medical products.

3.2.15 Selecting the participants

Selecting appropriate participants for this study was essential to ensure useful data were captured. The first interviews were held with specialists in the medical design field as they were key informants due to their expertise. The two surgeons from Cape Hip and Knee, Cape Town, South Africa, have extensive experience in medical design, as well as the specific requirements of their patients before and after knee surgery. The information gathered from these interviews allowed for the formulation of a product design brief that included requirements that would guide further SRT research. The interviews with Footwear Industry Trading were equally appropriate, as they have extensive experience in developing and producing shoe designs. The requirements for the diabetic shoe insole, were equally useful in guiding further SRT research and further supported the need for soft alternatives when developing medical products.

The interviews with industrial design experts were necessary as they had experience in developing medical products in a technologically advanced context. Being based in Shanghai, both design agencies had exposure to the latest material and production technologies on the market and provided the researcher with valuable insight. In addition to their extensive medical product design experience, both agencies were willing to discuss SRTs with the researcher and give their professional views on these technologies. This further supported the need to conduct a focus group and explore conceptual design using SRTs.

The interview with Stratasys was appropriate, as they are the world’s leading producer of additive manufacturing machines. They are not only the largest but have the most cutting-edge technology available for printing production grade plastics and rubbers. As the researcher was focusing on soft materials and production techniques that would allow for complex geometries to be manufactured easily, this production printing technology was appropriate to explore.

The focus groups and questionnaires were arranged with a group of industrial design students from the School of Design, at the Hunan University, Hunan, China. These students were selected to participate in the research study as they were studying at one of the world's leading industrial design institutes. The students have constant exposure to industry and real-world projects, which provides for a more realistic approach to their design work. As with the design agencies in Shanghai, the students had exposure to the latest manufacturing methods and technologies. In addition, the students were familiar with traditional robotic technologies, materials science and biotechnology as these subjects are also taught on the same university campus.

3.2.16 Individual interviews

The various interviews conducted over the course of this research study, will now be described in detail. The first of these were with specialists in the medical design and orthopaedic fields, for the sole purpose of looking at real-world design projects that could further inform and better direct this study. Once these initial interviews were conducted, the researcher was able to better plan the next phases of the research design, by doing further research into existing case studies with a narrower focus. This then assisted the researcher to identify key areas of SRT on which to focus for the following discussions with expert industrial designers in Shanghai. These discussions gave the researcher the necessary insight into how the design industry perceives SRTs and the general level of awareness. In addition, the researcher was able to interview Stratasys, the world leader in rapid prototyping. Through discussions with Stratasys, the researcher was able to explore futuristic production methods that could align well with overall project context and further support the viability of the concepts developed in the design focus groups.

3.2.16.1 Medical product expert interview – Cape Hip and Knee

Description of the interviewees: They are two medical experts, who are not only at the forefront of medical development in their field but have also designed various items to improve artificial joint surgery, reduce implant rejection and improve patient recovery.

Number of interviews: Two appointments were made for the researcher to meet for one hour at a time with both surgeons together.

Location of interviews: These interviews were held on site with the two surgeons who own the medical practice, Cape Hip and Knee at the Vincent Pallotti Hospital, Pinelands, Cape Town, South Africa.

Interview environment: The interviews were conducted on site at the Cape Hip and Knee practice. This was done to minimise any inconvenience to the two surgeons. Discussions were held in the boardroom as well as their personal offices where various medical devices that they have developed were on display. This provided an ideal environment for the interviews, as there were no interruptions and both surgeons were able to contribute freely as it was a space familiar to themselves.

Purpose of the interviews: The aim of these interviews was to develop a design brief for a real-world medical product. Through open discussion, a project design brief was formulated for a smart soft device, the Medi-dot, which could be worn by the patient before and after surgery in order to track patient recovery.

Outcome from the interviews: The project brief requirements were grouped to define the specific requirements of the Medi-dot product by category and so assisted the researcher to narrow the focus when doing further metadata analysis. This grouping, which followed the Miles and Huberman (2014) method, will be presented by means of a matrix in the next chapter.

3.2.16.2 Medical product expert interview – Footwear Industry Trading

Description of the interviewee: The main interviewee was the owner of Footwear Industry Training. He has extensive experience in footwear development and production.

Number of interviews: The interviewee agreed to meet with the researcher on three occasions, for approximately one hour each time.

Location of interviews: The first interview was held at the Cape Peninsula University of Technology, Bellville campus, Cape Town. The second interview was held at a coffee shop in the Bo-Kaap area of the Cape Town city centre. The third interview was held telephonically.

Interview environment: The first interview was held at the CPUT, Bellville campus, in a meeting room with several other key members and stakeholders in the project. This was handled as an informal discussion and information session where the researcher was presented with the details of the medical design project. The second interview was held at a coffee shop, and although there was a lot of noise and distractions present, it was possible to have a meaningful discussion around the medical product design requirements. The third interview was held telephonically and so was a practical opportunity for the researcher to reinforce the project requirements and design brief, in order to proceed with further research in this study.

Purpose of the interviews: The purpose of these interviews was to have access to a second real-world design project, in this case the “Fit diabetic shoe insole”. Interviews and discussions were held with the team that was to develop this medical product and the design brief was supplied to the researcher. This design brief was then coded in the same way by means of a matrix to show the overriding themes that formed the basis of the requirements.

Outcome from the interviews: The researcher was given access to and use of this medical project design brief. This medical project provided the researcher with additional real-world requirements for a medical device that was to be worn by the user, needed to have inherent flexibility, needed to incorporate advanced sensor and feedback functionality to allow for real-time data tracking. With these specific requirements as a guide, the researcher was able to conduct further and more focused metadata research, in preparation for further discussions and interviews with industrial design experts at two design agencies in Shanghai.

3.2.16.3 Industrial design agency interview – Wild Design

Description of the interviewees: The interview was held with the two lead industrial designers and owners of Wild Design. The two informants were friendly and accommodating. Both of the interviewees were generous with their time and openly shared their ideas around industrial design for the medical industry.

Number of interviews: One interview was held on site at Wild Design, Shanghai, China.

Location of interview: Wild Design offices, Changping Road 68, Shanghai, China

Interview environment: The interview was held on site at the Wild Design offices, which are very professional and comfortable. The researcher was invited into the glass walled boardroom for the first part of the interview, and then proceeded on a tour of the office space and to a presentation of the various medical products that Wild Design have completed successfully.

Purpose of the interview: The purpose of this interview was to get a view on the current perception and understanding of SRTs in the medical design industry, from the perspective of professional, experienced industrial designers. An open-ended questionnaire was used to guide the interview.

Outcome from the interview: By involving such specialists in advance of the practical portion of the research, the researcher was better able to ensure that co-design principles were considered when discussing applications for SRTs. This input was used in guiding two phases, namely, the discussion and planning phase where applications were identified, and the practical phase where those potential applications were put to the test and applied to creative design concepts.

3.2.16.4 Industrial design agency interview – designaffairs

Description of the interviewees: The interview was held with the Head of Industrial Design at designaffairs.

Number of interviews: One interview was held on site at designaffairs, Shanghai, China.

Location of interview: designaffairs Group China, 50-4A-205 Mo Gan Shan Road, 200060 Shanghai, China.

Interview environment: The interview was held on site at the designaffairs offices, which are situated in a design district of Shanghai, surrounded by art galleries and creative spaces. The researcher was invited into a meeting room that was adjacent to the materials presentation area, and so was able to get a view of the large range of materials and finishes available to the agency for use in their design work.

Purpose of the interview: The purpose of this interview was to get a view regarding the current perception and understanding of SRTs in the medical design industry, from the perspective of professional, experienced industrial designers.

Outcome from the interview: The interview was transcribed and then reduced to key data related to the current view of SRTs in the medical design industry.

3.2.16.5 3D printing agency interview - Stratasys

Description of the interviewees: The interview was held with the Senior Sales Manager, Direct Sales, Greater China and the Pre-sales and Application Engineer, South Asia.

Number of interviews: One interview was held on site at Stratasys' Shanghai head office.

Location of interview: Floor 1, A3, Ninghui Square, No. 718 Lingshi Road, 200072 Jing'an District, Shanghai, China.

Interview environment: The interview was held on site at the Stratasys head office in Shanghai, in their main boardroom. This was in close proximity to the display area for the various 3D Printing machines they produce.

Purpose of the interview: The purpose of this interview was to get a view regarding the latest technology available in the field of 3D printing, and an indication of future developments and advances that might occur in this industry. The materials used were also a main focus, where soft rubbers and polymers were of special interest.

Outcome from the interview: The interview was transcribed and then reduced to key data related to the current view of printing with soft polymers and multi-density printing for mass production.

3.3 Individual student questionnaires

Description of the questionnaires: The questionnaire was split into two parts, a pre-questionnaire with questions intended to gauge the students' knowledge of SRTs before the design workshop was conducted, and a post-questionnaire that was completed after the design workshop in order to see how the students understanding of SRTs had changed.

Number of questionnaires: Two questionnaires, one pre- and one post- design workshop.

Location where questionnaires were completed: School of Design, Hunan University, Hunan, China.

Questionnaire environment: The questionnaires were completed on site at the School of Design, Hunan University, Hunan, China. Various lecture rooms and classrooms were used by the students, to ensure they were filled in privately without influence from other students or the researcher.

Purpose of the questionnaires: The purpose was to gauge the students' knowledge of SRTs before the design workshop was conducted, and after the design workshop in order to see how the students' understanding of SRTs had changed. This was then used to demonstrate how the workshop either succeeded or failed in changing the students' perceptions of SRTs and the potential for use in the industrial design of medical products.

Outcome from the questionnaires: The data collected from the questionnaires were compiled into a matrix and used to show the overall change in the perception of SRTs among the students that participated. This matrix and the findings will be presented in Chapter Four.

3.4 Focus group interviews

A focus group of industrial design students from the School of Design Hunan University, China, participated in this study. This was comprised of six males and two female students. The focus group was set up with a pre- and post- questionnaire that all students were asked to complete. The purpose of the questionnaires was to get a view of their understanding and perception of SRTs before and after the workgroup design exercises were completed. The findings from these questionnaires and the design concepts produced will be presented and discussed in Chapter Four.

The students that participated were selected as Hunan University is a leading industrial design school and are at the forefront of technological developments with access to many technologically advanced companies and real-world projects. Facilities at the university include a robotics laboratory, a robotics engineering department and bioengineering, among others. The students have had exposure to many of the latest design trends and manufacturing techniques and so were well placed to provide an open-minded view of SRTs and their perceived potential for use in the industrial design of medical products.

The Hunan University has strong links with industry, as China has progressed rapidly in the robotics and soft robotics fields. They are an excellent focal point to evaluate to what degree these SRTs have been explored in industrial design and whether other potential applications have been explored.

The focus group made use of co-design methods, to ensure a participatory approach was followed (Schuler & Namioka, 1993). The intention was to work with the participants through the use of participatory co-design workshops to develop conceptual industrial designs that made use of one or more SRT - with a view to implement in a mass market and make them more accessible or affordable. Harvard Biodesign Lab follow a similar research method, where they involve the end-user during the development process to ensure their products are functional and ergonomically sound.

The participatory co-design workshops were arranged so that the participants could be engaged in an open discussion. The intention was to discuss viable and practical applications for SRTs. The main aim was to conceptualise product designs incorporating SRTs that could be reviewed and discussed collectively to gauge feasibility. With real-world projects being conducted by Hunan University on a regular basis, it was possible to make use of the students' user-centred experience and keep the focus on viable product ideas.

3.5 Data analysis

The data analysis portion of this study was a rigorous process that allowed for the extraction of meaning from the raw data collected. The researcher made use of a number of analysis tools in order to achieve this effectively. The challenge was to align the subjective and creative nature of design, with the grounded factual nature of engineering and materials science that makes up SRTs.

Firstly, the researcher made use of interviews and questionnaires to gauge the participants' subjective and personal views on SRTs. Interviews with medical experts were used to guide further research to help define positive attributes that would narrow the research focus. These interviews were then transcribed, and the data transferred into matrixes to provide a clear overview.

Secondly, a systematic literature review of the metadata to understand the raw state-of-the-art SRTs was then encoded, and the overriding themes understood. The data were categorised and filtered to focus the research further on SRTs that have inherent properties that could be of use in the industrial design of medical products.

Thirdly, these two lines of research were merged by means of the focus group workshops in order to provide conceptual designs that were based on scientific fact. The participants were given a clear description of a certain SRT, specifically EAPs, and then asked to explore using these in innovative concept design. It was these concept designs that were evaluated and described in the context of the main research question, to determine if the hypothesis is feasible or not. All concepts were created initially as pencil sketches, with some being developed further using 3D software to visualise them.

All findings, concept development and presentation work are presented and discussed in the next chapter.

3.6 Limitations of the study

The area of study is specifically related to the industrial design of medical products, focusing on soft robotics technology, and the advances in technologies within this field of study. The researcher has aimed to understand advancements in SRTs in order to ring-fence those technologies which could be applicable for use in products designed for the average person. The researcher has identified and described these applicable SRTs and shown how these may be applied for use in the product design of consumer and medical products.

The focus area has covered materials being developed and used in soft robotics, the methods used to drive motion/movement and the production methods to create support structures and frames. Manufacturing techniques have been assessed, and the feasibility for mass production has been key to justifying commercial viability. The same view on mass-producibility was kept in mind when designing the concepts in the focus group where these SRTs were explored. This feasibility for mass production was a key factor that was used to assess the viability of a design concept, with the view to presenting realistic product proposals in the research study.

The researcher has not repeated existing research or conducted materials development research. The focus has not been to hypothesise on future materials, but rather to build on existing technology currently being used. This research is not for the purpose of expanding on robotics technology, or the existing knowledge base in robotics. This study is not a study of robots in general, and the intention is not to be able to design robots with the information gathered through this research.

3.7 Ethical research practices

The researcher completed all prescribed Ethics Approval forms in advance of proceeding with any interviews or focus groups. In addition to the general Corporate Ethics agreement, an individual consent form was supplied to each participant in the research, to ensure that a clear understanding of the boundaries of this research study were set down. All participants were required to sign the CPUT's *Individual Consent for Research Participation* (FID/REC/iCv0.1) form.

No coercion or incentives have been used to encourage participation in any interviews or focus groups. Participants have had the option to remain anonymous if they so preferred. All data gathered have been kept in an encrypted file on a Dropbox server and remained so for the duration of the study after which they have been and will remain archived for five calendar years for audit purposes as required by the Cape Peninsula University of Technology (CPUT). There is no risk of compromising the data and participants' identity.

The researcher has abided by all ethical guidelines and requirements as set out by the CPUT. The researcher has respected the wishes of all participants in the study and protected their right to anonymity. The researcher has not and will not compromise any participants' intellectual property or make public any information that could be deemed secret or pending formal protection such as copyright, design registration or patent.

All participants have been kept anonymous in the research, even though their names have been captured on all individual signed ethics approval forms. Participation was voluntary and all who participated in the study were made to sign an individual ethics approval form.

3.7.1 Ethics approval

Ethics approval was granted by the CPUT before the researcher commenced with any interviews, focus groups or extension activities related to these (See Appendix G).

3.8 Chapter summary

In this chapter, the research design was shown with a logical flow that suited the mixed-method research methodology used for this study. The various stages were outlined and described in detail, covering individual interviews, focus group co-design workshops, case study data collected through questionnaires, design concepts development, focus group discussions and metadata analysis.

The researcher's approach to this study was based on pragmatism, and all aspects have followed a logical path with the aim of being able to present the research findings in a clear orderly way. The researcher followed a clear ethics line, ensuring all requirements were met according to the Cape Peninsula University of Technology's ethical standards for researchers. All data were gathered in line with the ethics code of conduct and encoded as required to allow for further analysis.

The collection of all metadata, interviews with medical experts, interviews with industrial design experts, interviews with industrial design students and focus groups with industrial design students was done through the lens of industrial design to ensure all findings could be related back to the research question.

These findings will be discussed in the next chapter.

CHAPTER FOUR

Data collection and presentation of findings

4.1 Introduction

This chapter will present the metadata, case study data, interviews with medical experts, interviews with industrial design experts, focus group data, related questionnaires and the exploration of design concepts making use of SRTs. The challenge of this research study was to investigate the SRTs currently in the body of knowledge and determine which of these could be useful to an industrial designer. By making use of real-world projects, namely, the FIT and Medi-dot Soft Garment as detailed in Appendix A and B, it was possible to narrow this search of SRTs and focus the research study.

After the initial exploration of the current status of soft robotics, which is compiled in the literature review in Chapter Two, the researcher was able to conduct interviews, focus groups and gather data through questionnaires. The initial interviews assisted the researcher to identify the most appropriate SRTs that could best be integrated and guide further investigation of their use in consumer and medical product design. Additional interviews were conducted with two design agencies, namely, Wild Design and designaffairs in Shanghai, China, to get a current view of how SRTs are perceived in the design industry. Usefulness and potential applications were discussed in order to further narrow the focus and direct the next stage of research, which consisted of a focus group where conceptual design work was explored, and simulations conducted using Solidworks CAD software.

The focus group included industrial design students from the School of Design at Hunan University, Hunan, China. The purpose was to assess their understanding of SRTs before and after the focus group work and explore potential applications for use in the industrial design of medical products. The Hunan University is ideally placed for this research, as they have advanced robotics and bio-engineering facilities which will allow for further development of this research topic in the future. The intention was to approach this from the perspective of conceptual design exploration, whereby the students were asked to produce creative product concepts and ideas without restrictions. The intended outcome of the focus group was to identify and work with potential applications for EAPs in the consumer product market or/and in medical devices. The participants were asked to use these EAPs in novel ways and so produce conceptual designs that would improve user experience, aesthetics and allow for functionality that is difficult to achieve with conventional technologies. The researcher made use of questionnaires to gauge the participants' understanding of SRTs before and after the focus group, and show the perception change that occurred. The potential for SRTs is demonstrated through the presentation of concept designs done in the focus group and discussed further in Chapter Five.

4.2 Literature review and metadata

The metadata that were reviewed as a part of this research study, have been analysed using various tools as described in Chapter Three. Coding, memos, thematic grouping and factoring were effectively used in order to sort the various studies and reports and uncover not only patterns but also key areas for further research and focus. This has allowed this study to remain pertinent, with the aim of addressing the research questions set.

4.2.1 Analysis of initial literature review and results

In order to clarify how SRTs differ from conventional robotics technologies, the researcher did initial reading of various journal articles, case studies and similar metadata. By looking at the advancements in the robotics industry and existing studies that compare these to technologies, it was possible to clarify categories and groupings that would be of use throughout the study. Table 4.1 sets out these differences, in order to delineate what sets SRTs apart from conventional rigid technologies and allowed the researcher to focus further research by using this as a guideline. In broad terms, SRTs exhibit certain properties that may appear as weaknesses at first, such as low accuracy, low load capacity and they are in general difficult to control. Further investigation was needed in order to understand these limitations in detail.

Table 4.1: Comparison of rigid robotics technologies and SRTs (Trivedi et al., 2008:100)

Properties:	**Rigid**	**Discrete hyper-redundant**	**Hard continuum**	**Soft**
Degrees of freedom	Few	Large	Infinite	Infinite
Actuators	Few, Discrete	Many, Discrete	Continuous	Continuous
Material strain	None	None	Small	Large
Materials	Metals, plastics	Metals, plastics	Shape memory alloys	Rubbers, Electro-active polymers
Capabilities:				
Accuracy	Very High	High	High	Low
Load capacity	High	Lower	Lower	Lowest
Safety	Dangerous	Dangerous	Dangerous	Safe
Dexterity	Low	High	High	High
Working environment	Structured only	Structured and unstructured	Structured and unstructured	Structured and unstructured
Manipulable objects	Fixed size	Variable size	Variable size	Variable size
Conformability to obstacles	None	Good	Fair	Highest
Design				
Controllability	Easy	Medium	Difficult	Difficult
Path planning	Easy	Harder	Difficult	Difficult
Position sensing	Easy	Harder	Difficult	Difficult
Inspiration	Mammalian limbs	Snakes, fish		Muscular hydrostats

4.2.2 Analysis of additional metadata and results

After the initial literature review was conducted, it was clear that more detailed research and investigation would be needed to understand the properties of SRTs. An extensive review of case studies on or related to soft robotics was done and the most relevant of these is presented in Table 4.2. The researcher identified common themes and areas of focus that would allow the various studies to be factored and grouped. The overriding focus of each study was identified and then listed in a matrix for clear presentation of the factors that were then used to define the overriding groups. The researcher was able to identify four key areas of research, based on the metadata reviewed, namely: actuation by means of artificial muscle, morphological computation, biomimetic inspired robotics and applications for SRTs.

Table 4.2: Grouping of soft robotics case studies (Author's construct, 2021)

GROUP 1: Actuation by means of artificial muscle		
Year	**Research / Case Study**	**Focus of the study**
1998	Shahinpoor, M., Bar-Cohen, Y., Simpson, J.O. & Smith, J. 1998. Ionic polymer-metal composites (IPMC) as biomimetic sensors, actuators and artificial muscles - a review. *Smart Materials and Structures, 7:* 1-27.	1. Ionic polymer actuators 2. Actuators as artificial muscles
2004	Bar-Cohen, Y., 2004. *Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges*. SPIE Press. San Diego, California.	1. Electroactive polymers 2. Actuators as artificial muscles
2005	Kim, K. J. & Tadokoro, S. 2005. Electroactive Polymers for Robotic Applications: Artificial Muscles and Sensors. Springer.	1. Electroactive polymers 2. Actuators as artificial muscles
2007	Jung, K., Koo, J.C., Nam, J., Lee, Y.K. & Choi, H.R. 2007. Artificial annelid robot driven by soft actuators. *Bioinspiration & Biomimetics,* 2(2): S42-S49.	1. Dielectric elastomer 2. Actuators as artificial muscles
2009	Laschi, C., Mazzolai, B., Cianchetti, M., Mattoli, V., Bassi-Luciani, L. & Dario, P. 2009. Design of a biomimetic robotic octopus arm. *Bioinspiration & Biomimetics,* 4(1): 015006.	1. Electroactive polymers 2. Actuators as artificial muscles 3. Bioinspiration 4. Biomimetics
2009	Laschi, C., Mazzolai, B., Mattoli, V., Cianchetti, M. & Dario, P. 2009. Design and development of a soft actuator for a robot inspired by the octopus arm. *Springer Tracts in Advanced Robotics,* 54: 25-33.	1. Electroactive polymers 2. Actuators as artificial muscles 3. Bioinspiration 4. Biomimetics
2009	Cianchetti, M., Mattoli, V., Mazzolai, B., Laschi, C. & Dario, P. 2009. A new design methodology of electrostrictive actuators for bio-inspired robotics. *Sensors and Actuators* (B142): 288-297.	1. Bioinspiration 2. Biomimetics 3. Dielectric elastomer
2009	Kim, S., Hawkes, E., Cho, K., Jolda, M., Foley, J. & Wood, R. 2009. Micro artificial muscle fiber using NiTi spring for soft robotics. *The 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems October 11-15, 2009 St. Louis, USA* pp. 2228-2234	1. Shape memory alloy actuators
2013	Yao, L., Niiyama, R., Ou, J., Follmer, S., Silva, C. D. & Ishii, H. 2013. PneUI: Pneumatically actuated soft composite materials for shape changing interfaces. *Proceedings of the 26th annual ACM symposium on User interface software and technology - UIST '13,* pp. 13-22.	1. Pneumatic actuation 2. Actuators as artificial muscles 4. Morphological control
2013	Onal, C.D & Rus, D. 2013. Autonomous undulatory serpentine locomotion utilizing body dynamics of a fluidic soft robot. *Bioinspiration & Biomimetics* (8) pp. 1-10.	1. Actuators as artificial muscles 2. Morphological computation 3. Fluidic elastomer actuators
2014	Holland, D. P., Park, E. J., Polygerinos, P., Bennett, G.J. & Walsh, C.J. 2014. The soft robotics toolkit: shared resources for research and design. *SoRo Soft Robotics,* 1(3).	1. Electroactive polymers 2. Actuators as artificial muscles 3. Pneumatic actuation 4. Biomimetics
2014	Laschi, C. & Cianchetti, M. 2014. Soft Robotics: new perspectives for robot bodyware and control. *Frontiers in Bioengineering and Biotechnology,* 2.	1. Actuators as artificial muscles 2. Electroactive polymers 3. Pneumatic actuation 4. Shape memory alloys actuators

2015	Marchese, A.D., Katzschmann, R.K. & Rus, D. 2015. A recipe for soft fluidic elastomer robots. *SoRo Soft Robotics,* 2(1): 7-25	1. Fluidic drive actuator 2. Actuators as artificial muscles 3. Morphological computation
2015	Hernan, W. & Cuellar, C. 2015. *A biologically inspired fish-like robot actuated by SMA-based artificial muscles.* Madrid: Universidad Politécnica de Madrid.	1. Shape memory alloys actuators
2015	Must, I., Kaasik, F., Poldsalu, I., Mihkels, L., Johanson, U., Punning, A. & Aabloo, A. 2015. Ionic and capacitive artificial muscle for biomimetic soft robotics. *Advanced Engineering Materials.* DOI: 10.1002/adem.201400246, pp. 1-11	1. Ionic and capacitate actuators 2. Actuators as artificial muscles 3. Biomimetics
2015	Shian, S., Bertoldi, K. & Clarke, D.R. 2015. Dielectric elastomer based “Grippers” for soft robotics. *Advanced Materials,* 27(43): 6814-6819.	1. Dielectric elastomers 2. Actuators as artificial muscles 3. Morphological computation
2017	Bar-Cohen, Y. 2017. Artificial muscles. *WorldWide ElectroActive Polymers Newsletter,* 19(1).	1. Actuators as artificial muscles
2017	Calisti, M. 2017. Soft robotics in underwater legged locomotion: from octopus–inspired solutions to running robots. In: *Soft robotics: trends, applications and challenges,* pp. 36-41.	1. Electroactive polymers 2. Actuators as artificial muscles 3. Pneumatic actuation 4. Biomimetics
2017	Calisti, M., Picardi, G. & Laschi, C. 2017. Fundamentals of soft robot locomotion. *Journal of The Royal Society Interface* 14.	1. Actuators as artificial muscles 2. Bioinspiration 3. Biomimetics
2017	Miriyev, A., Stack, K. & Lipson, H. 2017. Soft material for soft actuators. *Nature Communications,* 8(1): 1-8.	1. Electroactive polymers 2. Actuators as artificial muscles
2017	Maziz, A., Concas, A., Khaldi, A., Stålhand, J., Persson, N. & Jager, E.W.H. 2017. Knitting and weaving artificial muscles. *Science Advances,* (3) pp. 1-11.	1. Actuators as artificial muscles 2. Woven textile actuators 3. Assistive devices
2017	Godfrey, J.T. 2017. Soft robotic actuators. Thesis. University of California, Irvine.	1. Electroactive polymers 2. Actuators as artificial muscles 3. Pneumatic actuation

GROUP 2: Biomimetic inspired robotics

Year	Research / Case Study	Focus of the study
2008	Trivedi, D., Rahn, C.D., Kierb, W.M. & Walker, I.D. 2008. Soft robotics: Biological inspiration, state of the art, and future research Deepak. *Applied Bionics and Biomechanics,* 5(3): 99-117.	1. Bioinspiration 2. Biomimetics
2009	Yeom, S. & Oh, I. 2009. A biomimetic jellyfish robot based on ionic polymer metal composite actuators. *Smart Materials and Structures*, (18): 1-10.	1. Ionic polymer 2. Bioinspiration 3. Biomimetics
2011	Calisti, M., Giorelli, M., Levy, G., Mazzolai, B., Hochner, B., Laschi, C. & Dario, P. 2011. An octopus-bioinspired solution to movement and manipulation for soft robots. *Bioinspiration & Biomimetics,* 6(3): 036002.	1. Bioinspiration 2. Biomimetics
2012	Pfeifer, R., Lungarella, M. & Iida, F. 2012. The challenges ahead for bio-inspired ‘soft’ robotics. *Communications of the ACM,* 55(11): 76-87.	1. Bioinspiration 2. Biomimetics
2013	Kim, S., Laschi, C. & Trimmer, B. 2013. Soft robotics: a bioinspired evolution in robotics. *Trends in Biotechnology,* 31(5): 287-294.	1. Bioinspiration 2. Biomimetics 3. Electroactive polymers 4. Actuators as artificial muscles

		5. Pneumatic actuation 6. Shape memory alloys actuators
2014	Roche, E.T., Wohlfarth, R., Overvelde, J.T.B., Vasilyev, N.V., Pigula, F.A., Mooney, D.J., Bertoldi, K.& Walsh, C. J. 2014. A bioinspired soft actuated material www.advmat.de. *Advanced Materials,* 26(8): 1200-1206.	1. Pneumatic actuation 2. Bioinspiration 3. Biomimetics
2016	Laschi, C., Mazzolai, B.& Cianchetti, M. 2016. Soft robotics: technologies and systems pushing the boundaries of robot abilities. *Science Robotics,* 1-11.	1. Actuators as artificial muscles 2. Morphological computation 3. Bioinspiration 4. Biomimetics
GROUP 3: Morphological computation		
Year	**Research / Case Study**	**Focus of the study**
2007	Pfeifer, R., Lungarella, M. & Iida, F. 2007. Self-organization, embodiment, and biologically inspired robotics. *Science Magazine*, 16 November: 1088-1093.	1. Morphological computation 2. Biomimetics
2010	Seok, S., Onal, C. D., Wood, R., Rus, D. & Kim, S. 2010. *Peristaltic locomotion with antagonistic actuators in soft robotics.* Anchorage, Alaska, USA, IEEE International Conference on Robotics and Automation.	1. Actuators as artificial muscles 2. Morphological computation 3. Bioinspiration 4. Biomimetics 5. Peristaltic actuation
2011	Hauser, H., Ijspeert, A., Füchslin, R., Pfeifer, R. & Maass, W. 2011. Towards a theoretical foundation for morphological computation with compliant bodies. *Biological Cybernetics*, 105: 355-370.	1. Morphological computation
2011	Ilievski, F., Mazzeo, A., Shepherd, R. F., Chen, X. & Whitesides, G.M. 2011. Soft robotics for chemists. *Angewandte Chemie - International Edition,* 50(8):1890-1895.	1. Morphological computation 2. Pneumatic actuation
2012	Hiller, J. & Lipson, H. 2012. Automatic design and manufacture of soft robots. *IEEE Transactions on Robotics,* 28(2): 457-466.	1. Generative encoding
2013	Cheney, N., MacCurdy, R., Clune, J., & Lipson, H. 2013. Unshackling evolution: evolving soft robots with multiple materials and a powerful generative encoding. *Proceeding of the Fifteenth Annual Conference on Genetic and Evolutionary Computation - GECCO '13,* 167-174.	1. Generative encoding 2. Morphological computation 3. Biomimetics
2013	Galloway, K.C., Polygerinos, P., Walsh, C.J., & Wood, R.J. 2013. Mechanically programmable bend radius for fiber-reinforced soft actuators. *16th International Conference on Advanced Robotics (ICAR)*, 2013, pp. 1-6, doi: 10.1109/ICAR.2013.6766586.	1. Morphological computation 2. Pneumatic actuation
2014	Tolley, M.T., Shepherd, R.F., Mosadegh, B., Galloway, K.C., Wehner, M., Karpelson, M., Wood, R.J., & Whitesides, G.M. 2014. A resilient, untethered soft robot. *Soft Robotics,* 1(3): 213-223.	1. Morphological computation
2014	Mosadegh, B., Polygerinos, P., Keplinger, C., Wennstedt, S., Shepherd, R.F., Gupta, U., Shim, J., Bertoldi, K., Walsh, C.J. & Whitesides, G.M. 2014. Pneumatic networks for soft robotics that actuate rapidly. *Advanced Functional Materials*, 4: 2163–2170.	1. Morphological computation 2. Pneumatic actuation
2014	Marchese, A.D., Onal, C.D. & Rus, D. 2014. Autonomous soft robotic fish capable of escape	1. Actuators as artificial muscles

	maneuvers using fluidic elastomer actuators. *SoRo Soft Robotics,* 1(1): 75-87.	2. Morphological computation 3. Fluidic elastomer actuators
2015	Connolly, F., Polygerinos, P., Walsh, C.J. & Bertoldi, K. 2015. Mechanical programming of soft actuators by varying fiber angle. *SoRo Soft Robotics,* 2(1): 26-38.	1. Morphological computation 2. Fibre reinforced actuators
2016	Galloway, K.C., Becker, K.P., Phillips, B., Kirby, J., Licht, S., Tchernov, D., Wood, R.J.& Gruber, D.F. 2016. Soft robotic grippers for biological sampling on deep reefs. *SoRo Soft Robotics*, 3(1): 23-33.	1. Actuators as artificial muscles 2. Morphological computation 3. Fluidic elastomer actuators
2016	Wehner, M., Truby, R.L., Fitzgerald, D.J., Mosadegh, B., Whitesides, G.M., Lewis, J.A. & Wood, R.J. 2016. An integrated design and fabrication strategy for entirely soft, autonomous robots. *Springer Nature* (536): 451-467.	1. Actuators as artificial muscles 2. Morphological computation
2016	Yang, D., Verma, M.S., So, J., Mosadegh, B., Keplinger, C., Lee, B., Khashai, F., Lossner, E., Suo, Z. & Whitesides, G.M. 2016. Buckling pneumatic linear actuators inspired by muscle. *Advanced Material Technologies,* (1): 1-6.	1. Actuators as artificial muscles 2. Morphological computation 3. Pneumatic actuation
2016	Yang, Y., Chen, Y., Lia, Y., Chena, M. Z.Q. & Weia, Y. 2016. Bio-inspired robotic fingers based on pneumatic actuator and 3D printing of smart material. *SoRo Soft Robotics,* (34): 1-26.	1. Actuators as artificial muscles 2. Morphological computation 3. Heat-based actuators
2017	Connollya, F., Walsha, C.J. & Bertoldia, K. 2017. Automatic design of fiber-reinforced soft actuators for trajectory matching. *Paulson School of Engineering and Applied Sciences,* 114(1): 51-56.	1. Actuators as artificial muscles 2. Morphological computation
2018	Marchese, A.D., Komorowski, K., Onal, C.D. & Rus, D. 2018. Design and control of a soft and continuously deformable 2D robotic manipulation system. *IEEE International Conference on Robotics and Automation (ICRA),*	1. Morphological computation 2. Fluidic drive actuator

GROUP 4: Applications for SRTs

Year	**Research / Case Study**	**Focus of the study**
2004	Bicchi, A. & Tonietti, G. 2004. Fast and “soft-arm” tactics. *IEEE Robotics and Automation Magazine,* 11(2): 22-33.	1. Elastomeric actuators 2. Mechanical compliance
2005	Dario, P., Carozza, M.C., Guglielmelli, E., Laschi, C., Menciassi, A., Micera, S. & Vecchi, F. 2005. Robotics as a future and emerging technology. *IEEE Robotics and Automation Magazine,* 29-45.	1. Actuators as artificial muscles 2. Human augmentation 3. Assistive devices 4. Wearable robots
2013	Bongard, J.C. 2013. Evolutionary robotics. *Communications of the ACM,* 56(8): 73-83	1. Robotics design 2. Actuators as artificial muscles 3. Assistive devices
2014	Ventola, C.L. 2014. Medical applications for 3D printing: current and projected uses. *P & T,* 9(10) 704-711.	1. 3D printing for medical applications
2014	Cianchetti, M., Ranzani, T., Gerboni, G., Nanayakkara, T., Althoefer, K., Dasgupta, P. & Menciassi, A. 2014. Soft robotics technologies to address shortcomings in today’s minimally invasive surgery: the STIFF-FLOP Approach. *SoRo Soft Robotics,* 1(2): 122-131.	1. Robotics design 2. Actuators as artificial muscles 3. Assistive devices 4. Medical devices

2015	Rus, D. & Tolley, M.T. 2015. Design, fabrication and control of soft robots. *Nature,* 521(7553): 467-475.	1. Robotics design 2. Actuators as artificial muscles 3. Morphological computation
2015	Polygerinosa, P., Wang, Z., Gallowaya, K.C., Wood, R.J. & Walsha, C.J. 2015. Soft robotic glove for combined assistance and at-home rehabilitation. *Robotics and Autonomous Systems,* 73: 135-143.	1. Assistive devices 2. Wearable robots 3. Pneumatic actuation
2016	Rossiter, J. & Hauser, H. 2016. Soft robotics - The next industrial revolution? *IEEE Robotics and Automation Magazine,* 23(3), pp. 17-20.	1. Actuators as artificial muscles 2. Human augmentation 3. Assistive devices 4. Wearable robots 5. Industrial applications
2016	Muth, J.T., Vogt, D. M., Truby, R.L.; Mengüç, Y., Kolesky, D.B., Wood, R.J. & Lewis, J.A. 2016. Embedded 3D printing of strain sensors within highly stretchable elastomers. *Advanced Materials, 26*, 6307–6312.	1. 3D printing sensors into soft elastomers
2017	Laschi, C., Iida, F., Rossiter, J., Cianchetti, M. & Margheri, L. 2017. *Soft Robotics: Trends, Applications and Challenges. s.l.*: Springer.	1. Actuators as artificial muscles 2. Human augmentation 3. Assistive devices 4. Wearable robots

4.2.3 Result of focused metadata and literature analysis

From the analysis of additional metadata research there were four main groups of SRTs research found, namely: actuation by means of artificial muscle, biomimetic inspired robots, morphological computation and applications for SRTs. The metadata as set out in Table 4.2 can be summarised into a simplified matrix in order to better show the overriding themes and commonality between the groups. Within these groups, there were two focus areas common to all four, namely, actuators as artificial muscles and morphological computation. Table 4.3 will present this view, which is discussed further in Chapter Five.

It was at this point that the researcher interviewed medical design experts, in order to gather real-world design requirements for two case study projects. This is a key step in the research method used, as the researcher has aimed to anchor the research to real-world applications and needs, with the aim of conducting valid and worthwhile research. This pragmatic approach has assisted in the gathering of data that not only speak to the research problems described in Chapter One, but also aided the researcher to filter out data and information that might otherwise distract or confuse the study. The findings from these two case studies and interviews, described in

Section 4.3, “Interviews with medical experts and results”, helped guide further detailed metadata and literature research.

Table 4.3: Overriding themes present in the metadata (Author’s construct, 2021)

GROUP 1: Actuation by means of artificial muscle	**GROUP 2: Biomimetic inspired robotics**	**GROUP 3: Morphological computation**	**GROUP 4: Applications for SRTs**
Actuators as artificial muscles	Actuators as artificial muscles	Actuators as artificial muscles	Actuators as artificial muscles
Morphological computation	Morphological computation	Morphological computation	Morphological computation
Bioinspiration	Bioinspiration	Bioinspiration	Medical devices
Biomimetics	Biomimetics	Biomimetics	Assistive devices
Pneumatic actuation	Pneumatic actuation	Pneumatic actuation	Wearable robots
Peristaltic actuation	Peristaltic actuation	Peristaltic actuation	Robotics design
Electroactive polymers	Electroactive polymers	Electroactive polymers	Human augmentation
Fluidic elastomer actuators	Fluidic elastomer actuators	Generative encoding	3D printing Sensors into soft elastomers
Fluidic drive actuator	Fluidic drive actuator	Mechanical compliance	Mechanical compliance
Ionic polymer	Ionic polymer		
Shape memory alloy actuators	Shape memory alloy actuators		
Dielectric elastomers			
Woven textile actuators			

4.3 Interviews with medical experts and results

After the literature review was completed, and the above themes identified, the researcher was able to meet with appropriate experts in the field of medical design. Two real-world projects were used as case studies to further focus the research. The design briefs for these two case studies can be seen in Appendices C and D. The researcher analysed the requirements from these two project design briefs in order to identify areas where the SRT research could be of use and form the foundation for further discussions with industrial design experts. This will be described here now.

4.3.1 Consolidation of interview and design brief data

Both case studies provided the researcher with real-world requirements for medical devices that were intended to be worn by the user, needed to have inherent flexibility and incorporate advanced functionality. With these requirements as a guide, the researcher was able to prepare for further discussions and interviews with expert industrial designers at two design agencies in Shanghai. These requirements are set out in a simple matrix in Table 4.4 to show commonality between the two projects, namely, the *Medi-dot* a soft intelligent device that could be worn on the patient's knee to track patient recovery after knee surgery and the *Fit Shoe Sole* an intelligent soft in-sole to track glucose levels and gait analysis. This table also shows how these requirements align with the overriding research being conducted. As set out in the limitations of the study in Chapter One, the researcher did not focus on electronics development, sensors and related technologies, but rather on requirements that related to the main theme defined during the literature review, namely, soft robotic actuation technologies. This ensured the research remained focused on the exploration of uses for SRTs in the industrial design of medical products on a mechanical level, allowing for conceptual testing of these SRTs during the planned focus group design work.

Table 4.4: Consolidated design requirements for the two case studies (Author's construct, 2021)

Requirements related to soft smart materials	**Medi-dot**	**FIT**
Device is to be worn by the user/patient	Yes	Yes
The device should be lightweight and comfortable to wear	Yes	Yes
Ergonomic and flexible	Yes	Yes
Must be able to wear the device under clothing	Yes	Yes
Adaptable to each user – for correct placement on the user	Yes	Yes
Soft garments and wearable technologies	Yes	Yes
Elasticity to allow for post-op swelling	Yes	No
Requirements related to actuation	**Medi-dot**	**FIT**
May require some form of actuation/compression to stimulate blood flow in the area around the surgery	Yes	No
Research actuators and compression technologies available.	Yes	No

4.4 Relation of soft robotics actuators to case study requirements

As described, the focused metadata research and interviews with medical design experts allowed for more focused and detailed research into SRTs to be conducted. The common theme of actuation identified in the focused metadata research phase was covered in more detail, as is outlined in the literature review in Chapter Two. The soft robotics actuation technologies were then related back to the design requirements gathered from the two medical design case studies. This is shown in Table 4.5., where the soft robotics actuation technologies are listed and their suitability for each requirement is marked as either Yes or No.

Table 4.5: Relation of soft robotics actuators to case study design requirements (Author's construct, 2021)

SRT actuator properties in relation to industrial design requirements (identified in the case studies)		**Soft robotics actuation technologies**				
		Electro-active polymers	Shape memory alloys	Ionic polymer actuator	Pneumatic actuator	Fluidic drive actuator
Industrial design requirements: (as determined from the analysis of the two medical case studies)	Allows compression	Yes	Yes	Yes	Yes	Yes
	Elastic or flexible	Yes	Yes	Yes	Yes	Yes
	Soft	Yes	Yes	Yes	Yes	Yes
	Ergonomic	Yes	Yes	Yes	Yes	Yes
	Adaptable to each user	Yes	Yes	Yes	Yes	Yes
	Wearable by the user	Yes	Yes	No	No	No
	Wearable under clothing	Yes	Yes	No	No	No
	Lightweight	Yes	No	No	No	No

From Table 4.5., it is clear that electro-active polymers (EAPs) were the only SRT that met all the requirements derived from the medical case studies. It was for this reason that EAPs were chosen as the focus for further exploration in this study.

4.5 Interviews with industrial design agencies

By completing the detailed literature review and using real-world design requirements gathered from the medical design case studies, the focus of this study was narrowed to a specific group of SRTs, namely, EAPs. The researcher was now prepared for further interviews with industrial design experts in the medical field, to begin exploring the current understanding of EAPs in the medical design industry, with a view to conducting further practical research through the use of a focus group. Two industrial design agencies were included in this phase of the research and the findings from these interviews will subsequently be described.

4.5.1 Wild design: Shanghai-based industrial design agency

The first industrial design agency that was interviewed was the Wild Design Agency – Shanghai, China. Through the use of specific interview questions, the researcher was able to get a clear understanding of this specific agency's experience and understanding of industrial design for the medical industry. Further questions were then focused on their exposure to SRTs in general, with a final focus on the possible use of EAPs in the industrial design of medical products. The two participants in the interview were both experienced senior industrial designers. The design process used by Wild Design was discussed in detail and is provided here for clarity in Figure 4.1. The purpose of reviewing their design process was to understand at what stage, if any, they might look into using new technologies for a specific design project. It was then affirmed that they make use of a research phase at the beginning of all projects, in which design requirements, manufacturing requirements, materials, processes and end-user experience are all covered.

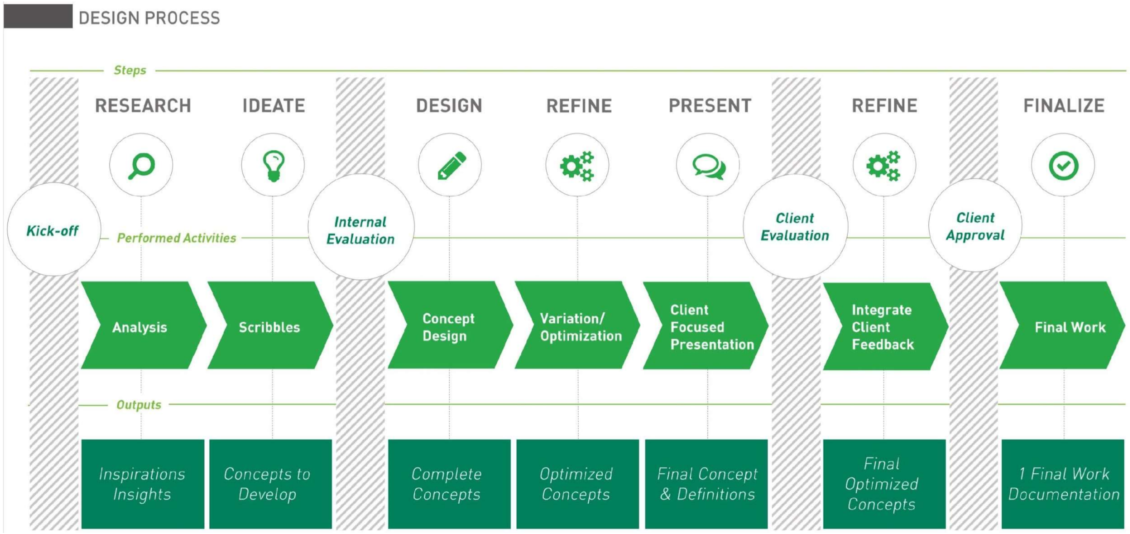


Figure 4.1: Design process – Wild Design, China (Wild Design)

The interview was audio recorded and then transcribed for ease of analysis. The most relevant findings from this interview are presented in Table 4.6. The researcher grouped the questions into three main categories. The first group of questions was designed to show Wild Design's experience and knowledge of industrial design for the medical industry. The second group of questions was designed to get a view of Wild

Design's understanding of innovation and the adoption of new technologies when developing products for the medical industry. The third group of questions was designed to get a view of Wild Design's understanding of the use of SRTs in the industrial design of medical products. The researcher has summarised the answers under "relevance to the study", to allow for further expansion and discussion in Chapter Five. Points of particular noteworthiness and relevance are highlighted in yellow.

Table 4.6: Findings from interview with Wild Design (Author's construct, 2021)

Questions related to context of design for the medical industry		
Interview question	**Answer by Wild Design**	**Relevance to the study**
What are your areas of experience in medical design?	"…medical devices and like all electronic wearables, home care, elderly, surgery, laboratory equipment, so they cover the full spectrum."	- Medical devices - Electronic wearables - Home care, elderly
What is your main focus?	"... their focus now is we're always trying to reference in on the user experience and the usability on a human sense of design."	- User experience - Usability
What challenges do you experience in the field of medical design?	"…regulation can make or break the kind of companies for investment in a medical device."	- Regulation in medical industry - Investment limitations
What do you understand to be typical of the medical design industry?	"…these types of companies are massive, they've got many different devices across many different ranges, so they've just got a lot of production, engineering knowledge, manufacturing. So…it's now just a matter of them shifting that knowledge across to R&D."	- Big medical device companies have in-house knowledge that can be leveraged for R&D - Multi-faceted development
How long has Wild Design been developing medical products?	Our office here, we've been here 12 years.	- Experienced at medical design
Do you find medical development companies in China work in a structured, regulated way, or is the focus on speed?	"…quickly trying to learn, build steps and fail, get it out to market as quick as possible, maybe fail but still take it as a learning experience to build up."	- Speed to market is critical
What challenges do you experience in designing new medical devices?	"... it might be a disregard to design, it's coming from a financial partner, investor or just wanting to grow, get product on the market."	- Clients want to go to market as priority - New solutions take longer to develop - Repeat what works
How do you design for the future and	"Sometimes it's a hard conflict between us and the client when we	- Difficult to innovate with new technologies

encourage your clients to think ahead?	want to try and develop…across the different touch points.”	
Would you say Europe is ahead of China in terms of medical development?	“…Europe is definitely ahead, the regulation, CE, there is the highest, and the new medical device NDR, that is definitely on the global level kind of pushing and changing a lot of things.”	- Europe is ahead of Asia in terms of regulations and medical development
Do you see a difference between the mindset of an international client versus a client in China?	“Chinese companies are going in let's say headfirst and getting to market and are gaining some return where someone else is still four years down and not in the market.”	- Development in China is often faster paced, with higher risks
Are the sizes of markets in Europe versus China different?	“China has got a massive market, certain things now, you're looking at 20,000 hospitals, plus some of it coming would be... it's like one product that goes into one hospital, Europe might have 200/300 hospitals, and so the market for that device is completely different.”	- China has a much larger market than Europe. - Easier to launch new products at a lower level of development
Are there any areas of the medical industry that are developing faster than others?	“Biotech has definitely got a lot of money coming into it. The offshoot of that is med tech, but I definitely don't think it has the same amount of backing compared to biotech.”	- Biotech is developing faster than other areas in the medical field

Questions related to medical design and innovation using new technologies

Interview question	**Answer by Wild Design**	**Relevance to the study**
Do you have a lot of experience working with medical companies to develop new products?	“…our German office has got a massive collection of medical companies they've worked with over the years. Some of them are brands that we help build up…”	- Experienced in the field of medical design
Is there a specific focus that you are trying to create?	“…new product development, better ergonomics, better usability…”	- Innovation often starts with the industrial designer
Do you find you have to encourage and educate the client on the importance of usability and user experience?	“All the time.”	- Change client mindset - Highlight the importance of usability and user experience
Do you get involved in innovation using new technologies?	“…because we are not developing any real technology ourselves, we're really just supporting usability or the aesthetics, design…”	- No focus on innovation using new technologies
Do you do user testing in-house then?	“We do a little bit of user testing internally… we are just trying to understand the user flow, the workflow of the device.”	- Minimal user testing in-house
How do you help keep your client’s product up-to-date and on trend?	“So, every two or three years they want to do a trend study report…”	- Trend forecasting and analysis

		- Product development planning - Product development strategy
What areas of product development have you been focused on?	“So, some of it is consumer products, which we are doing bathrooms, we've been doing robotics, we've been doing escalators designs, laboratory equipment.”	- Robotics
Why these areas of focus?	“So, here in China we have gone across a very broad spectrum, and that's because being here in Shanghai, China, I guess 10 years ago the med tech centre was well established here, so that's growing quickly now, and too there is a five-year plan from the government, so there is money that's investing where it is.”	- Government funding promotes development - Med tech centre in Shanghai

Questions related to soft robotics technologies used in medical design

Interview question	Answer by Wild Design	Relevance to the study
What is your understanding of soft robotics tech?	“Soft robotics, for me from what you explained it's to my understanding would be more or less kind of I guess health care, point of care tech. Obviously, robotics I guess is more to do with the sensors and... actuators.”	- Soft robotics is used in health care, point-of-care - Actuators
Do you know of any applications for soft robotics technologies in the medical industry?	“Exoskeletons. You're getting into mostly people with like kind of spine damage or something there that this would help, just help them exercise. And where there was no resistance to then a little bit of resistance for them that they can develop again.”	- Soft robotics in exoskeletons - Used for resistance training
What are the main drivers to use soft robotics technologies?	“…the main things we try and talk about was how to soften (designs)…They also make it feel comfortable and stuff for them that is not scary...”	- SRT used to create softer designs
Where will it be feasible to implement them or use them?	“I think probably you will see the biggest drive in rehab. I think they will be the ones who will push that market the most.”	- SRT may be used in rehabilitation first
Are there companies or people in the medical field that have looked at already implementing them?	“I think the big drivers will be the sporting industry rehab.”	- Sporting industry rehabilitation
Do you see believe a soft device could be used in the medical industry to replace current rigid solutions?	“I think most definitely those solutions, they will be a viable means”	- Potential for SRTs to replace rigid alternatives

What is your experience with integration of SRTs into wearable devices or garments?	"…it's like all the stitching, the electrodes are stitched…the fabric itself stretches. So, we are aware of these…"	- SRTs in wearables
What manufacturing processes might suit this type of soft technology?	"…3D printing in mass production could be the way to integrate soft technologies into products. There is a company in Shanghai called Stratasys that you should speak to, they might have more information…"	- 3D printing for mass production

4.5.2 Designaffairs: Shanghai-based industrial design agency

The second industrial design agency that was interviewed was designaffairs – Shanghai, China. For this interview, the researcher kept the questions focused specifically on robotics development at designaffairs and their understanding of SRTs. Additional questions were asked, based on the course of the interview, to further understand certain points designaffairs raised, namely, those related to designing with the 4D approach. The participant in the interview was an experienced senior industrial designer. The researcher has summarised the answers under "relevance to the study", to allow for further expansion and discussion in Chapter Five.

Table 4.7: Findings from interview with designaffairs (Author's construct, 2021)

Questions related to medical and robotics design and the use of SRTs		
Interview question	**Answer by designaffairs**	**Relevance to the study**
Do you have experience in designing for the medical industry?	"Yes. We also developed some healthcare robots. This was a... basically I led the project, and we observed the competitors in terms of how they are understanding the relation between the robots and the elderly people. When we talk about healthcare robots it means someone who is 24/7 with you at home following you and communicating with you. So, there is one term that we have been trying to use for explaining these, and we call it 4D, that is four dimensions."	- Healthcare robots
Are there any examples you can give of medical design work you have done?	"Yes… with Siemens we have been collaborating with them to do the whole line of products for medical and Healthcare."	- Healthcare - Medical products

My understanding of 4D is that it is more than touch and sight, and that it is to do with emotion?	“Yes. I think humanising the devices is the future of long-lasting products.”	- Humanising devices - Designing in emotion
I want to understand the potential for how these technologies can be used to develop products that are in line with the 4D approach. So, instead of having a screen, maybe the body is a gelled silicon body that's nice to touch or to hold onto for support. And instead of it just being a shell, it compresses. And then maybe it gets warm, so it's nice to hold if you're feeling lonely.	“Yes correct, that is the idea.”	- Humanising devices - Designing in emotion
What is your exposure to soft robotics and the use of soft materials as opposed to rigid alternatives?	“For the Bingo robot we explored the textiles for the shell.”	- Textiles in robotics
Have you explored or used electroactive type materials or soft sensors?	“No, not yet.”	
Have you been involved in any robotics design or industrial design for robots?	“Yes…a home robot. Ecovacs was a start-up some years ago and they wanted to break through the robotics market with a very defined design language.”	- Rigid robot design
Have you designed anything for the healthcare sector related to robotics?	“So, we have the medicine box, we have their oxygen measurement, their blood pressure. And we understood if the robot is trying to be your companion it should take them to you.”	- Companion robot

4.6 Interview with 3D printer manufacturer - Stratasys

During the interview with Wild Design, it was recommended to the researcher that an additional interview be arranged with Stratasys in Shanghai, an additive manufacturing specialist company that develops high-end, production grade 3D printers. Two representatives from Stratasys participated in the interview and provided insights into the functioning of the company's full range of 3D printers. Of particular interest to the researcher were the printers that were able to print in multi-density polymers, as these aligned to the basic material properties in the EAP actuation technology being explored. As EAPs are rubber-like, and can be shaped as desired, the potential for integrating this SRT into a product by means of 3D printing would free up the possible designs. Various interview questions were prepared in advance of the meeting and are presented in Table 4.8.

Table 4.8: Findings from interview with Stratasys (Author's construct, 2021)

Questions related to 3D printing with multi-density polymers and EAPs		
Interview question	**Answer by Stratasys**	**Relevance to the study**
Is 3D printing possible to use in mass production?	"Yes. They already are."	- Feasible for mass production
Why is 3D printing a good option for mass production?	"…both in terms of material properties, a big one, and in terms of the cost and speed. If you are talking about highly complicated parts…"	- Suitability for mass production
Are you able to 3D print in rubber material?	"Yes, we have a line of 3D printers and materials specifically for that."	- 3D printing in rubber is possible
Are you able to 3D print in different densities of rubber at the same time on one machine?	"Yes, we can print like many different rubber materials in one part."	- 3D printing of multi-density rubbers in a single part is possible
Can you show examples of printing in single or multi-density rubber?	"Yes, here is some samples of different pieces we have printed. The heart is printed in different samples to show the internal structure too…"	- Examples of multi-density 3D printing supplied
Are there requirements from the market to develop specific 3D printing machines to allow for specific end products?	"We do get pressures from the market that we interface from day-to-day, people are asking for actual rubber, not just rubber-like."	- Market-driven development of 3D printing machines - Production grade rubber 3D printing has been requested
Have you had any requests to allow for printing of electro-active polymers or similar materials?	"So, if you are interested, we do have some universities researchers are working on what they call 4D printing, kind of a similar idea, but you actuate something, whether it's electricity or water, light, the model changes."	- Electro-active polymer 3D printing is currently being researched
Who is developing or researching these electro-active polymers for 3D printing?	"MIT"	- MIT are actively researching 3D printing of electro-active polymers
Is there any development in China into advanced polymers for 3D printing?	"Shanghai University also has a lab, flexible robotics, is working on that. And in Asia I think we have someone in Singapore, SUTD, Singapore University of Technology and Design, I think.	- Additional research into 3D printing of advanced polymers is being conducted in Shanghai and Singapore

	So, they are pretty advanced in this as well.”	
How close to production-grade rubber products are you able to 3D print?	“If you talk about like memory speed, in terms of the softness, right now we are at ShA 27, and these guys go to about ShA 5, or even they are thinking of going to zero.”	- Production-grade rubber printing
What challenges are you facing in terms of production-quality 3D printing of polymers?	“Thermal resistance, that's our biggest testing overtime. And water is another big one too.”	- Low thermal resistance - Low resistance to water absorption
Do you know of any examples where electronics and conductive materials were incorporated into a 3D printer during printing?	“So, back in the day, Disney had done some amazing projects we found… they were able to insert sensors using boards…into the printed parts, or during the printing process. So, that's… a work-around to what's in conductive material, which we don't have at the moment.”	- No conductive materials available for 3D printing at time of interview
Do you have any information regarding the development of electro-active polymers for 3D printing?	“I'll select… some materials suggestion and see if it's possible to connect you guys to get it to such time for future design, future research. It's pretty futuristic.”	- No research on 3D printing EAPs available at time of interview

As described in Table 4.8, Stratasys have developed a line of printers that are able to 3D print in multi-density polymers that are rubber-like. This allowed for the following example of a human heart to be printed, where the complex organic internal structure was printed in a rubber-like polymer to simulate the internal structure of a human heart and valves as shown in Figure 4.2. The example shown in Figure 4.2 was printed separately to show the detail of the internal structure.

Figure 4.2: 3D printed heart – soft polymer, internal structure (Stratasys)

The material around this structure was printed in a much softer polymer that compressed easily and felt similar to organic muscle tissue. This could be done at the same time on a single 3D printing machine, so that the rigid internal structure is completely encapsulated by the softer external matrix. Figure 4.3 and Figure 4.4 show this finished 3D printed heart, where both the internal structure and external matrix are printed together in one print. For the purposes of this research study, it is significant, as it demonstrates how one could design a medical device or product to include internal structures that have differing densities and properties, if the method of production is intended to be 3D printing. The interview confirmed that 3D printing as a means of mass production is not only feasible, but already in practice as a recognised production process. For this production method to be used to incorporate EAPs into a product will, however, require further developments in materials research, but this is currently underway by both MIT and the Singapore University of Technology. The researcher will use this to support the viability of the concept designs developed in the focus group, which will be described next in this chapter.

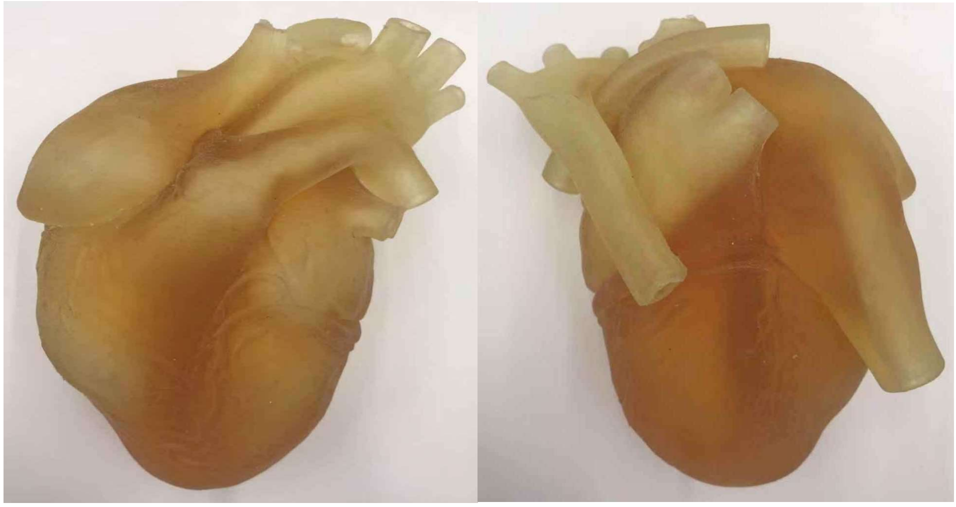


Figure 4.3: 3D printed heart – soft polymers, multi-density single print (by author)

Figure 4.4: 3D printed heart – soft polymers, multi-density single print (by author)

4.7 Focus group and questionnaires

This section will discuss the design focus group and concept development done at the Hunan University with a group of industrial design students. A pre-focus group questionnaire was used to evaluate the participants' knowledge and understanding of SRTs before commencing with the workshop, and a post-focus group questionnaire was used after the workshop completion to evaluate the change in perception and understanding of these technologies. The outcome of this exercise aimed to show the potential for using SRTs in product design.

4.7.1 Pre-focus group questionnaire and results

The pre-focus group questionnaire was completed by all eight participants, before proceeding with the design focus group, in order to gauge their understanding and familiarity with SRTs beforehand. The results of this questionnaire are shown in Table 4.9.

Table 4.9: Findings from pre-focus group questionnaire (Author’s construct, 2021)

Pre-focus group questionnaire (8 participants)			Grouping
Interview questions	**Answers by participants**	**Respondents**	
Question 1: What soft robotics technologies (SRTs) do you know of?	ICPF high polymer	- 1 student	SRTs
	EAP	- 1 student	
	Air inflation	- 3 students	Vague reference to SRTs
	Air and organic solvents	- 1 student	
	Pressure hose and fluid chamber	- 1 student	
	Chemical reaction (produce some gas to drive the soft body)	- 1 student	
	Liquid or gas engine	- 1 student	
	Fluid materials	- 1 student	
	Flexible structures	- 2 students	
	Some technologies that apply to scientific research and exploration.	- 1 student	
	As far as I know, it is a technique inspired by soft organisms. I heard that robots used these technologies to exhibit the same elasticity and deformability as soft organisms.	- 1 student	
	Flexible clamping jaws in Beijing	- 1 student	Applications
	Paper robot	- 1 student	
	Worm robot	- 2 student	
	Under marine soft robotic	- 1 student	
	Industrial making soft robotic	- 1 student	
	Tissue engineering using polymers (organic materials with cells implanted into synthetic polymers)	- 1 student	
	Sorry I know nothing about SRTs	- 1 student	None
Question 2: What SRT applications do you know of?	Artificial muscle	- 5 students	Bioinspired
	Artificial heart	- 1 student	
	A kind of artificial fish	- 1 student	
	Bio-robots	- 1 student	
	Bionic robots	- 2 students	
	Actuator	- 1 student	Vague
	Sensor	- 1 student	
	Measure shape change	- 1 student	
	Intelligent hardware	- 1 student	
	Minimally invasive surgery	- 1 student	Medical and
	Inspection robot	- 1 student	
	Endoscope	- 1 student	
	Medicine translation	- 1 student	
	Health care	- 4 students	

	Maybe in healthcare, but I’m not sure	- 1 student	
	Due to its flexibility, SRTs are now applied to fields like medical and field survey, but at present most of them are still under research.	- 1 student	
	Medical help	- 1 student	
	Used to clamp machine parts in factories.	- 3 students	Factory
	Factory (used to lift things)	- 1 student	
	AI light in factory	- 1 student	
	Sorry, there’s not a specific case in my mind.	- 1 student	None
	I really don’t know…	- 1 student	
Question 3: What SRTs have you worked / designed with?	None	- 7 students	None
	Just have made some polymer artificial tissues.	- 1 student	
Question 4: Have you got experience using SRTs in industrial design?	No	- 8 students	None
Question 5: Do you see potential for SRTs to be used in industrial design (specifically medical and consumer product design)?	Yes	- 1 student	Potential for SRTs to be used in medical and consumer product design
	Yes, I believe the SRTs are useful since they can create different stimulation for touching and form depending on the voltage.	- 1 student	
	I think the SRTs will be a great technology to be used in products. Because of its flexible body and touch, it has the special characteristics that other technologies don’t have.	- 1 student	
	Healthcare, medicine transfer, actuator	- 1 student	
	Yes, I think this is an innovation for the future design.	- 1 student	
	Yes, help doctor to do operations inside human’s body	- 1 student	
	Of course, yes. Every new technology should be considered as a breakthrough point of a new product or an updated product. In the medical field, SRTs may make robotic surgery accurate, faster and simpler. Also, it may be useful in medical attention. In other respects, it can be applied to various fields such as transportation, service, special concern, etc.	- 1 student	
	At present, because of the lack of flexibility of medical tools, some operations are very risky and difficult. If we can design medical products with SRTs that can do the operations precisely, the medical industry will have a huge breakthrough. For example, in the future when having a heart surgery, the only wound will be a small hole that used to be put in part of a robot.	- 1 student	

	Of course! It has great potential. Especially in the medical industry, it can make the medical equipment more flexible and softer.	- 1 student	🟨
	Sure. It can help people do some exquisite work to reduce the rate of fault.	- 1 student	
	Yes, in contrast with the mechanical robots, they are evidently more suitable for human life.	- 1 student	
	When it comes to consumer products, I think it might be a good direction if we try to make robots that can go into places like unknown caves and deep sea for photography just like drones.	- 1 student	
	After I searched the internet, I think that it surely has potential to be used in industrial design. Maybe some emergency situations need SRTs to finish tasks which are too dangerous for human beings.	- 1 student	

In response to Question 1, *What soft robotics technologies (SRTs) do you know of?,* it is clear that the participants had a sporadic and limited awareness of SRTs. Where some of the answers such as “air inflation” and “flexible structures” appear to refer to pneumatic actuation and the use of soft elastic materials, it is not specific and instead more a vague indication of the types of technologies that might exist. Of the eight participants, only one was aware of the existence of EAPs, which, as discussed earlier, is the SRT that appears most suitable for exploration in the design focus group. A number of answers were in fact references to applications for SRTs, which shows that the concept of a soft robot is not new to the participants, but their understanding of the technologies that these robots make use of is not understood. One participant confirmed that they have no knowledge of SRTs, which is interesting to note when five of the other participants did not, in fact, refer to a specific SRT directly. From this it can be concluded that only two students had any knowledge of SRTs, and they were each aware of only one.

In response to Question 2, *What SRT applications do you know of?,* there was a better understanding of where SRTs might be used. Five of the students were aware that SRTs have been used to create artificial muscles, with two examples of this being mentioned, namely, an artificial heart and an artificial fish. Again, there were some vague references to general functions of SRTs, namely: actuator, sensor, measure shape changes and intelligent hardware. Six of the eight participants referred to the medical industry or healthcare as areas in which SRTs might be used but were not able to refer to specific examples other than endoscope and inspection robot. What is interesting here is that the students expressly mention the medical field. Four of the participants mentioned factory applications for SRTs in the form of soft grippers to lift items, with one participant also referring to an AI light for factory environments. Two participants stated that they did not know of any applications for SRTs at all.

In response to Question 3, *What SRTs have you worked / designed with?.* only one participant had any experience as the participant stated: “Just have made some polymer artificial tissues”. Seven of the eight participants stated that they have never used SRTs in any of their design projects or any other work-related exercise.

In response to Question 4, *Have you got experience using SRTs in industrial design?.* all eight participants answered that they had no experience using SRTs in industrial design. This shows without question that the participants had not attempted to explore the technologies on any of the projects they had been tasked with during their time of study. This also shows the lack of focus on these SRTs by the Hunan School of Design. As has been described earlier in Chapter Three, the Hunan School of Design is at the forefront of advances in technology and design, with direct links to industry and many advanced facilities on their campus, including a robotics department. It follows that if these participants, which included industrial design master’s students, had no exposure, then it is likely that industrial design students in general have limited, if any, exposure to SRTs.

In response to Question 5, *Do you see potential for SRTs to be used in industrial design (specifically medical and consumer product design)?*, all eight participants responded with positivity and enthusiasm. Various ideas were suggested where SRTs might be implemented, showing the participants’ willingness to explore conceptual applications. This was of particular interest to the researcher, as it set the foundation for the focus group conceptual design work that was to be conducted with the participants. Regardless of the applications mentioned in their answers, whether they be for use in surgeries, healthcare, marine applications or robotics, the fact that the participants showed such openness to using what one described as “…an innovation for the future design.”, shows that there is an opportunity to explore applications for these technologies in partnership with industrial design students. This will be demonstrated subsequently in the focus group and results section of this study.

4.7.2 Focus group and concept development workshop results

The researcher developed a focus group conceptual design exercise in order to evaluate the participants' understanding of SRTs and explore the potential for developing new and innovative products using these technologies. The focus group was structured to allow for each participant to explore innovative concept design without any limits, in order to encourage free thought. This was done by first discussing the purpose of the design exercise and ensuring the students did not feel any pressure to design. The task was treated as one where they could have fun designing a product they were either personally interested in, or in line with a type of product design they were already comfortable conceptualising, such as a shoe, lamp or electronic device. It was stressed that there were no marks for this exercise or penalties for not producing anything impressive. Students were reassured to work at their own pace and to use whatever method they preferred, whether it be hand sketching, marker drawings, or computer-aided design, for example.

As explained earlier in this chapter, the researcher chose to focus on one SRT, specifically EAPs (electro-active polymers) and explained the technology to the participants by means of discussion, making use of images, and video material. The aim was for the students to develop new product design concepts making use of EAPs to drive motion in the product and so becoming familiar with EAPs and their basic function. This focus on actuation aligns to the findings from the literature review, where it was seen as a common theme across all metadata analysed. After the initial concept development stage was completed, the focus group discussed their design concepts, and a single concept was chosen for further development by each participant. In order to ensure the design would stand up to critique, the parameters of currently available EAPs were adhered to. This would ensure that the concept could in fact be fabricated and tested if required. A selection of these conceptual designs will now be presented.

4.7.2.1 Lamp shade concept designs

To further clarify the goal of the first exercise, the researcher produced an example conceptual design, as shown in Figure 4.5: *Circular luminaire hanging lamp concept*, in order to stimulate and guide the students. This provided a starting point for the participants to then use EAPs in their own way. As expected, two of the participants chose to design lamp shades that could actuate, these are described further in this section.

4.7.2.1.1 Circular luminaire

A simple lamp was drawn by the researcher, as an example, to demonstrate the ability of EAPs to actuate parts of an everyday product, in this case a hanging lamp (refer to Figure 4.5). The lamp would be in the circular ("wings" pointing down) position when off. The "wings" open outwards when electricity is supplied to the EAP incorporated into each section, to cause a shape change and increase the area of illumination. The degree to which the arms rise can be controlled through a simple dimmer switch and the amount of electricity supplied to the EAP at each segment. Thus, the actuation in this concept is not only an aesthetic but also functional attribute, to control the focal point and distribution of light. Once the participants had clear direction, they were able to produce their own concepts and design ideas making use of this SRT, which will be presented in the following section.

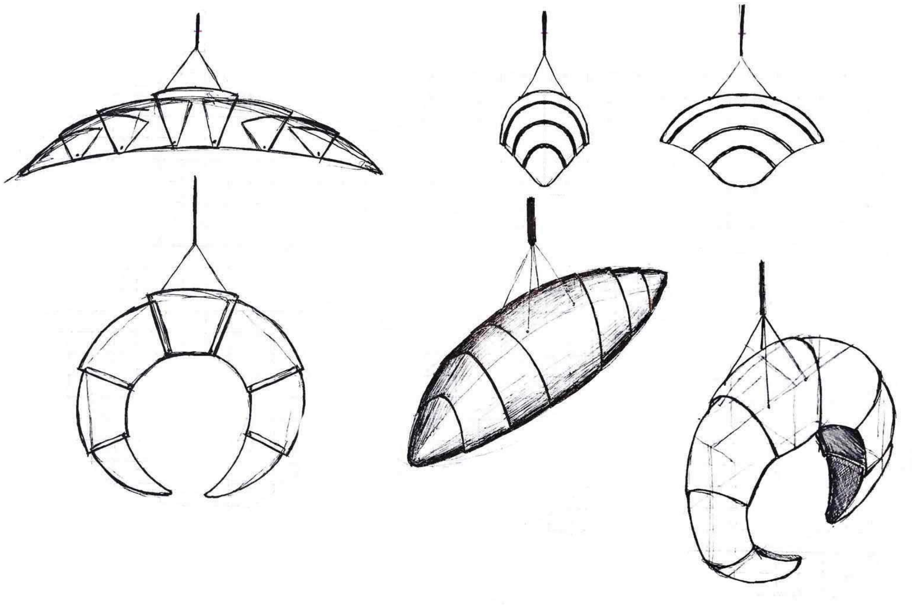


Figure 4.5: Circular luminaire hanging lamp concept (by Author)

4.7.2.1.2 Fan lampshade

This fan lampshade concept by C. Wan in Figure 4.6, shows how a standing lamp might open and close with a concertina or "fan" effect. Again, the degree to which the lamp shade "opens" will affect the amount of light transmitted out and so the physical shape can be adjusted by the user as desired. Although simple in concept, this application or use of movement is not seen in current light designs due to the cost and complexity of conventional technologies currently available.

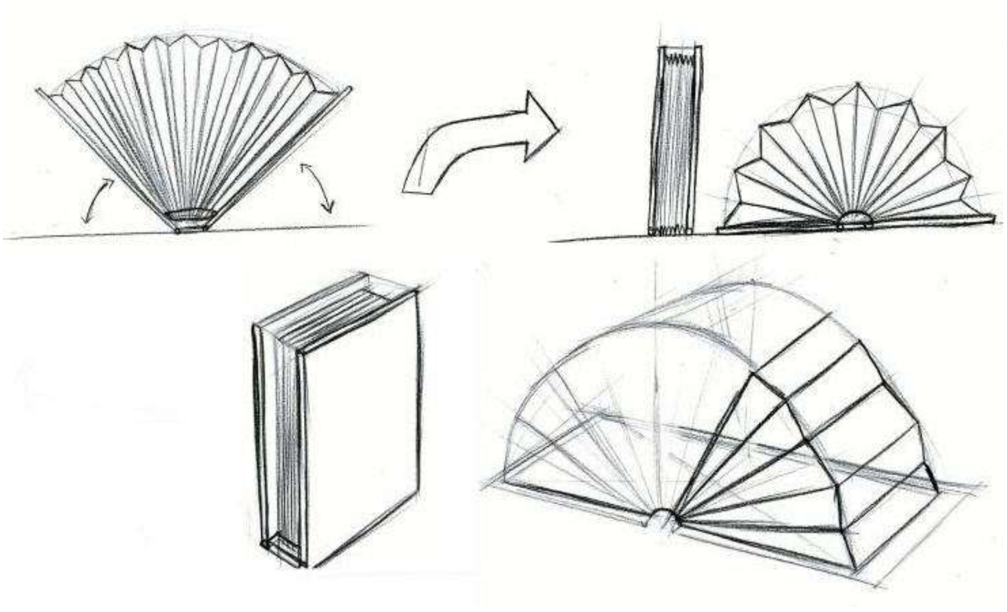


Figure 4.6: Expandable fan lampshade concept (Wan 2018)

4.7.2.1.3 Origami lampshade

The origami lampshade concept by Gu, shown in Figure 4.7., also explores the idea of using EAPs to expand and compress the lampshade structure to affect how the internal light is transmitted through film. This motion of expansion and contraction could be controlled through integrated electronics, to allow for continuous motion by adjusting the amount of electricity being delivered to the incorporated EAP at the various crease lines and sections. The end result would be a product that would “pulse” and give the impression of life as the biomimetic connotations would become part of the final product's function. Such a product, which would appear to have a life of its own and move/pulse in a natural way could change the way people perceive objects that are currently static and impersonal.

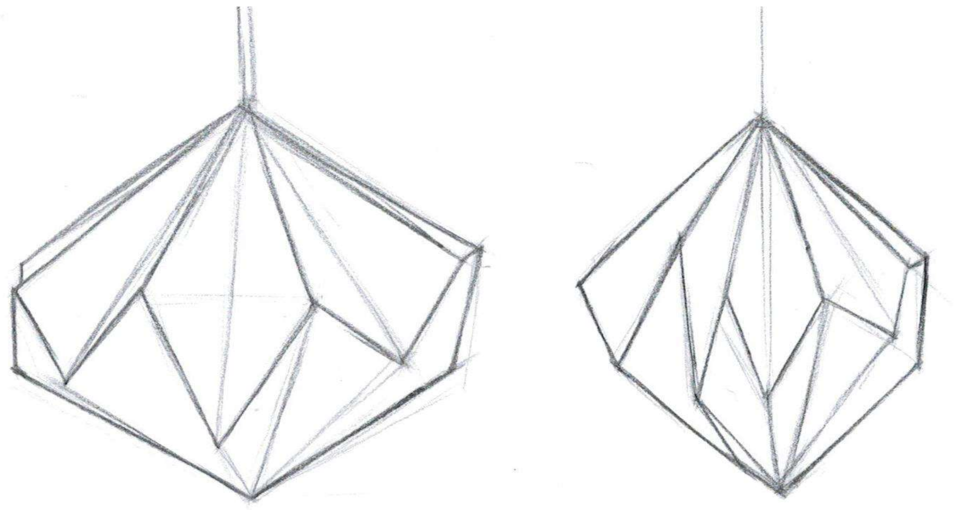


Figure 4.7: Origami lampshade concept (Gu 2018)

As an example, Gu was encouraged to develop a second, more advanced concept, making use of EAPs to actuate some aspects of a product design. The result of this can be seen in Figure 4.8 in the Braille Box.

4.7.2.2 From braille box to braille pad - DBR in operation

In this design, shown in Figure 4.8, a grid of plastic pins is able to protrude above the top surface as required, to allow for conventional braille patterns to be displayed and touched by the user. In addition to the braille pattern or writing that is displayed on the top surface, the Braille Box produces sound or audio words to describe the item. This is activated by placing a token onto the front recess of the Braille Box, which is read by electronics within the unit and used to teach the user to read braille by touch and sound. For example, a token for the word “tree” is placed on the recess and the Braille Box will display the word “tree” in braille on the top surface as well as saying the word “tree” in the language of choice. The plastic pins used to create the braille text are each operated independently by a small amount of EAP that will expand or contract and so lift or lower each pin. This again is possible to control very simply by supplying an electrical charge to each EAP as required and can be managed by an onboard set of programmed electronics.

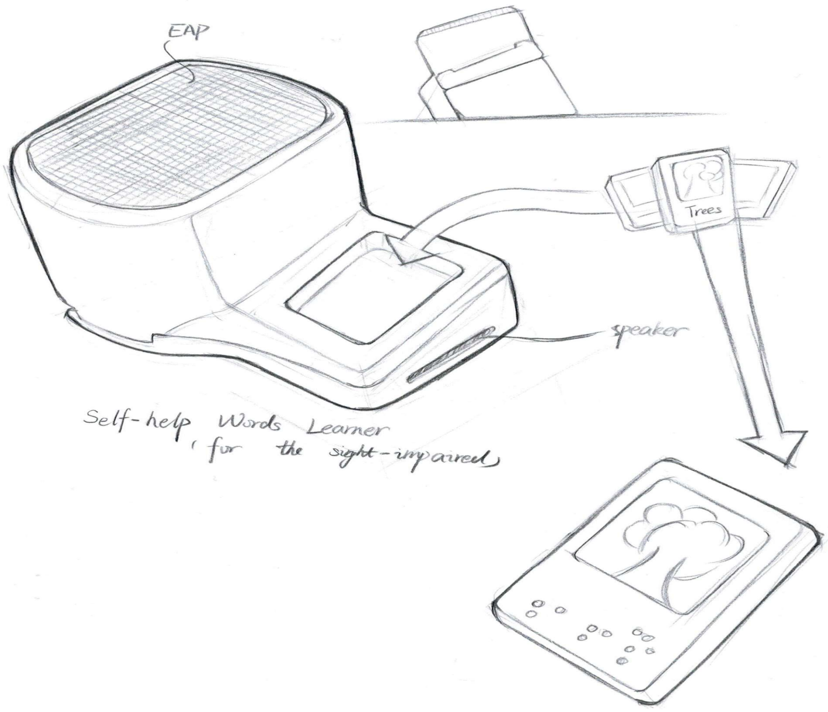


Figure 4.8: Braille Box (Gu 2018)

This development from the initial origami lamp concept shows a marked improvement in Gu's understanding of how EAPs could be used to actuate parts of a design and has allowed for a rather advanced concept to be developed. This much-improved knowledge generated during the workshop process has shown his progress in conceptual use of EAPs and execution of this SRT in an industrial design application for consumer goods development. The Braille Box can be seen as a combination of 'consumer' and 'medical' product design with the added benefit of being an educational device. Further improvements through iterations to the design, show the conceptual development and refinement of the Braille Box through to the braille pad shown in Figure 4.9. This example of design-based research demonstrates the combination of consumer, medical and educational design in a single product concept.

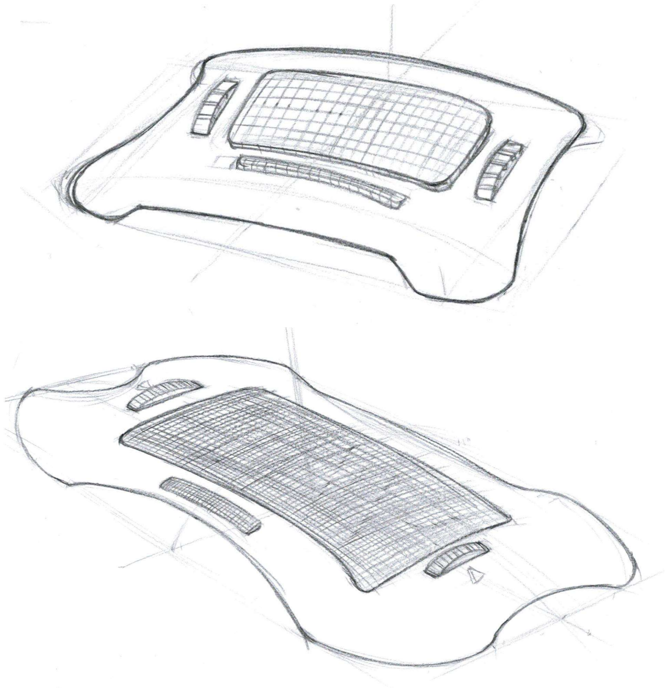


Figure 4.9: Braille Pad (Gu 2018)

Gu was encouraged to take full advantage of the compact nature of EAP and the overall reduction in a product's volume it would allow. The Braille Box was refined by Gu and reduced from a large rectangular box to a low-profile curved Braille Pad, as seen in Figure 4.9. This design is far more ergonomic, makes use of rotary buttons instead of tokens to change the words being displayed and spoken, and is more aesthetically pleasing. The reduction in volume will certainly reduce the cost to produce such an item and have further cost savings due to reduced volume during transport, space on shelves, amongst others. When one considers the leap in complexity from the initial concept for the origami lamp to this design, it is not only impressive, but also encouraging to see such an innovative and useful idea being developed without needing a deep understanding of EAPs. Once the base principles of volume change to drive motion were understood, it was possible for Gu to conceptualise this functional design concept and demonstrate the potential effectiveness of using EAPs in product design.

4.7.2.3 Helios solar tree charging station

Participant Wu produced a concept for the Helios solar-powered charging station (refer to Figure 4.10). This would be positioned in public spaces to allow the general public to make use of the charging facilities to charge their phones or other electronic devices. The concept involves a set of eight “arms” spaced radially around a central support post. The arms are powered to lift up by the solar energy gathered and will be raised according to the amount of solar energy they receive from the sun.

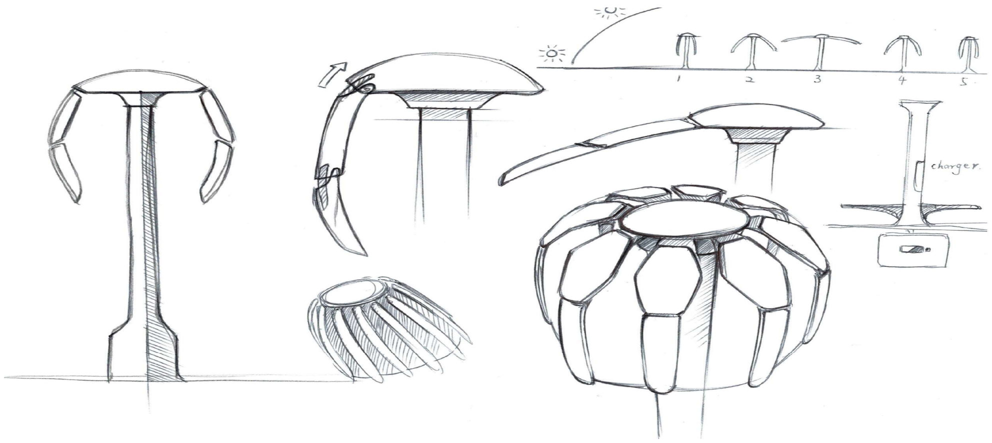
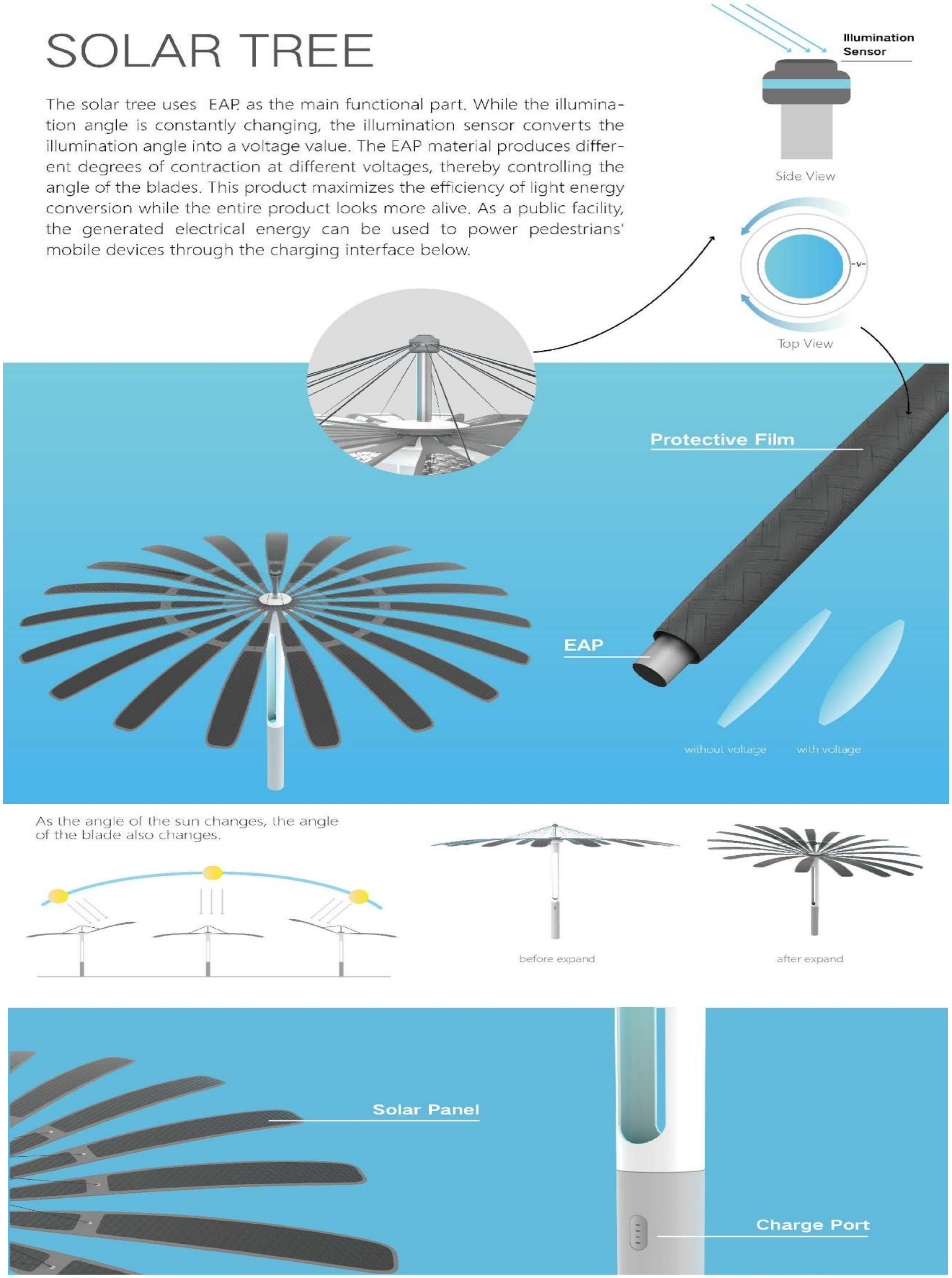


Figure 4.10: Helios solar-powered charging station sketches (Wu 2018)

In this way, the solar panels will be positioned to make optimal use of the sun’s rays, and only expend energy on actuating the EAP when it will result in increased efficiency and solar energy capture. In broad terms, this design is intended to follow the sun in the same way a flower follows the sun and uses EAP actuators instead of mechanical motors, hydraulics or pneumatics to achieve this motion. This concept again is an advanced application of EAP for actuation and would require sensors, electronics and solar cells for energy capture to be engineered into the mechanical structure. For the purposes of this research exercise, it has demonstrated not only the student’s understanding of the technology, but also the potential to create innovative product designs that are less bulky and more elegant. It is vital for an industrial designer to have access to tools that allow for improved aesthetics, ergonomics and efficiency to be able to drive design forwards and improve user experience. It would appear from these conceptual designs that SRTs and in this case EAPs could allow for this. Wu chose to pro-actively develop the concept further, as part of the design-based research for this study. The initial sketches and concept were refined by Wu using 3D software, and presentation images were generated. These were then compiled into a poster for display purposes to clearly communicate the design concept, as shown in Figure 4.11.


SOLAR TREE

The solar tree uses EAP. as the main functional part. While the illumination angle is constantly changing, the illumination sensor converts the illumination angle into a voltage value. The EAP material produces different degrees of contraction at different voltages, thereby controlling the angle of the blades. This product maximizes the efficiency of light energy conversion while the entire product looks more alive. As a public facility, the generated electrical energy can be used to power pedestrians' mobile devices through the charging interface below.

As the angle of the sun changes, the angle of the blade also changes.

Figure 4.11: Helios solar-powered charging station poster (Wu 2018)

4.7.3 Post-focus group questionnaire and results

The post-focus group questionnaire was completed by all eight participants, after completing the design focus group, in order to gauge the change in their understanding of SRTs and the potential for use in the industrial design of medical and consumer products. The results of this questionnaire are shown in Table 4.10.

Table 4.10: Findings from post-focus group questionnaire (Author's construct, 2021)

Post-focus group questionnaire (8 participants)		
Interview Questions	**Answers by participants**	**Respondents**
Question 1: Has your understanding of SRTs improved?	Yes, definitely	8 Students
Question 2: Are there applications for SRTs in industrial design?	Yes	8 Students
Question 3: What applications do you believe exist for developing medical and consumer products using SRTs?	I believe that artificial legs or muscles will use this technology.	1 Student
	The robots for grabbing vulnerable or soft amorphous objects which are suitable for food, automotive, daily chemical, medical, 3C electronics and other fields.	1 Student
	And it can be integrated into intelligent assembly, automatic sorting, logistics warehousing and food processing lines.	1 Student
Question 4: How could SRTs change the way we design medical and consumer products?	It can make the product quiet and smaller.	2 Students
	We can use SRT to clamp machine parts in factories.	1 Students
Question 5: What could the future of medical and consumer products be if we use SRTs?	More comfortable, smaller, lighter, quiet and so on.	4 Students
	It can be functional accessories for scientific research equipment, intelligent entertainment equipment or service robots to achieve intelligence, no injury, high security, high adaptability.	1 Students

In response to Question 1, *Has your understanding of SRTs improved?*, all eight participants answered simply, “Yes”. This shows that the focus group and design exercises increased the participants’ understanding of SRTs at the very least.

In response to Question 2, *Are there applications for SRTs in industrial design?,* all eight participants answered simply “Yes” again. This shows that the conceptual design exercise gave the participants a certain level of confidence in the potential of using SRTs in the industrial design of products.

With regard to Question 3, *What applications do you believe exist for developing medical and consumer products using SRTs?,* only three participants chose to answer this question. The answers are quite broad, as they refer to artificial muscle transplants, robots for handling various items in various industries such as medical, food handling and sorting. These do not speak to the question asked, as the researcher was specifically looking to receive innovative ideas for medical and consumer products that one might design. It is unclear why the participants did not provide specific product applications but chose to rather speak to the industries where these technologies might best be applied. However, from the examples shown that were developed in the focus group, it is clear that innovative applications do exist, as was demonstrated by the development of the Braille Pad by Gu.

In response to Question 4, *How could SRTs change the way we design medical and consumer products?*, again only three participants chose to answer the question. Two participants answered that it could make products quieter and smaller, which indicates that there was some discussion between the participants when answering the post-focus group questionnaire. The answer to this question did not speak to the question asked and referred to a general application for use in factories.

In response to Question 5, *What could the future of medical and consumer products be if we use SRTs?*, five participants chose to answer this question. Four responded that the future of medical and consumer products could be “…more comfortable, smaller, lighter, quiet and so on.” The fact that the response was identical again indicates that the participants were discussing the question and their responses. The response is, however, remarkably interesting, as it indicates certain perceived benefits of using SRTs in developing future medical and consumer products. One participant answered: “It can be functional accessories for scientific research equipment, intelligent entertainment equipment or service robots to achieve intelligence, no injury, high security, high adaptability." From this answer it is clear that the participant sees many potential applications for SRTs in vastly different industries and products. By referring to "no injury" and "high adaptability" the participant is indirectly speaking to key design requirements defined in the two medical case studies described earlier in this study.

As can be clearly seen in the results from the post-focus group questionnaire, the concept design workshop and exploration of uses for EAPs through the industrial design of conceptual products has had a marked increase in the participants' understanding and awareness of the potential for SRTs to be used by industrial designers in the development of new innovative product designs. This development will be discussed further in Chapter Five, where feasibility and adaptability of SRTs for use in the industrial design of medical products will be further discussed in the context of the entire study.

4.8 Chapter summary

As shown in this chapter, the researcher has implemented the pragmatic research methodology in a systematic and logical manner to extract meaningful data. From the *first phase* of research, which covered soft robotics on a high level, the researcher was able to identify broad themes and areas for further research. The focus area of actuation was chosen due its mechanical nature, and good fit for use by industrial designers to develop product designs. Other areas, such as soft electronics and soft sensors, were excluded from the study at this point.

The researcher then conducted the *second phase* of research, an intensive analysis of SRT studies where the focus was either on the whole or in-part on actuation. This detailed metadata analysis allowed for the various studies to be grouped, using various tools such as factoring, into four key groups. These groups include Actuation by means of artificial muscle, Morphological computation, Biomimetic inspired robots and Applications for SRTs. Within these groups there were factors common to all groups, namely, Actuator as Artificial Muscle and Morphological Computation. As morphological computation focuses mainly on the way the technology is used, and the geometry designed to affect a specific or desired motion, this was treated as secondary to the focus of developing actuators as artificial muscles. A detailed analysis of the various actuation technologies currently available and being explored in soft robotics is covered in the literature review in Chapter Two. By listing these various SRTs and their inherent attributes, both positive and negative, it was possible to produce a simple overview of soft robotics actuation technologies.

The *third phase* of research involved interviews with medical design experts and the inclusion of two real-world medical design case studies, in order to define real-world industrial design requirements that would be used to guide further research. These requirements were then refined and those specific to the mechanical design of medical products were listed in a simple table. There were clear similarities between the two projects, where soft structures were specific requirements. The Medi-dot case study had a specific need for actuation, and so aligned well to the narrower focus area chosen by the researcher. These requirements were then compared to the various actuation SRTs, and one technology was able to meet all requirements set, namely, EAPs. This SRT was then chosen as the basis for further study.

At this point, the researcher was well prepared to conduct the *fourth phase* of research, which involved interviews with industrial design experts. The aim of these interviews was to gauge a view of the medical design industry, and the general awareness of SRTs among professional industrial designers that focus on developing medical products. In addition, the feasibility for using EAPs was discussed, and the findings from these interviews are presented in table format with relevance to this study clearly shown. By conducting these interviews, and interrogating the hypothesis, the researcher was able to present an industry view on SRTs and put the question of feasibility forward. This allowed for cross-analysis through the use of triangulation, as will be described in Chapter Five.

The next and *fifth phase* of research involved an interview with a 3D printing specialist, where new production methods were discussed. This followed from discussions with the industrial design experts and provided further credibility for the use of EAPs as an integrated part of future product designs. The findings from this interview were condensed into a simple table, and it was noted that development had already started to allow for EAPs to be 3D printed on their machines.

The researcher was now well prepared to conduct the *sixth phase* of research, where the findings from the literature review, interviews with medical experts, interviews with industrial design experts and an interview with a 3D printing specialist formed a solid base. These findings were also used to prepare for a design focus group where the researcher used participatory co-design methods to explore the use of EAPs in the industrial design of medical products. The focus group was split into three stages, namely: a pre-focus group questionnaire, a focus group concept development workshop and a post-focus group questionnaire. The findings from these three stages are presented to show a clear picture before and after the concept development workshop was conducted. By establishing the participants' knowledge and understanding of SRTs before the design work was conducted, it was possible show the impact of these design exercises, and whether their perceptions had changed. In terms of an overview, the participants' perception and understanding of SRTs has improved. This improvement in perception and the concept designs developed in the focus group implies that exposing industrial designers to SRTs does have an impact. It is certainly feasible that other applications may be developed that can incorporate adapted SRTs. It would follow that a comprehensive and detailed archive of SRTs could be presented in such a way as to encourage further exploration in industrial design, instead of being ring-fenced to robotics applications alone. For example, in the case of artificial muscles, not only can these be used to drive motion or control the limbs of a robot, they can also be integrated into a product like the Braille Pad that drives simple motion of key components. It is this creative, or innovative switch that will allow for the technologies to be adapted, where possible, for the industrial design of medical products.

CHAPTER FIVE
Discussion of findings

5.1 Introduction

This chapter will now discuss the findings of the research study and place these findings in the context of the research questions.

5.1.1 Outcome of initial literature review

As has been shown in the literature review, an initial broad investigation of soft robotics technologies allowed for a clear differentiation of factors from conventional robotics technologies. These are summarised in Table 5.1 and list the key defining attributes that make SRTs better suited for use in applications where they are either interacting with delicate or fragile objects or are in direct contact with people. SRTs are much safer than rigid mechanical alternatives and so less likely to cause injury or harm. In addition, SRTs have certain attributes that mechanical robots simply cannot achieve, such as high dexterity, infinite degrees of freedom, continuous actuation, large material strain and they make use of soft materials such as rubbers and electro-active polymers to drive motion.

Table 5.1: Properties of SRT actuators (Trivedi et al., 2008:100)

Properties:	**Soft actuators**
Degrees of freedom	Infinite
Actuators	Continuous
Material strain	Large
Materials	Rubbers, Electro-active polymers
Capabilities:	
Accuracy	Low
Load capacity	Lowest
Safety	Safe
Dexterity	High
Working environment	Structured and unstructured
Manipulable objects	Variable size
Conformability to obstacles	Highest

5.1.2 Outcome of focused literature review

In order for the researcher to answer the main research question, a more focused analysis was required to understand what SRTs exist, and what differentiates these SRTs from one another. The findings of this focused metadata analysis are presented in Chapter Four, and show clear focus areas, grouping and themes. In terms of focus areas, the researcher has chosen to narrow the focus to actuation technologies and exclude SRTs that relate to other focus areas such as soft sensors and soft electronics. By keeping the focus on actuation technologies, it was possible to get a deeper understanding through a detailed literature review. This detailed review allowed for specific themes to be highlighted and grouping of the literature according to the main drive or intention behind the study. It was found that SRT studies could be separated into four main groups, where the study investigated a specific SRT from the point of view of actuating artificial muscle, mimicking the biomimetic movement of living things, the use of morphological computation to develop controlled movement in soft robots and finally on applications for SRTs in soft robotics. By analysing these four groups it became clear that one could define a hierarchy of sorts, where both applications for SRTs in soft robotics and the aim to achieve biomimetic motion were higher-level investigations. Almost all the studies made use of artificial muscles of some sort to achieve the end result, whether it be a more dextrous medical robot or a robotic fish. Thus, it was shown that artificial muscles, or more accurately actuators, are a group that have more specific and definable SRTs. Within all groups it was found that there is a large focus on the use of morphological computation to assist in the design of the artificial muscle/actuator to function as desired, in a repeatable and predictable manner. This is understandable, as soft actuators generally have an infinite degree of freedom, and so by adjusting the geometry of the actuator or structure into which it is integrated, one can limit this to a more functional zone. Although this may seem abstract, it is a critical feature in designing or engineering for SRTs, and so will form a key parameter.

5.1.3 Outcome of detailed literature review and medical design case study requirements

The four groups described in the preceding section, allowed the researcher to narrow the focus of the metadata research to those studies that were focused on the theme of actuation, and thereby establish and compare the attributes of the various SRTs in this specific niche. This was then compared to the industrial design requirements for two real-world medical design projects, and the results showed that EAPs were the only soft actuator that could meet all the requirements set. This has been further refined in Table 5.2, to show the correlation between the properties of EAPs and the industrial design requirements for the two medical products. This formed the first step in triangulation, where the researcher aimed to keep the research in line with the main research topic and research question.

Table 5.2: Relation of EAPs to industrial design requirements (Author's construct, 2022)

EAP actuator properties in relation to industrial design requirements		Electro-active polymers
Industrial design requirements:	Allows compression	Yes
	Elastic or flexible	Yes
	Soft	Yes
	Ergonomic	Yes
	Adaptable to each user	Yes
	Wearable by the user	Yes
	Wearable under clothing	Yes
	Lightweight	Yes

5.1.4 Outcome of interviews with industrial design experts

With this clear list of parameters and requirements, and the understanding of EAPs as a potential SRTs that could meet these requirements, the researcher could then conduct further field research to test feasibility, industry acceptance and manufacturability, and the potential for use in developing innovative product designs for the medical industry. The first stage was to gauge industry awareness of EAPs, and the likeliness for professional industrial designers to make use of such technologies if they were made available. The findings from the two agencies interviewed have been presented in Chapter Four and will be expanded upon here. The researcher posed various questions to get an understanding of the medical design industry. As the design agencies were both based in Shanghai, China, they have access and exposure to the latest technologies in use. As shown in Table 5.3, the general impression of the medical industry is that it is dominated by large companies and new product design is often forced to market on a tight timeline. In order to adopt new technologies, they need to be proven and trusted before the industry is willing to risk implementation in a product being developed. The medical industry is heavily regulated, and so there are many barriers one needs to traverse before a technology can be accepted. At times new regulations need to be developed to keep up with such developments. China has the advantage of a larger market, and so it is easier to launch a new product in China, at an earlier stage of development, even with the risk of failure or slow market acceptance. In addition, government funding to certain sectors of medical development, such as biotech, has allowed for rapid development in these areas. It follows that with the right support, SRTs could receive similar support if feasible applications and proven case studies validate this investment.

Table 5.3: Outcome from interviews with industrial design agencies (Author's construct, 2022)

Medical industry	**Consolidated data from interviews**
Status of the medical design industry	- Big medical device companies have in-house knowledge that can be leveraged for R&D - Multi-faceted development - Europe is ahead of Asia in terms of regulations and medical development - Development in China is often faster paced, with higher risks - China has a much larger market than Europe - Easier to launch new products in China at a lower level of development - Government funding promotes development - med tech centre in Shanghai - Biotech is developing faster than other areas in the medical field
Challenges in the field of medical design	- Regulation in medical industry - Investment limitations - Speed to market is critical - Clients want to go to market as priority - New solutions take longer to develop - Repeat what works - Difficult to innovate with new technologies
Medical design and SRTs	**Consolidated data from interviews**
Experience of design agencies	- Experienced at medical design - Medical devices - Electronic wearables - Home care, elderly - User experience - Usability - Robotics - Healthcare robots
Focus areas of design agencies	- Innovation often starts with the industrial designer - Change client mindset

	- Highlight the importance of usability and user experience. - Trend forecasting and analysis - Product development planning - Product development strategy
Understanding of SRTs	- Soft robotics is used in health care, point of care - Actuators - SRT used to create softer designs - Potential for SRTs to replace rigid alternatives
Limitations to innovate with SRTs	- No focus on innovation using new technologies - Minimal user testing in-house
Applications in the medical industry	- Soft robotics in exoskeletons - Used for resistance training - SRT may be used in rehab first - Sporting industry rehabilitation - SRTs in wearables - Healthcare - Medical products - Textiles in robotics - Companion robot
Benefits of using SRTs in medical product design	- Humanising devices - Designing in emotion
Manufacturability of medical products using SRTs	- 3D printing for mass production

The design agencies both had extensive experience in the development of medical products, including wearable devices such as those described in Chapter Two, and healthcare robots. Their focus was on innovation and they both experienced the challenge of trying to educate their clients to think ahead and be open minded to new ideas. Again, with proven case studies, it would be easier to point to something that has been proven to work, giving the client the confidence to “risk” exploring new technologies such as SRTs. The industrial designer plays a key role here in helping the client to forecast the future trends, plan an effective product development strategy and improve the end-user experience. There is a proficient understanding of the potential for SRTs to improve design, by replacing rigid alternatives, especially in the healthcare sector. Both agencies treat user experience as a high priority when developing a new product, and the potential for softer alternatives to be used that could allow for inventive uses was shared. The idea of bringing emotion into a design and humanising a product was also raised, and various potential applications for this were suggested. Both agencies could see the potential to develop a wide range of products using EAPs, from soft exosuits such as those developed by Seismic and Harvard Biodesign Lab, to companion robots. In most cases the potential applications involved some level of assistance to the user, as either a healthcare, rehabilitation device or sporting aid. When asked about new production methods that might suit this form of

SRT, namely, EAPs, the suggestion was to look at production-grade 3D printing and meet with the market leader in this technology, Stratasys, who were also based in Shanghai.

5.1.5 Outcome of interview with 3D printing specialist - Stratasys

The researcher met with Stratasys, as presented in Chapter Four, and received a clear idea of the state-of-the-art technology at the time. This has been further consolidated into Table 5.4, to show that 3D printing is indeed feasible for mass production and is already in use by many companies for this purpose. The technology can accommodate various rubberlike materials and print varying densities of this material at the same time in a single part. This level of integration provides the industrial designer with complete freedom to use EAPs within a part, on the assumption that EAPs will be available as a material for 3D printing in the future. As confirmed by Stratasys, various research institutions are currently developing these materials for 3D printing, including MIT as well as universities in Shanghai and Singapore. The request for these materials has already been received from the market, so it is promising that this might be made available in the near future for further experimentation and concept development. There are some limitations to the 3D printing technology, when printing with softer polymers, namely, low thermal resistance and low resistance to water absorption. It follows however, that such limitations could either be improved on in the future as the 3D printing technology develops or could be accommodated by the industrial designer when developing the product design. For the purposes of this study, these will not be treated as impassable, but should be noted for any future expansion on this study. In terms of relating this back to the industrial design requirements and the inherent properties of EAPs, it does confirm the feasibility of using EAPs in mass production and so triangulation is used again to support the hypothesis. This speaks directly to the research question, as the integration of EAPs would not only be feasible to integrate in theory, but also in practice. This will subsequently further be expanded on in the discussion of the focus group and related conceptual design work.

Table 5.4: Outcome from interview with Stratasys (Author's construct, 2022)

3D printing and mass production	Relevance to study
Feasibility for use in mass production	- Feasible for mass production - Suitability for mass production - 3D printing in rubber is possible - 3D printing of multi-density rubbers on single part is possible - Examples of multi-density 3D printing supplied - Production-grade rubber printing
Limitations of 3D printing for mass production	- Low thermal resistance - Low resistance to water absorption - No conductive materials available for 3D printing at time of interview - No research on 3D printing EAPs available at time of interview
Innovation and materials development	- Market-driven development of 3D printing machines - Production-grade rubber 3D printing has been requested - Electro-active polymer 3D printing is currently being researched - MIT are actively researching 3D printing of electro-active polymers - Additional research into 3D printing of advanced polymers is being conducted in Shanghai and Singapore

5.1.6 Outcome of focus group and concept development workshop

The findings from the focus group are presented in Chapter Four and comprise three stages. Stage One included a pre-questionnaire where the participants were asked about their experience and knowledge of SRTs and their use in industrial design. The participants were all Industrial Design students at the Hunan School of Design, Hunan, China. They provided an excellent perspective into the general perception of SRTs by industrial designers, as they are one of the leading schools for industrial design in China. The outcome of this pre- focus group questionnaire showed that there was limited exposure or awareness to SRTs, with only some of the participants having any real knowledge relevant to this study. Most of the participants' knowledge was superficial, and the shared impression between the participants was that SRTs are applicable for use in robotics, not industrial design. Some were open to the idea of using SRTs for product development but had no understanding of the limitations or design parameters when working with these technologies.

Stage Two comprised a series of concept design workshops in which the participants were given the task of developing innovative design concepts making use of EAPs in some way to actuate a part of the design. For the first design exercise, the researcher provided a detailed explanation of EAPs, their uses in soft robotics and also generated an initial concept design to function as an example to the participants of how one might implement EAPs to actuate the design. The first concept designs developed by the participants were rather simplistic, and some examples have been provided in Chapter Four. The review of these designs in a focus group discussion allowed the participants to learn from what the others had attempted and prepared them for further concept development exercises.

The second set of concept designs were markedly more advanced, with some surprising ideas being put forward. Two examples were chosen to demonstrate this leap in design thinking, namely, the Braille Box and the Helios solar-powered charging station. The researcher then guided the participants to refine their concept designs further in a final concept design workshop, the results of which have been presented in Chapter Four. The Helios solar-powered charging station was refined, and a presentation poster was created to better illustrate the idea. The Braille Box was further refined to reduce the size and bulkiness of the initial concept, to produce the Braille Pad. This concept design is very appropriate for this research study as it is both an assistive device for the blind and has many ergonomic requirements that are similar to a general product for the consumer or medical market.

The product of these exercises, being concept sketches and renderings, show that the participants' understanding of SRTs, in this case, specifically EAPs, had improved dramatically. There was also a general excitement experienced by the participants, as the potential of working with a new technology might make innovative designs possible that were previously impractical or just not feasible. The concept of the Braille Pad will be expanded on further in this chapter by the researcher to demonstrate how this concept might be realised and refined for mass production, in order to further support the claim that EAPs can be adapted for use in the industrial design of medical products.

Stage Three included a post-focus group questionnaire, the results of which are conclusive. All participants reported that their understanding of SRTs had improved and that they could see potential for the use of SRTs in industrial design. Some areas where SRTs could be used were suggested, and the key benefits were noted, those being that they could allow for a product design that is softer, lighter, smaller, more comfortable and quieter. For the purpose of this study, this was an excellent outcome as it showed not only the change in their understanding, but also a willingness to adopt these technologies if the opportunity arose in the future.

5.2 Analysis of the possible use of SRTs in the industrial design of medical products to improve inherent properties and functionality

In order to answer the main research question, it was necessary for the researcher to understand the benefits and limitations of SRTs as well as have reference case studies for real-world medical design projects. These requirements can be seen as the defining criteria that SRTs would need to meet in order to answer the overriding research question, i.e., "How can SRTs be used in the industrial design of medical products to improve inherent properties and functionality in order to enhance the user experience?" The answer is, therefore, twofold: The first stage needs to establish if it is possible for SRTs to improve the end product and resultant user experience, and the second stage needs to establish how SRTs can be used by industrial designers when designing medical or other products. In order to answer the first stage, we will use triangulation to draw clear comparisons between SRTs, EAPs, the design requirements from the two medical design case studies and the Braille Pad concept design, and ultimately show the improved end-user experience. Table 5.5 will be used to depict these associations.

Table 5.5: Triangulation of all outcomes (Author's construct, 2022)

	SRT actuator properties	**EAP actuator properties**	**Case study requirements**	**Braille Pad requirements**
Materials:	Rubbers, electro-active polymers	Soft material: electro-active polymers	Soft materials	Soft interface
Degrees of freedom:	Infinite	Elastic and flexible	Elastic or flexible	Flexible interface
Actuators:	Continuous or intermittent	Actuation as required	Compression as required	Actuation as required
Compact:	Very compact	Very compact	Wearable under clothing	Very compact
Safety:	Very safe	Very safe	Must be very safe	Must be very safe

	SRT actuator properties	EAP actuator properties	Case study requirements	Braille Pad requirements
Ergonomics:	Structured or unstructured	Very ergonomic	Must be very ergonomic	Must be very ergonomic
Conformability:	Highest	Very conformable	Adaptable to each user	Adaptable to each user
Weight:	Lightweight	Lightweight	Lightweight	Lightweight
Load capacity:	Lowest	Allows compression	Allows deformation	Allows deformation under pressure
Manufacturable:	Highly	Mass producible	Must be mass producible	Must be mass producible
Manufacture method:	Various	Moulding or 3D printing - Affordable	Must be affordable / accessible to end-user	Must be affordable / accessible to end-user

As shown in Table 5.5, there is total alignment between the requirements set by the two medical case study projects and the Braille Pad concept design. The requirements match directly to SRT properties in general, and also specifically to EAPs. By triangulating these requirements against the properties of the EAPs, it is easy to demonstrate their appropriateness for use in the development of the Braille Pad. By cross-checking the design requirements continuously during the research phase, the researcher was able to retain the focus on those SRTs that meet these, ultimately assisting in the selection of EAPs for further investigation and exploration. Therefore, the first stage of the question has been answered; yes, SRTs, in this case EAPs, can be used in the industrial design of medical products to improve inherent properties and functionality in order to enhance the user experience. How this can be done is shown through the concept designs developed in the focus group concept development workshops, and will be expanded on further in this chapter, through the use of the Braille Pad concept. The researcher will show the potential for a design shift from hard mechanical designs towards softer, more organic design solutions with improved ergonomics, that better meet the end-user's needs and improve the user's experience.

5.3 Analysis of enhanced user experience linked to new applications of SRTs in medical product design

The researcher will now show the enhancements to the end-user experience that are possible through the use of SRTs in the industrial design of medical products. As stated previously, the Braille Pad concept, developed by one of the participants in the focus group concept design workshop, will be used to demonstrate this. For clarity, the concept sketch developed by Gu will be shown here again in Figure 5.1, as this formed the basis for the refined design of the Braille Pad by the author. As described in Chapter Four, the device is intended to serve as an assistive device for the blind, in order to teach the user to read braille writing. The Braille Pad unit incorporates sound, to support the 3D image shown on the functional braille surface. When the left rotary dial is rotated by the user, the word and image that is displayed on the braille pad changes and is accompanied by an audio recording of the word being spoken. This provides the user with the support of hearing the word spoken, as well as a 3D touchable image or symbol of the word to help clarify its meaning further. The word is displayed in braille text next to the "image" so that the user can learn to read braille writing by touch and association.

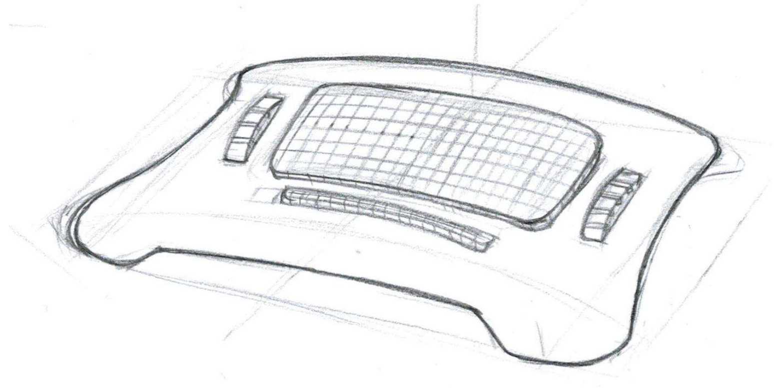


Figure 5.1: Braille Pad (Gu 2018)

The researcher made use of Solidworks 3D Software in order to generate the following detailed industrial design of the Braille Pad. As the researcher has 18 years of working experience in industrial design and related CAD Software, the aim was not only to realise the design as 3D images, but also to address the ergonomics, materials, manufacturing processes and effective adaptation of EAPs into the design. The visualised result is shown in Figure 5.2.

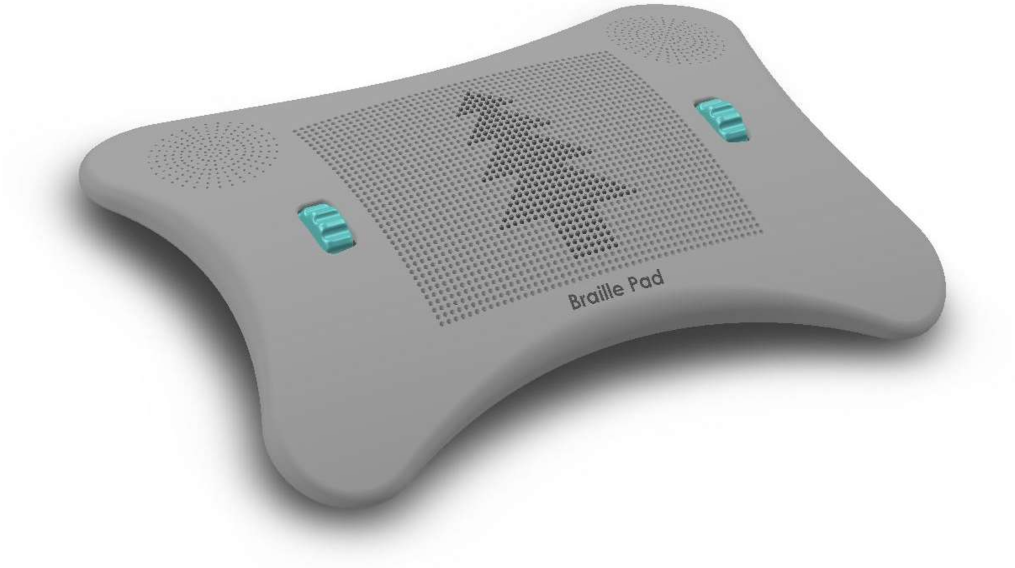


Figure 5.2: Braille Pad (by Author)

As shown in Figure 5.2, it was possible to develop a compact, curved design with no sharp edges or corners. The overall form is symmetrical, to allow for equal function between left- or right-hand favoured people. The functional braille area consists of 50 braille pins in width and 40 braille pins in depth. This allows not only for single words and images to be displayed, but also full sentences for more advanced teaching and learning. The left rotary knob is still intended for use in cycling through a list of items. The right-hand rotary knob is now intended for increasing the level of teaching, where the user can choose between various teaching levels from single letters, single words, simple sentences and then ultimately, complex sentences. This is an intuitive interaction with the device, as the levels are indicated through the audio function, where the user is told what the lesson content and difficulty is. Two audio speakers are incorporated into the design to allow for equal audio output from both sides of the device, to support users with impaired hearing in either ear. The unit is lightweight and includes a rechargeable Lithium-ion battery.

The braille functional surface area forms part of the top casing, where the 2000 braille pins are fitted into a grid of 2000 holes. As the top cover is intended to be injection moulded in a medium-density TPE rubber, the inclusion of these holes in the top cover is a simple part of the tool making process, with each top cover component being manufactured in seconds. The surface finish is matte, soft and tactile, to ensure that it feels comfortable in the users' hands during use and does not slip when held or placed on a flat surface. A closer view of the functional braille surface is shown in Figure 5.3, where braille pins protrude from the functional surface in the symbol of a tree. Any combination of pins can be displayed within this grid.

Figure 5.3: Braille pins in a tree pattern (by Author)

For the user, it is simple to rotate the left rotary dial in order to cycle through the lesson. This aims to support the learning and avoid irritation, distraction or loss of interest due to unnecessary complexity of the user interface. As shown in Figure 5.4, the proportions allow for the maximum functional surface area, while still allowing a sufficient area for grip, speaker holes and the required internal electronics and battery. The curvature of the functional surface is subtle, as shown in Figures 5.5 and 5.6, to provide a fully convex surface that remains functional for the braille text grid. This curvature also provides additional internal volume for the electronics, battery, speakers and braille pin assembly. The overall volume of the assembled braille pad is thinner around the perimeter of the unit, to give the impression of it being thinner and ensure it is not bulky in hand. The exploded view shown in Figure 5.7, shows the cover parts separated so that the internal braille pin assembly is visible. It is this braille pin assembly that incorporates the EAP actuators which drive the motion of each individual plastic braille pin. The braille pins are injection moulded in ABS plastic in a family tool, meaning all pins are moulded together at the same time. A thin, sacrificial layer of ABS is left between the pins in order to keep them together as a single part for the next stage of the production process. The plastic braille pins are then fitted into a new injection tool, and the EAP is injected to fill the cavities in each pin and to allow a pillar of additional EAP below each pin. This single part can then be removed from the tool and placed into a fixture where the sacrificial layer of ABS is cut away. What remains is the array of braille pins, each with individual EAP actuators moulded onto them. The pins remain in the holding fixture to allow for ease of assembly onto the flexible printed circuit board, after which the sub-assembly is aligned and fitted into the top casing holes.

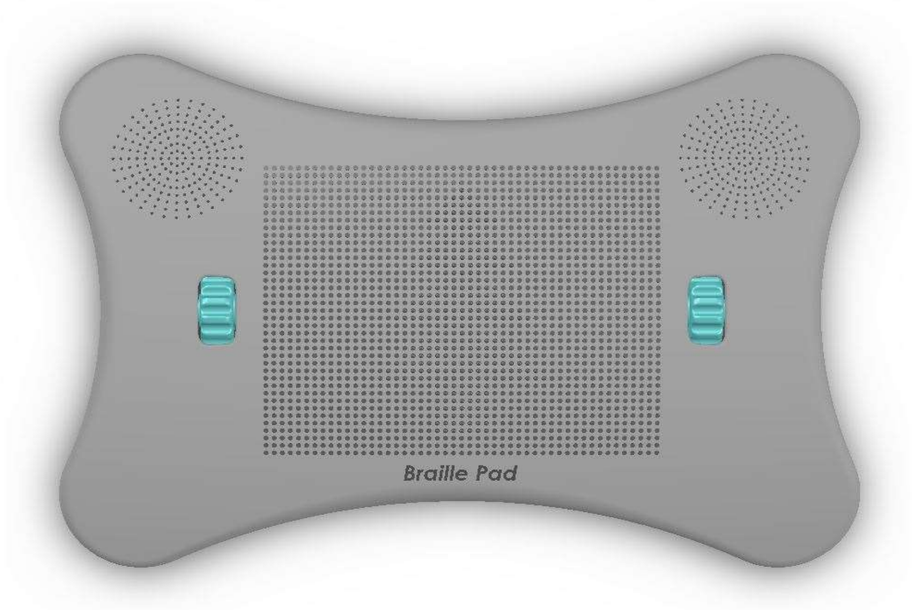


Figure 5.4: Braille Pad top view (by Author)

Figure 5.5: Braille Pad front view (by Author)

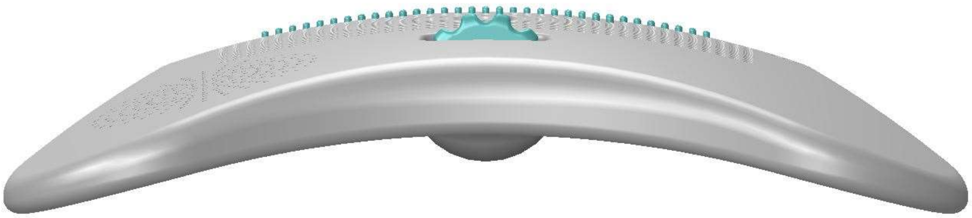


Figure 5.6: Braille Pad side view (by Author)

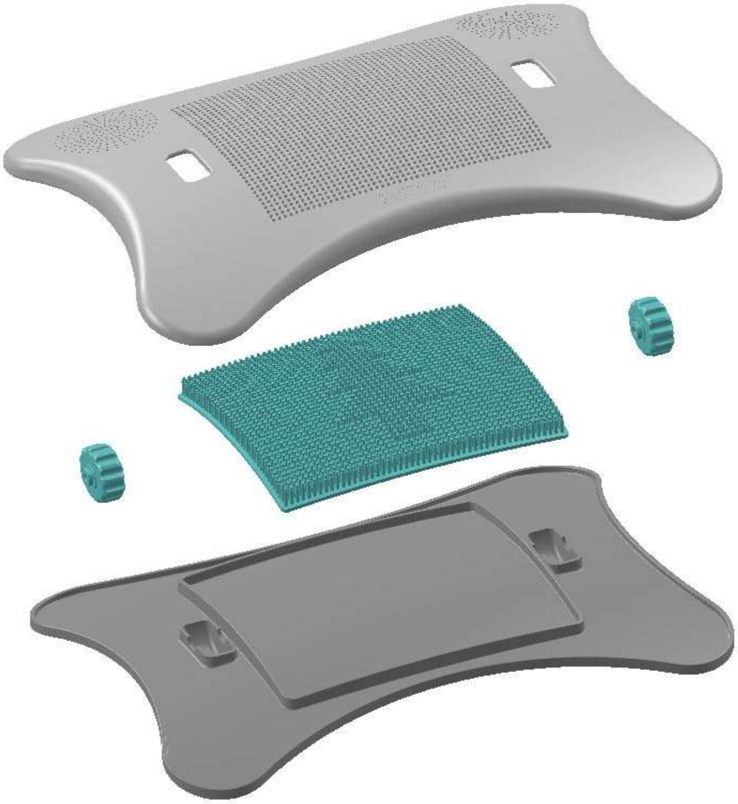


Figure 5.7: Braille Pad exploded view (by Author)

After the braille pin sub-assembly is fitted to the top cover, all electronic wiring and internal components can be assembled into the unit. The bottom cover, which is also injection moulded in medium-density TPE rubber is then snapped into place by means of snap fixing geometry all around the perimeter. This provides for an easy and rapid assembly. The complete unit can then be tested to ensure it meets all quality and production standards. An appropriate bonding agent is used between the top and bottom covers to provide a permanent bond during the final assembly of the unit after testing. The finished design is semi-rigid, as the TPE used for the covers will allow for a certain degree of flex and twisting. This is only possible due to the way in which the EAP actuator's function. The distortion to the casing caused through flexion or twisting does not damage the EAP as it is in itself elastic and the function of each EAP actuator in the design is to increase volume when stimulated by electric current. A cross-section through the centre of the complete assembly is shown in Figure 5.8, and the braille pin sub-assembly can clearly be seen interlocked with the top cover.

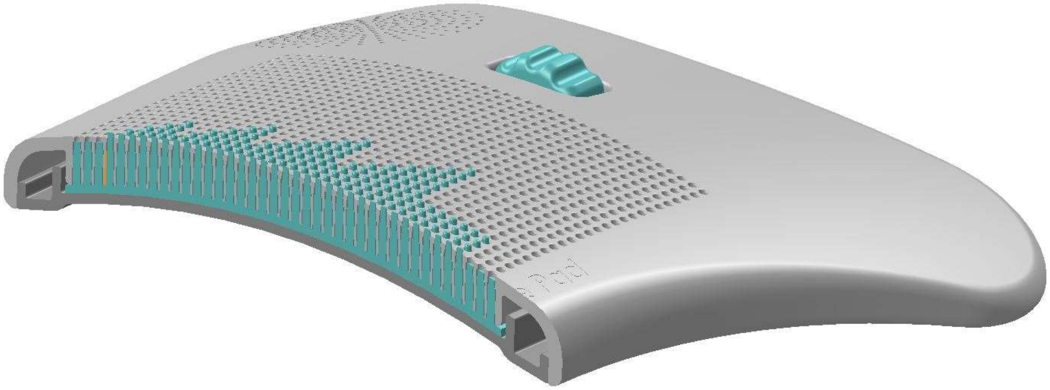


Figure 5.8: Braille Pad cross-section view (by Author)

In order to further clarify the function of the braille pins and EAP actuators, a detailed cross-section has been provided in Figure 5.9. Here the individual ABS braille pins can be seen in blue with the individual EAP actuators in yellow. Each EAP actuator is assembled onto a positive and negative electrode on the flexible printed circuit board. This allows for the pins to be activated individually be means of electric current, controlled by the onboard electronics.

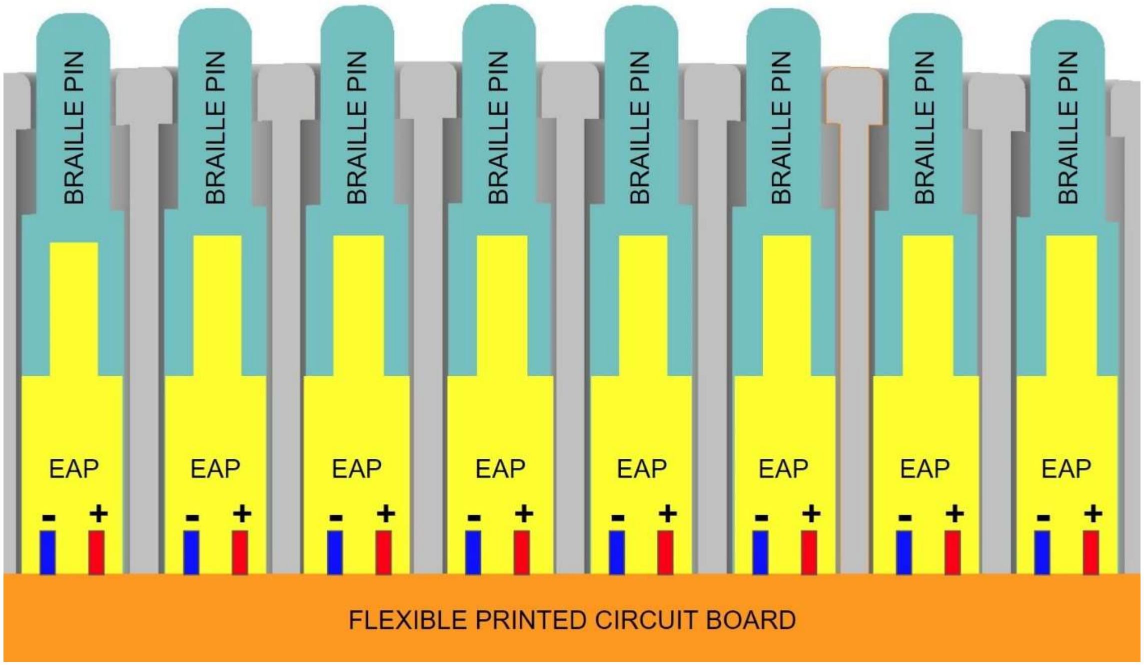


Figure 5.9: Braille Pad cross-section view through EAP braille pins (by Author)

The braille pins only protrude above the top functional braille surface when the EAP is stimulated, as the electric current causes a volume increase of the EAP actuator, thereby pushing the ABS pin upwards. Mechanical stops in the braille pin holes of the top cover prevent the pins from protruding out too far, and so control consistency in the height of the pin that is available to the user. Through user testing this can be refined to a precise measurement, by tuning the injection moulds for the top cover braille holes and ABS pins.

As shown through this design refinement of the Braille Pad concept, not only can EAPs be integrated into a product to provide for innovative functionality and in this case the actuation of braille pins, but they allow for a product that is more compact, flexible and lightweight to better meet the ergonomic requirements of the end-user. This has formed the final step of triangulation in this study, as this aligns directly to the requirements defined in the two medical case studies, the beneficial properties of EAPs as the chosen SRT, the ambitions described by the industrial design agencies, the requirements for the end product and to be feasible to manufacture.

Triangulation has been used to discuss and verify the overriding themes and results, and to show overlaps or discrepancies in any outcomes. This has formed a control step in the research method, to help ensure the final conclusions of the research are logical and justified. Seen from this point of view, data triangulation is *the use of a variety of data sources, including time, space and persons, in a study.* Findings can be corroborated and any weaknesses in the data can be compensated for by the strengths of other data, thereby increasing the validity and reliability of the results. (Yeasmin & Rahman, 2012).

5.4 SRTs that could be adapted for use in the industrial design of medical products

As shown through the refinement of the Braille Pad concept, it is a strong proposition that SRTs can be adapted for use in the industrial design of medical products. The research has shown how one particular SRT, namely, EAPs, could be adapted in order to drive actuation. It is, therefore, worth noting that the potential of other SRTs such as SMAs, pneumatics, soft electronics, soft conductors and soft smart materials has solid grounds for further study. EAPs are, based on the research conducted, the most interesting for initial exploration and experimentation, however, other SRTs may prove to have value in specific applications and products.

5.5 How to adapt SRTs for use in the industrial design of medical products

Based on the outcomes of this study, it has been shown that an effective means of adapting SRTs for use in the industrial design of medical products is to have a multi-phased approach to assessing the SRT. Understanding the beneficial properties as well as the limitations of each SRT is crucial in being able to align the SRT to an appropriate application or implementation. In this case, the requirements set by the two medical case studies required the end product to be lightweight, flexible and to be worn by the user. This limited the focus to SRTs that did not require large or bulky mechanics to operate, such as compressor pumps and motors in the case of pneumatic actuators. However, there may be applications where this is not a limitation, and pneumatic actuators can be integrated into a device where a compressor or motor is a separate module that simply provides the air pressure needed. If the user does not need to move around with the device, then it is feasible that pneumatic actuators integrated into garments or braces could serve to provide compression, or actuation in a controlled environment such as a rehabilitation clinic. This example serves to demonstrate the need for further systematic study by industrial designers into potential applications for each SRT. Table 5.6 aims to show how the various SRTs covered in this study have been related to existing and future applications for these technologies. This forms the final step of triangulation in the study where the SRTs are related to potential applications, to not only justify further study in this field of research, but to provide starting points for future studies and SRT development.

Table 5.6: Triangulation of SRT actuators, existing applications and potential applications
(Author's construct, 2022)

SRT (actuators)	Favourable properties	Existing applications	Potential applications for further research and development
EAP	- Lightweight - Soft - Safe - Elastic and flexible - Deformable - Conformable - Infinite DOF - Compact - Ergonomic - Easily integrated - Low cost - Manufacturable	- Festo manta robot	- Braille Pad - Wearable rehabilitation device, e.g., Medi-dot - Wearable device for applying compression, e.g., soft exosuit - Adaptable product designs - Actuated solar-powered charging station - Actuated lighting fixtures - Synthetic heart as organ replacement - Device for resistance training - Sporting industry for rehabilitation - Healthcare devices - Textiles in robotics - Companion robot
SMA	- Lightweight - Safe - Low cost - Manufacturable	- Worm robot - Octopus tentacle - Fish	- Small actuation device with access to a large power source, e.g., a plug-in unit for rehabilitation
Pneumatic	- High output force - Deformable - Robust	- Elephant trunk - Worm robot - Artificial heart - OctArm VI - Soft grippers	- Minimally invasive surgeries - Rehabilitation device
Hydraulic	- High output force - Deformable - Robust	- Submarine grippers	- Deep sea applications

5.6 Chapter summary

As shown in this chapter, the initial literature review provided the framework for the study. By understanding the overriding properties and favourable characteristics of SRTs in comparison to conventional rigid robotics technologies, the researcher was able to identify key areas of research through a general thematic analysis. This allowed the researcher to select one branch for further study, specifically soft robotics actuation technologies. By conducting a more in-depth and thorough review of the various soft robotics actuation technologies in use, the researcher was able to compare these SRTs by means of a matrix. Incorporating the design requirements from two real-world medical design case studies into the matrix, made it possible to not only correlate those design requirements to the inherent properties of each SRT, but also to focus the study on one particular actuation technology, specifically EAPs. As the favourable characteristics of EAPs aligned perfectly with the design requirements for the medical case studies, it was chosen as the SRT for further study and exploration.

Interviews with expert industrial designers, experienced at developing products for the medical industry, provided further grounding and support for the exploration of EAPs as a suitable technology. By understanding the medical design industry on a high level, the researcher has shown that with appropriate case studies and research, it may be possible to expand on and prove that these new technologies are viable for commercial use in medical product design. If sufficient cases are proven, this area of research may receive focused support through corporate or government funding and incentives.

A further interview with Stratasys, the world leader in additive manufacturing technologies, provided confirmation that not only has 3D printing technology become feasible for mass production, but there is ongoing development of EAP materials that can be 3D printed on their machines. As shown in the examples in Chapter Four, the ability to print multi-density materials with varying properties at the same time in a single print, will allow for innovative product design where EAPs are integrated inside a part or product to provide actuation in ways previously not possible.

The researcher was then able to conduct a focus group with industrial design students, where conceptual designs were developed to test the findings gained at that point. Through the exploration of these various concept designs, it was shown that EAPs are not only appealing for the use in the industrial design of softer, more ergonomic products, but that the industrial designers that participated in the study were also amenable to working with EAPs and other SRTs in the future. This further supports the need to expand on this area of research and provide exposure to these technologies at industrial design universities and schools.

The final step in the study involved the researcher refining one of the design concepts developed in the focus group, specifically the Braille Pad, to a more realistic and evolved point. Through the aid of Solidworks CAD software and leveraging the researcher’s 18 years of experience as a practicing industrial designer, it was possible to produce 3D visualisation images to clearly communicate the design of the Braille Pad, and how EAPs could be integrated into the device in order to individually actuate the braille pins. These technical illustrations show how EAPs would function in such a device, as well as the impact using such a compact technology has on the rest of the design. It was possible to create a flexible, ergonomic and lightweight design that is compact, highly manufacturable, and ultimately less costly to produce. This would allow for similar products to be developed for the mass market, and so make such product designs accessible to a broader segment of the population. By focusing on improved user experience, lower production cost, speed of manufacture and basing this on a systematic research methodology, the researcher has answered the main research question and sub-questions in a clear and believable manor.

The researcher has shown that SRTs can indeed be adapted for use in the industrial design of medical products to improve the inherent properties and functionality, as demonstrated by the refinement of the Braille Pad assistive device concept. The two sub- questions have also been answered, and Table 5.6 shows that EAP is certainly one SRT that can be adapted for use by industrial designers in the development of innovative medical devices. How this could be done has been demonstrated throughout this study, in the form of pragmatic and systematic research that follows a strong methodology. The researcher has been diligent in the praxis of the research methodology in this case, with the aim of producing a body of work that would be of use to others and motivate further study in this field. An overview of potential applications for future research and development has been provided in Table 5.6 to benchmark the findings from this study and provide a clean starting point for further research.

CHAPTER SIX

Conclusions and Recommendations

6.1 Discussion of limitations

The area of study was specifically focused on the feasibility of incorporating SRTs into the industrial design of medical products. The researcher aimed to understand advancements in SRTs in order to ring-fence those technologies which could be applicable for use in products designed for the average person. The researcher has identified and described these applicable SRTs and shown how EAP may be applied for use in the industrial design of an assistive device, the Braille Pad.

The focus area has covered materials development in soft robotics, the methods used to drive actuation. Manufacturing techniques have been considered throughout this study, and the feasibility for mass production has been key to justifying commercial viability. This was a critical factor when coding and grouping the metadata, as well as reviewing the various design concepts created in the focus groups. This ensured that “feasibility” was followed from start to finish to further add support and credibility to the findings.

The researcher has not repeated existing research or conducted materials development research. The focus has not been to hypothesise on future materials, but rather to build on existing technologies currently being used. This research is not for the purpose of expanding on robotics technology or the existing knowledge base of robotics. This study is not a study of robots in general and the intention is not to be able to design robots with the information gathered through this research.

6.2 Study overview and contributions

An overview of the study will now be given, with reference to the theoretical, methodological and practical contributions provided by this research.

6.2.1 Context of the study

In the medical and consumer products market, there is a limitation to design solutions as a result of the materials and technologies currently available. Conventional materials and manufacturing processes are driving product design towards more rigid end products. Technologies and materials have been developed in the robotics industry that could allow for new design solutions and advanced products that have inherent customisability and adapt to the user as required (Rossiter et al., 2016). Adapting these technologies for use in industrial design could lead to an advancement in the way we design products, especially when the product is worn or in direct contact with the user. These technologies cost less to mass produce than the rigid alternatives, thereby reducing the total cost and making the end products more accessible to a broader segment of the population. By looking to new materials and methods of production "…we might in fact be on the way to a new industrial revolution" (Pfeifer et al., 2012:78).

The research study employed qualitative research methods. The researcher evaluated SRTs in order to identify unique properties that could be worth adapting for use in medical product design. These were then tested through focus groups and simulation and the findings presented. The findings were discussed and recommendations for further study and research on this topic were described.

6.2.2 Theoretical contribution: potential for SRTs to allow for improved product development

It is widely believed that the robots of the future will have soft bodies and will be capable of safe interaction with humans (Pfeifer et al., 2012:76). The unique characteristics that are found in soft robotics, namely, embodied intelligence, self-organisation, soft morphology and materials allow for novel designs to be developed. This requires a new set of design principles to be used when developing soft robots that are useful and functional. In terms of robot design this will help support the move from a hard to soft engineering approach, which appears from the research covered to be quite different (Pfeifer et al., 2012:78).

With advances in manufacturing techniques such as additive manufacturing, it may be possible to integrate sensors, actuators and conductive networks into a single body through multilayer printing (Pfeifer et al., 2012:83). For the purpose of prototyping and rapid design evolution, this will have a major impact on the speed at which this technology becomes proven and accessible. The development of effective and functional soft robots will allow for safer interactions with humans and other fragile systems, adaptive machines with inherent mechanical intelligence and a broader level of access to such machines due to the reduced cost to manufacture (Kim et al., 2013:293).

In the same way that many organisms incorporate a skeleton or semi-rigid structure, we may see the construction of soft robotics and other soft structures incorporating this in their design. This combination of a partial substructure or internal framework would allow for the use of soft actuators and materials without compromising the need for a stable body that still allows for changes in morphology. The further development and use of smart and electro-active materials will continue to be of interest to soft robotics researchers and developers. This will be one of the key factors that determines feasibility and the rate at which this technology can be refined and adapted for use elsewhere.

6.2.3 Methodological contribution: pragmatism as the basis for logical, systematic qualitative research

The research design was shown to have a logical flow that suited the mixed-method research methodology used for this study. The various stages were outlined and described in detail, covering individual interviews, focus group co-design workshops, case study data collected through questionnaires, design concepts development, focus group discussions and metadata analysis.

The researcher's approach to this study was based on pragmatism, and all aspects have followed a logical path with the aim of being able to present the research findings in a clear orderly way. The researcher followed a clear ethics line, ensuring all requirements were met according to the Cape Peninsula University of Technology's ethical standards for researchers. All data gathered were done in line with the ethics code of conduct and encoded as required to allow for further analysis.

The review of all metadata, interviews with medical experts, interviews with industrial design experts, interviews with industrial design students and focus groups with industrial design students was done through the lens of industrial design to ensure all findings could be related back to the research question.

The researcher has implemented the pragmatic research methodology in a systematic and logical manner to extract meaningful data. From the *first phase* of research, which covered soft robotics on a high level, the researcher was able to identify broad themes and areas for further research. The focus area of actuation was chosen due its mechanical nature, and good fit for use by industrial designers to develop product designs. Other areas, such as soft electronics and soft sensors were excluded from the study at this point.

The researcher then conducted the *second phase* of research, an intensive analysis of SRT studies where the focus was either on the whole or, in part, on actuation. This detailed metadata analysis allowed for the various studies to be grouped, using various tools such as factoring, into four key groups. These groups included: Actuation by means of artificial muscle, Morphological computation, Biomimetic inspired robots and Applications for SRTs. Within these groups there were factors common to all groups, namely, *actuator as artificial muscle* and *morphological computation*. As morphological computation focuses mainly on the way the technology is used, and the geometry designed to affect a specific or desired motion, this was treated as secondary to the focus of developing actuators as artificial muscles. A detailed analysis of the various actuation technologies currently available and being explored in soft robotics is covered in the literature review in Chapter One. By listing these various SRTs and their inherent attributes, both positive and negative, it was possible to produce a simple overview of actuation technologies.

The *third phase* of research involved interviews with medical design experts and the inclusion of two real-world medical design case studies, in order to define real-world industrial design requirements that would be used to guide further research. These requirements were then refined and those specific to the mechanical design of medical products were listed in a simple table. There were clear similarities between the two projects, where soft structures were a specific requirement. The Medi-dot case study had a specific need for actuation, and so aligned well to the narrower focus area chosen by the researcher. These requirements were then compared to the various actuation SRTs, and one technology was able to meet all requirements set, namely, EAPs. This SRT was then chosen as the basis for further study.

At this point, the researcher was well prepared to conduct the *fourth phase* of research, which involved interviews with industrial design experts. The aim of these interviews was to gauge a view of the medical design industry, and the general awareness of SRTs among professional industrial designers that focus on developing medical products. In addition, the feasibility for using SRTs was discussed, and the findings from these interviews were presented in table format with relevance to this study clearly shown. By conducting these interviews, and interrogating the hypothesis, the researcher was able to present an industry view on SRTs and put the question of feasibility forward. This would allow for cross-analysis through the use of triangulation, as described in Chapter Five.

The next and *fifth phase* of research involved an interview with an additive manufacturing specialist, where new production methods were discussed. This followed from discussions with the industrial design experts and provided further credibility for the use of EAPs as an integrated part of future product designs. The findings from this interview were condensed into a simple table, and it was noted that development had already started to allow for EAPs to be 3D printed on their machines.

The researcher was then well prepared to conduct the *sixth phase* of the research, where the findings from the literature review, interviews with medical experts, interviews with industrial design experts and an interview with a 3D printing specialist formed a solid base. These discoveries were also used to prepare for a design focus group where the researcher planned to use participatory co-design methods to explore the use of EAPs in the industrial design of medical products. The focus group was split into three stages, namely: a pre-focus group questionnaire, a focus group concept development workshop and a post-focus group questionnaire. The findings from these three stages were presented to show a clear picture before and after the concept development workshop was conducted. By establishing the participants' knowledge and understanding of SRTs before the design work was conducted, it was possible show the impact of these design exercises, and how their perceptions had changed. In terms of an overview, the participants' perception and understanding of SRTs had improved. This improvement in perception and the concept designs developed in the focus group implies that exposing industrial designers to SRTs does have an impact. It is certainly feasible that other applications may be developed that can incorporate adapted SRTs. It would follow that a comprehensive and detailed archive of SRTs could be presented in such a way so as to encourage further exploration in industrial design, instead of being ring-fenced to robotics applications alone. For example, in the case of artificial muscles, not only can these be used to drive motion or control the limbs of a robot, but they can also be integrated into a product like the Braille Pad that drives simple motion of key components. It is this creative, or innovative switch that will allow for the technologies to be adapted, where possible, for the industrial design of medical products.

6.2.4 Practical contribution: industrial design of medical products using EAP

As shown, the initial literature review provided the framework for the study. By understanding the overriding properties and favourable characteristics of SRTs in comparison to conventional rigid robotics technologies, the researcher was able to identify key areas of research through a general thematic analysis. This allowed the researcher to select one branch for further study, specifically soft robotics actuation technologies. By conducting a more in-depth and thorough review of the various soft robotics actuation technologies in use, the researcher was able to compare these SRTs by means of a matrix. Incorporating the design requirements from the two real-world medical design case studies into the matrix, made it possible to not only correlate those design requirements to the inherent properties of each SRT, but also to focus the study on one particular actuation technology, specifically EAPs. As the favourable characteristics of EAPs aligned perfectly with the design requirements for the medical case studies, it was chosen as the SRT for further study and exploration.

Interviews with expert industrial designers, experienced at developing products for the medical industry, provided further grounding and support for the exploration of EAPs as a suitable technology. By understanding the medical design industry at a high level, the researcher has shown that with appropriate case studies and research, it may be possible to expand on and prove that these new technologies are viable for commercial use in medical product design. If sufficient cases are proven, this area of research may receive focused support through corporate or government funding and incentives.

A further interview with Stratasys, the world leader in additive manufacturing technologies, provided confirmation that not only has 3D printing technology become feasible for mass production, but that there is ongoing development of EAP materials for this purpose. As shown in the examples in Chapter Four, the ability to print multi-density materials with varying properties at the same time in a single print, will allow for innovative product design where EAPs could be integrated inside a part or product to provide actuation in ways previously not possible.

The researcher was then able to conduct a focus group with industrial design students, where conceptual designs would be developed to test the findings gained so far. Through the exploration of these various concept designs, it has been shown that EAPs are not only appealing for the use in the industrial design of softer, more ergonomic products, but that the industrial designers that participated in the study were also amenable to working with EAPs and other SRTs in the future. This further supports the need to expand on this area of research and provide exposure to these technologies at industrial design universities and schools.

The final step in the study involved the researcher refining one of the design concepts developed in the focus group, specifically the Braille Pad, to a more realistic and evolved point. Through the aid of Solidworks CAD software and leveraging the researcher's 18 years of experience as a practicing industrial designer, it was possible to produce 3D visualisation images to clearly communicate the design of the Braille Pad, and how EAPs could be integrated into the device in order to individually actuate the braille pins. These technical illustrations show how EAP would function in such a device, as well as the impact that using such a compact technology has on the rest of the design. It was possible to create a flexible, ergonomic and lightweight design that is compact, highly manufacturable and ultimately would cost less to produce. This would allow for similar products to be developed for the mass market, and so make such product designs accessible to a broader segment of the population. By focusing on improved user experience, lower production cost, speed of manufacture and basing this on a systematic research methodology, the researcher has answered the main research question and sub-questions in a clear and believable manner.

6.3 Suggestions for further research

The researcher has shown that SRTs can indeed be adapted for use in the industrial design of medical products to improve the inherent properties and functionality, as is demonstrated by the refinement of the Braille Pad assistive device concept. The two sub- questions have also been answered, and Table 5.6 shows that EAP is certainly one SRT that can be adapted for use by industrial designers in the development of innovative medical devices. How this could be done has been demonstrated through this study, in the form of pragmatic and systematic research that follows a strong methodology. The researcher has been diligent in the praxis of the research methodology in this case, with the aim of producing a body of work that would be of use to others and motivate further study in this field. An overview of potential applications for future research and development has been provided in Table 5.6, to benchmark the findings from this study, and provide a fresh starting point for further research. This has provided clear direction and listed potential applications for SRTs that could be used to initiate further research on this topic. It is also the researcher's intention to continue research on this topic in the pursuit of a doctorate. Through the presentation of findings and discussing these in a logical systematic fashion, the researcher has aimed to not only answer the research question, but also provide a clear understanding of the way the study was conducted, so that others might be motivated to replicate or expand on it. It is the researcher's hope that this study assists in opening up SRTs for use by industrial designers, and helps create awareness of these cutting-edge technologies, so that innovative products might be developed that are more accessible to a wider segment of the population.

6.4 Closing

As described by Miles and Huberman (2014), and as is evident from this research study, one cannot enter into a discussion of how goodness criteria flow from epistemological positions. Rather, we should remain broadly in the critical realist tradition. To achieve this, the researcher has aimed to address five main issues:

(1) the *objectivity/confirmability* of qualitative work, through the use of multiple sources at each stage of the research study.

(2) *reliability/dependability/auditability*, through the use of multiple sources that can be cross-examined and reviewed. The researcher has also provided all references and supporting data to ensure this study can be audited if required.

(3) *internal validity/credibility/authenticity*, through the use of key research tools and accepted research methods to capture, present and analyse the various datasets in this study.

(4) *external validity/transferability/fittingness,* through the discussion of findings with experts in the field and remaining true to the core research topic and question. The researcher has followed where the data have led and provided recommendations for further research based on the outcomes of the theoretical and practical research conducted.

(5) *utilisation/application/action orientation*, through the use of the theoretical and practical data to test the hypothesis and determine whether the “adaptation of soft robotics technologies for use in the industrial design of medical products” is possible. The researcher has concluded in this study that this can be achieved, and with excellent results.

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LINKS OF INTEREST

- SoRo soft robotics:
    - http://www.liebertpub.com/overview/soft-robotics/616/
- ROBOSOFT
    - http://www.robosoftca.eu/
- Soft robotics toolkit:
    - http://softroboticstoolkit.com/
- Human augmentation video
    - https://www.youtube.com/watch?v=PHD2qOY6bfw
- Electroactive polymer (EAP) actuators as artificial muscles - reality, potential and challenges
    - https://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm
- EAP muscle video – NASA
    - https://www.youtube.com/watch?v=CSvdq2fmSq0
- Worldwide electroactive polymer (WW-EAP) newsletter
    - https://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html

APPENDICES

Appendix A: Case Study 1 (FIT diabetic shoe-sole design brief)

The next set of interviews were held with Footwear Industry Training (PTY) Ltd in Cape Town. They were working with various professionals, including textile experts from CPUT, on a new device that would allow real-time monitoring of plantar pressure distribution and gait analysis. The device would be worn inside a shoe as an in-sole and incorporate the various sensors and functionality needed. The researcher was invited to participate in the project and to include the project requirements as part of this study. The project brief for this project will subsequently be described.

Project outline

Development of wireless sensors in shoe in-soles

Footwear Industry Training (PTY) Ltd – FIT – requires a provider to design and develop a novel pressure-sensitive foot in-sole for real-time monitoring of plantar pressure distribution and gait analysis.

The device should consist of a sensor or sensors with pressure-sensitive elements and an integrated electronic board for high frequency data acquisition, pre-filtering and wireless transmission to a remote data/computing/storing unit.

Ideally, the device should be low-power battery-driven.

Foot plantar pressure is the pressure field that acts between the foot and the support surface during everyday locomotor activities. In designing the plantar pressure measurement device, the key requirements are:

Very mobile: it must be light and small, overall size, i.e., 300g or less.

The foot plantar system should have limited wiring, ideally be wireless, to ensure natural gait.

Shoe and sensor placement: the sensor must be thin, flexible and light. A mass of 300g or less does not affect natural gait.

Low cost: the sensor must be affordable for general application.

Low power consumption: it should exhibit low power consumption such that energy from a small battery is sufficient for collecting and recording the required data.

Plantar pressure sensor requirements

The key specifications for sensor performance include linearity, hysteresis, sensing size, pressure range, temperature sensitivity and operating frequency.

Linearity: the response of the sensor to the applied pressure, when plotted, will show the linearity figure of merit, i.e., how straight the plotted line is.

Hysteresis: can be determined by observing the output signal when the sensor is loaded or unloaded.

Temperature sensitivity: sensors may produce different pressure readings as the ambient temperature changes. A sensor with a low temperature sensitivity in the 20-37ºC range is preferred.

Pressure range: The pressure range is the key specification for a pressure sensor. Maximum pressure is the upper limit that the pressure sensor can measure and vice versa.

Sensing area of the sensor: size and placement of the sensor are critical. It is suggested that a minimum size of 5mm x 5mm be used, whereas sensors smaller than that must be designed as array sensors.

Operating frequency: it is recommended that to measure foot plantar pressure precisely for running activities, the sensors must be capable of sampling at 200Hz. This frequency is generally considered sufficient for sampling most everyday gait activities.

Creep and repeatability: creep is the deformation of the material under elevated temperature and static stress and relates directly to the time-dependent permanent deformation of material when subjected to a constant load and stress. Low creep sensors are one of the key requirements in foot pressure measurement. Repeatability refers to the ability to produce reliable results, even after long periods of time. Repeatability problems can be eliminated if the sensor exhibits no creep or deformation over repetitive or high cycle loads.

Foot plantar pressure sensors commercially available

The most common commercially available plantar pressure sensors are capacitive sensors, resistive sensors, piezo-electric sensors and piezo-resistive sensors.

Appendix B: Case Study 2 Medi-dot soft garment design brief

The first interviews were held at the Cape Hip and Knee medical practice in Cape Town, with two leading surgeons who are not only at the forefront of medical development in their field, but who have personally designed and patented various items to improve artificial joint surgery, reduce implant rejection and improve patient recovery.

The outcome of these discussions was that they required a soft intelligent device that the patient could wear after surgery, the device needed to track and transmit real-time patient data and allow real-time tracking of patient recovery. The researcher was supplied a design brief for the project, which will be described here now.

Project outline

The Cape Hip and Knee medical practice specialises in knee and hip surgeries. There are currently limitations to effectively assess the patient's pre-op and post-op range of motion and compare these in a non-biased or subjective manner. The current method involves basic measuring apparatus, and visual inspection of the patient's movements. There is a need for a device that can be worn by the patient pre-op in order to gather accurate scientific data to measure *range of motion*, *gait* and *general patient-specific data*. These data could then be stored, and the same device used post-op to gather the same user specific measurements. The two sets of data could then be compared in a controlled, repeatable way to ensure the reliability of the results and separation from the need for visual assessment alone. It would be further possible to develop capabilities into the software to present such data in a meaningful way to the medical professional to analyse patient recovery, and further advise on ways to aid/expedite a healthy recovery in patients.

Project requirements

The device should be lightweight and comfortable to wear.
Ergonomic and flexible (elasticity to allow for post-op swelling).
Must be able to wear the device under clothing.
Adaptable to each user – Customisable for comfort and correct placement on the user to gather accurate reliable data.
Must gather range of motion at various points of the body – i.e., knee, ankle, hip, etc.
Must allow for accurate gait analysis and representation in a functional software-based user interface.
Have Bluetooth capabilities to transfer data captured to an app on the patient's smartphone (these data are then uploaded to a server where advanced analytics can be done on the data).
Have sufficient battery life to require minimal recharging of the device – minimum eight hours.

The electronics selected should allow for further development of the device to incorporate additional functionality in the future: such as sensors for tracking blood flow, Temperature and muscle stimulation.

May require some form of actuation/compression to stimulate blood flow in the area around the surgery.

The “Medi-dot” electronics module and battery should be compact and removable from the device/garment to allow for washing of the device/garment.

The same “Medi-dot” should be usable on various devices/garments that would be designed to be work on a specific part of the body, i.e., ankle, knee, hip, etc.

The “Medi-dot” should be able to function as a stand-alone or single unit or as a set of data dots to track increasingly complex and co-related user movement data. This would be a single joint in the simplest form up to the full body kinematics in the most advanced configuration.

The hardware should be designed to allow for upgrading of the components in future models without having to change the physical garment design, i.e., only the “Medi-dot” would need to be replaced to allow for increased functionality.

On-going software development would allow for increased functionality on existing hardware which would be managed through automated software updates.

Technologies to investigate

Accelerometer function.

Goniometer function.

Range of motion analytics.

Gait analysis and representation.

Soft garments and wearable technologies.

Soft robotics technologies (actuation, soft materials, soft sensors, soft electronics, soft elastomeric electrodes).

Motion tracking and analytics.

Actuators and compression technologies available.

Appendix C: Design agency interviewed – Wild Design

Andrew Berno (AB):
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Alejandro Lara (AL):
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Website: www.wilddesign.de/en

Andrew Berno and Alejandro Lara: Wild Design Agency – Shanghai, China

Appendix D: Design agency interviewed – designaffairs

Carolina Villalobos:

Role: Head of Industrial Design
WeChat ID: cavillalobos
Phone: +86 21 6298 4733
Email: Carolina.villalobos@designaffairs.com.cn
Address: designaffairs Group China, 50-4A-205 MoGanShan Road,
200060 Shanghai, China
Website: www.designaffairs.com

Carolina Villalobos: designaffairs – Shanghai, China

Appendix E: 3D printing company interviewed – Stratasys

Anthony Tian:

Role:	Senior Sales Manager, Direct Sales, Greater China.
WeChat ID:	AnthonyT1209
Phone:	+86-21-3319 6052
Email:	anthony.tian@stratasys.com
Address:	Floor 1, A3, Ninghui Square, No. 718 Lingshi Road, 200072 Jing'an District, Shanghai, China
Website:	www.stratasys.com

Marcus Liang:

Role:	Pre-sales and Application Engineer, South Asia
WeChat ID:	Freakingnolife
Phone:	+86-21-3319 6066
Email:	Marcus.Liang@stratasys.com
Address:	Floor 1, A3, Ninghui Square, No. 718 Lingshi Road, 200072 Jing'an District, Shanghai, China
Website:	www.stratasys.com

Appendix F: Example of completed focus group questionnaire

Cape Peninsula
University of Technology

湖南大學 设计艺术学院
SCHOOL OF DESIGN
HUNAN UNIVERSITY

Student: Wu fan
Academic Level: Master's student in Industrial Design (School of Design, Hunan University)
Date: 12th OCT 2018

Pre-focus group questions

Question 1: What soft robotics technologies (SRTs) do you know of?

Answer to Question 1:
- Air inflation
- Flexible structures (like a snake)
- Tissue engineering using polymers (organic materials with cells implanted)
- EAP
- Fluid materials
- Chemical reaction (produce some gas to drive the soft body)

Question 2: What SRTs applications do you know of?

Answer to Question 2:
- Artificial muscle
- Minimally invasive surgery
- Factory (used to lift things)
- Inspection robot
- Endoscope

Question 3: What SRTs have you worked/designed with?

Answer to Question 3:
- No.
- Just have made some polymer artificial tissues.

Question 4: Have you got experience using SRTs in industrial design?

Answer to Question 4:
- No.

Question 5:
Do you see potential for SRTs to be used in industrial design (specifically medical and consumer product design)?

Answer to Question 5:
- Yes.
- I think the SRTs will be a great technology to be used in products. Because of its flexible body and touch, it has the special characteristics that other technologies don't have.

Post-focus group questions:

Question 6: Has your understanding of SRTs improved?

Answer to Question 6: Yes.

Question 7: Are there applications for SRTs in industrial design?

Answer to Question 7: Yes. There are many of the applications.

Question 8: What applications do you believe exist for developing medical and consumer products using SRTs?

Answer to Question 8: Exoskeleton.

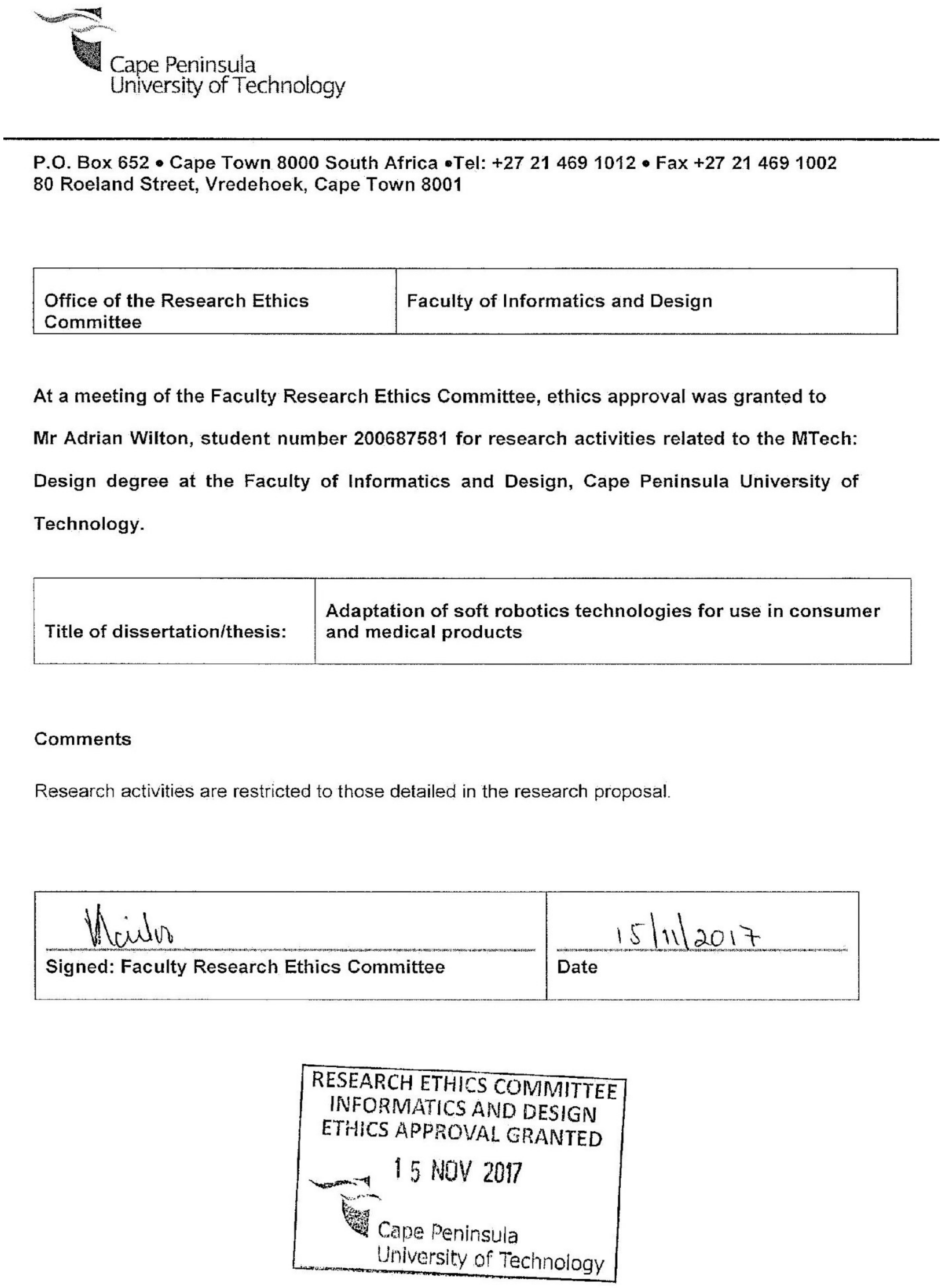
Question 9: How can SRTs change the way we design medical and consumer products?

Answer to Question 9: I think it can make this kind of design softer and more organic.

Question 10: What could the future of medical and consumer products be if we use SRTs?

Answer to Question 10: They may look like an alive thing and can easily change their shape.

Appendix G: Ethics approval for MTech: Industrial Design – CPUT



Cape Peninsula
University of Technology

P.O. Box 652 • Cape Town 8000 South Africa •Tel: +27 21 469 1012 • Fax +27 21 469 1002
80 Roeland Street, Vredehoek, Cape Town 8001

Office of the Research Ethics Committee	Faculty of Informatics and Design

At a meeting of the Faculty Research Ethics Committee, ethics approval was granted to Mr Adrian Wilton, student number 200687581 for research activities related to the MTech: Design degree at the Faculty of Informatics and Design, Cape Peninsula University of Technology.

Title of dissertation/thesis:	Adaptation of soft robotics technologies for use in consumer and medical products

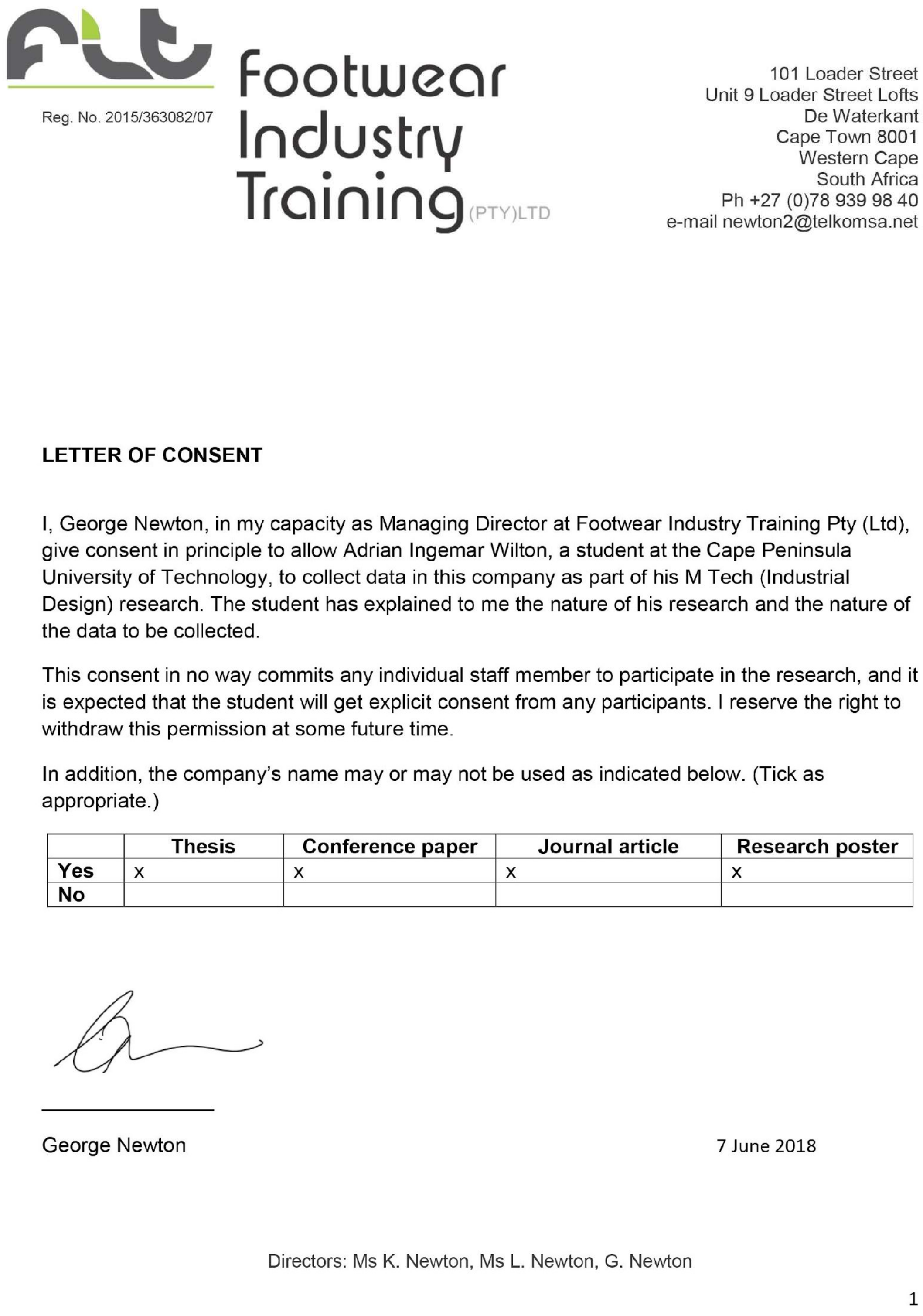
Comments

Research activities are restricted to those detailed in the research proposal.

Signed: Faculty Research Ethics Committee	15/11/2017 Date

RESEARCH ETHICS COMMITTEE
INFORMATICS AND DESIGN
ETHICS APPROVAL GRANTED
15 NOV 2017
Cape Peninsula
University of Technology

Appendix H: Ethics consent form - Footwear Industry Training



Reg. No. 2015/363082/07

Footwear
Industry
Training (PTY)LTD

101 Loader Street
Unit 9 Loader Street Lofts
De Waterkant
Cape Town 8001
Western Cape
South Africa
Ph +27 (0)78 939 98 40
e-mail newton2@telkomsa.net

LETTER OF CONSENT

I, George Newton, in my capacity as Managing Director at Footwear Industry Training Pty (Ltd), give consent in principle to allow Adrian Ingemar Wilton, a student at the Cape Peninsula University of Technology, to collect data in this company as part of his M Tech (Industrial Design) research. The student has explained to me the nature of his research and the nature of the data to be collected.

This consent in no way commits any individual staff member to participate in the research, and it is expected that the student will get explicit consent from any participants. I reserve the right to withdraw this permission at some future time.

In addition, the company's name may or may not be used as indicated below. (Tick as appropriate.)

	Thesis	Conference paper	Journal article	Research poster
Yes	x	x	x	x
No				

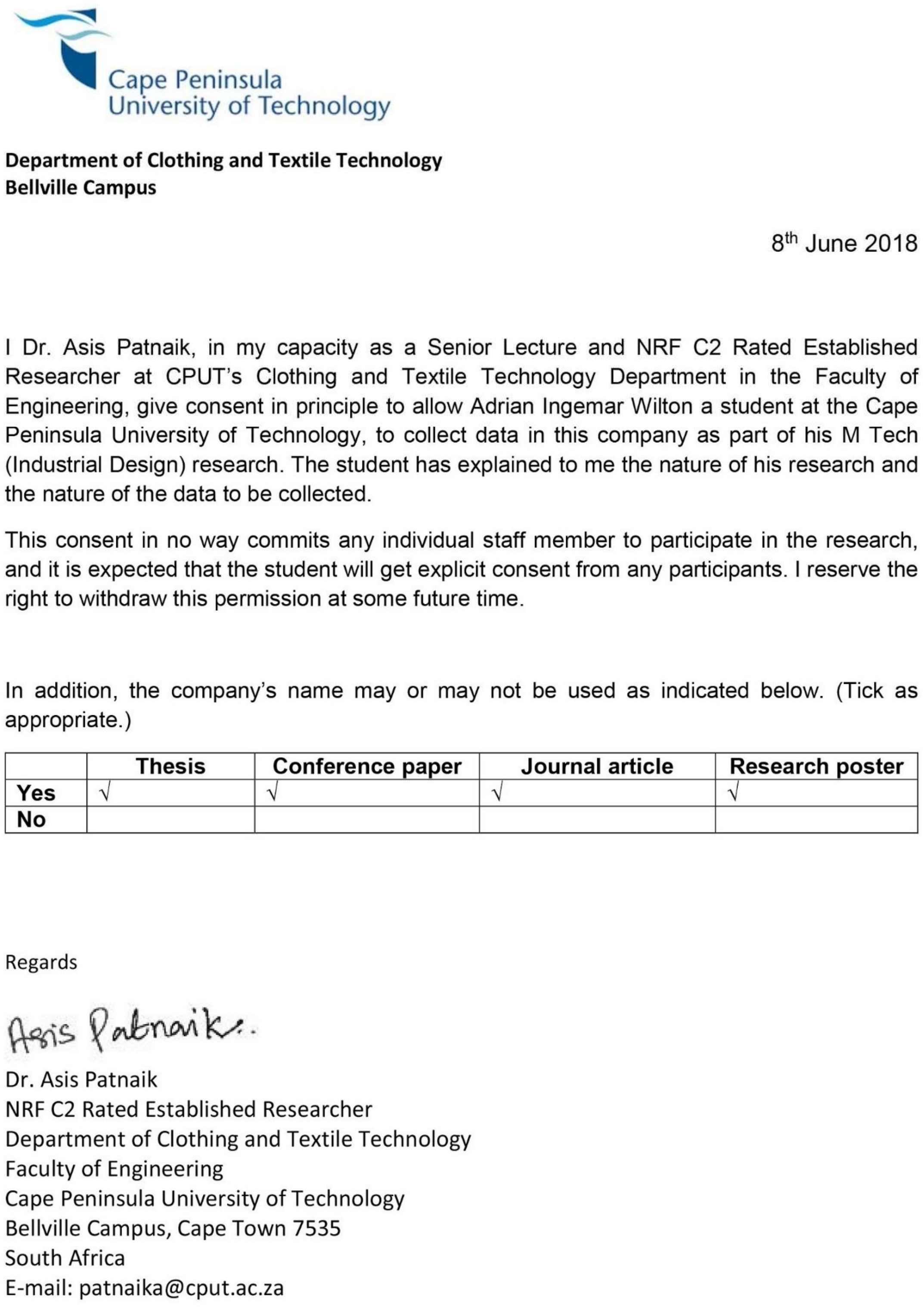
George Newton

7 June 2018

Directors: Ms K. Newton, Ms L. Newton, G. Newton

1

Appendix I: Ethics consent form - Cape Peninsula University of Technology



Cape Peninsula
University of Technology

Department of Clothing and Textile Technology
Bellville Campus

8th June 2018

I Dr. Asis Patnaik, in my capacity as a Senior Lecture and NRF C2 Rated Established Researcher at CPUT's Clothing and Textile Technology Department in the Faculty of Engineering, give consent in principle to allow Adrian Ingemar Wilton a student at the Cape Peninsula University of Technology, to collect data in this company as part of his M Tech (Industrial Design) research. The student has explained to me the nature of his research and the nature of the data to be collected.

This consent in no way commits any individual staff member to participate in the research, and it is expected that the student will get explicit consent from any participants. I reserve the right to withdraw this permission at some future time.

In addition, the company's name may or may not be used as indicated below. (Tick as appropriate.)

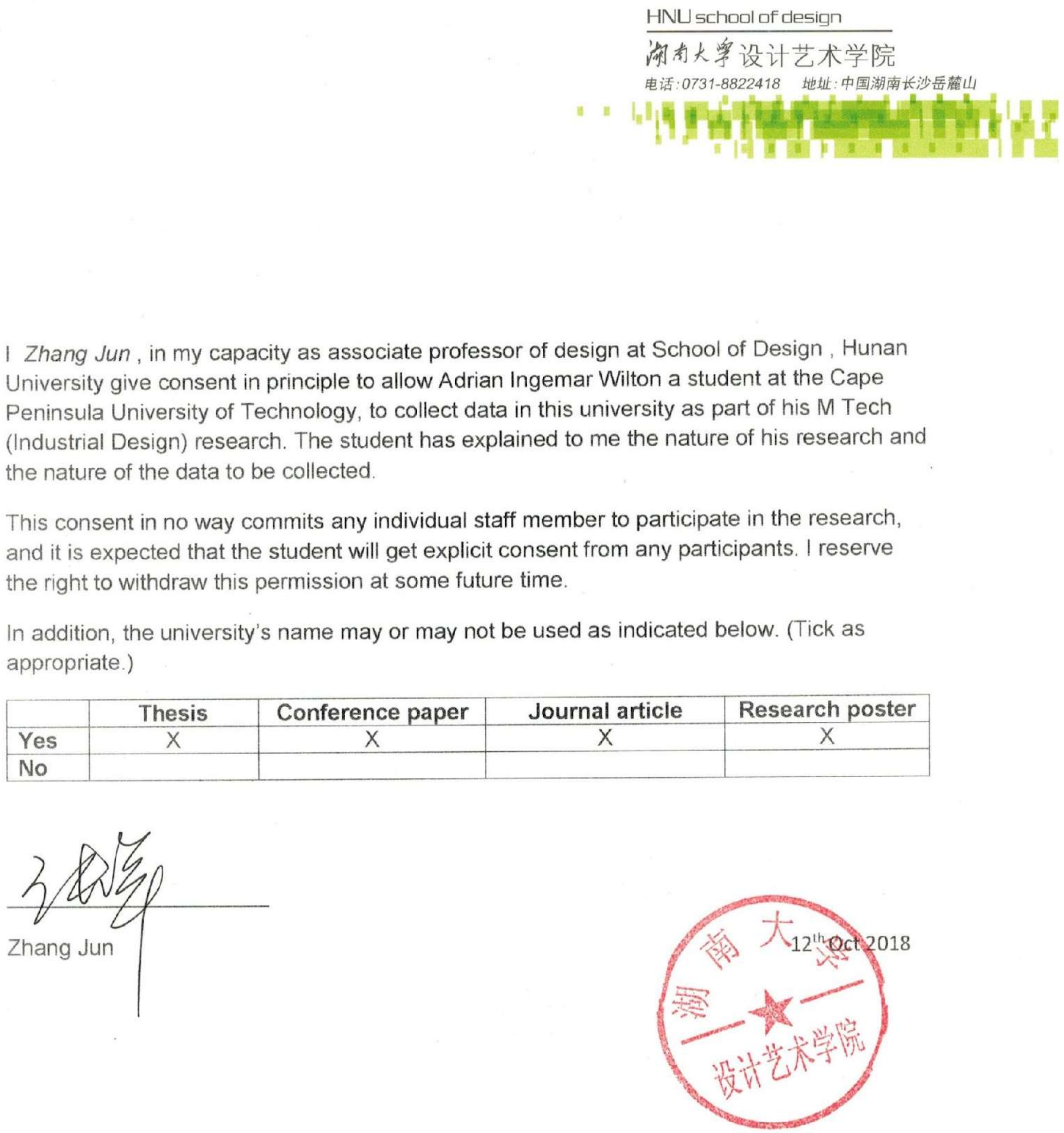
	Thesis	**Conference paper**	**Journal article**	**Research poster**
Yes	√	√	√	√
No				

Regards

Asis Patnaik.

Dr. Asis Patnaik
NRF C2 Rated Established Researcher
Department of Clothing and Textile Technology
Faculty of Engineering
Cape Peninsula University of Technology
Bellville Campus, Cape Town 7535
South Africa
E-mail: patnaika@cput.ac.za

Appendix J: Ethics consent form - School of Design, Hunan University, China



HNU school of design
湖南大学设计艺术学院
电话:0731-8822418 地址:中国湖南长沙岳麓山

I *Zhang Jun* , in my capacity as associate professor of design at School of Design , Hunan University give consent in principle to allow Adrian Ingemar Wilton a student at the Cape Peninsula University of Technology, to collect data in this university as part of his M Tech (Industrial Design) research. The student has explained to me the nature of his research and the nature of the data to be collected.

This consent in no way commits any individual staff member to participate in the research, and it is expected that the student will get explicit consent from any participants. I reserve the right to withdraw this permission at some future time.

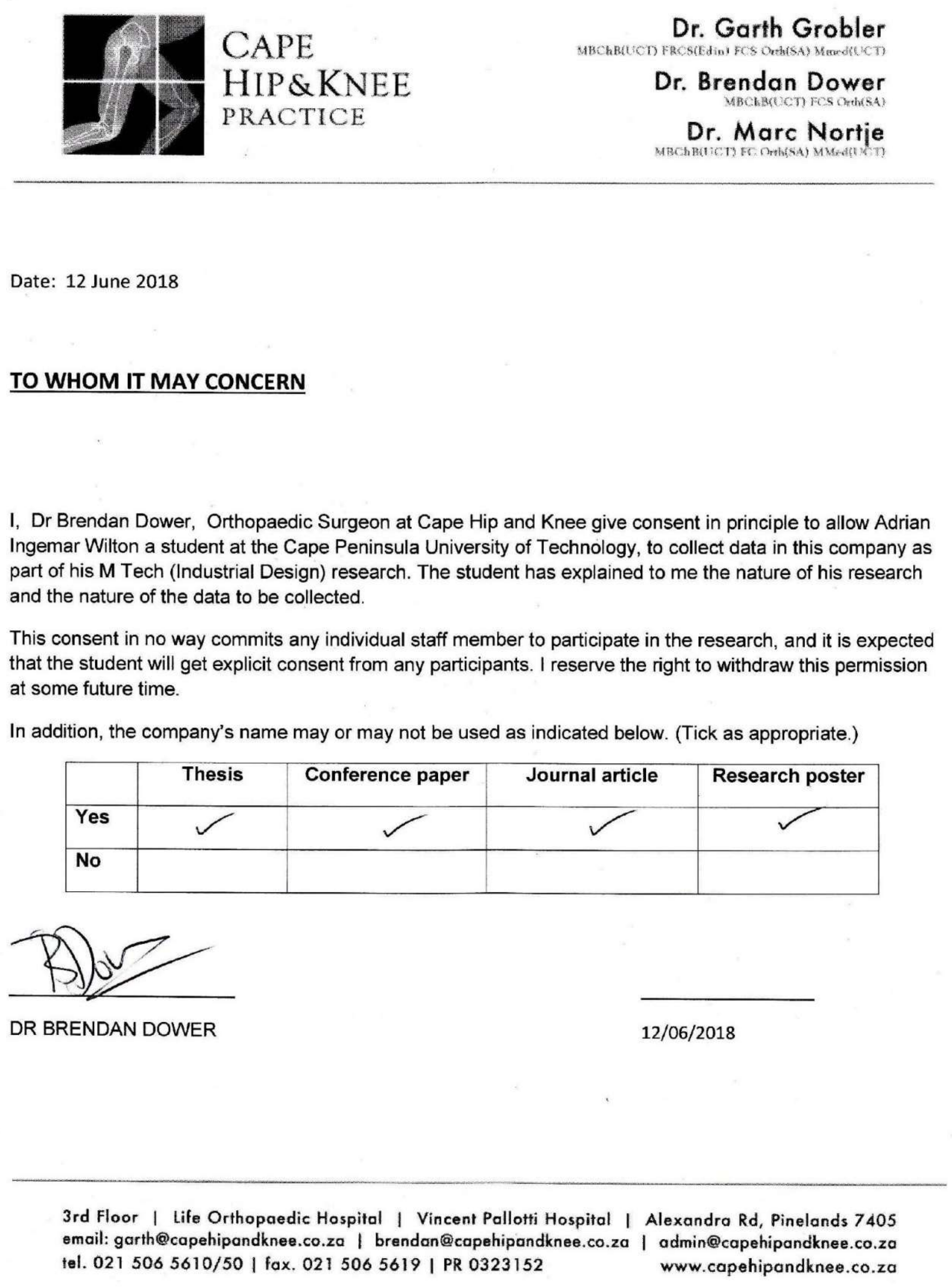
In addition, the university's name may or may not be used as indicated below. (Tick as appropriate.)

	Thesis	Conference paper	Journal article	Research poster
Yes	X	X	X	X
No				

Zhang Jun

12th Oct 2018

Appendix K: Ethics consent form - Cape Hip & Knee



CAPE
HIP&KNEE
PRACTICE

Dr. Garth Grobler
MBChB(UCT) FRCS(Edin) FCS Orth(SA) Mmed(UCT)
Dr. Brendan Dower
MBChB(UCT) FCS Orth(SA)
Dr. Marc Nortje
MBChB(UCT) FC Orth(SA) MMed(UCT)

Date: 12 June 2018

TO WHOM IT MAY CONCERN

I, Dr Brendan Dower, Orthopaedic Surgeon at Cape Hip and Knee give consent in principle to allow Adrian Ingemar Wilton a student at the Cape Peninsula University of Technology, to collect data in this company as part of his M Tech (Industrial Design) research. The student has explained to me the nature of his research and the nature of the data to be collected.

This consent in no way commits any individual staff member to participate in the research, and it is expected that the student will get explicit consent from any participants. I reserve the right to withdraw this permission at some future time.

In addition, the company's name may or may not be used as indicated below. (Tick as appropriate.)

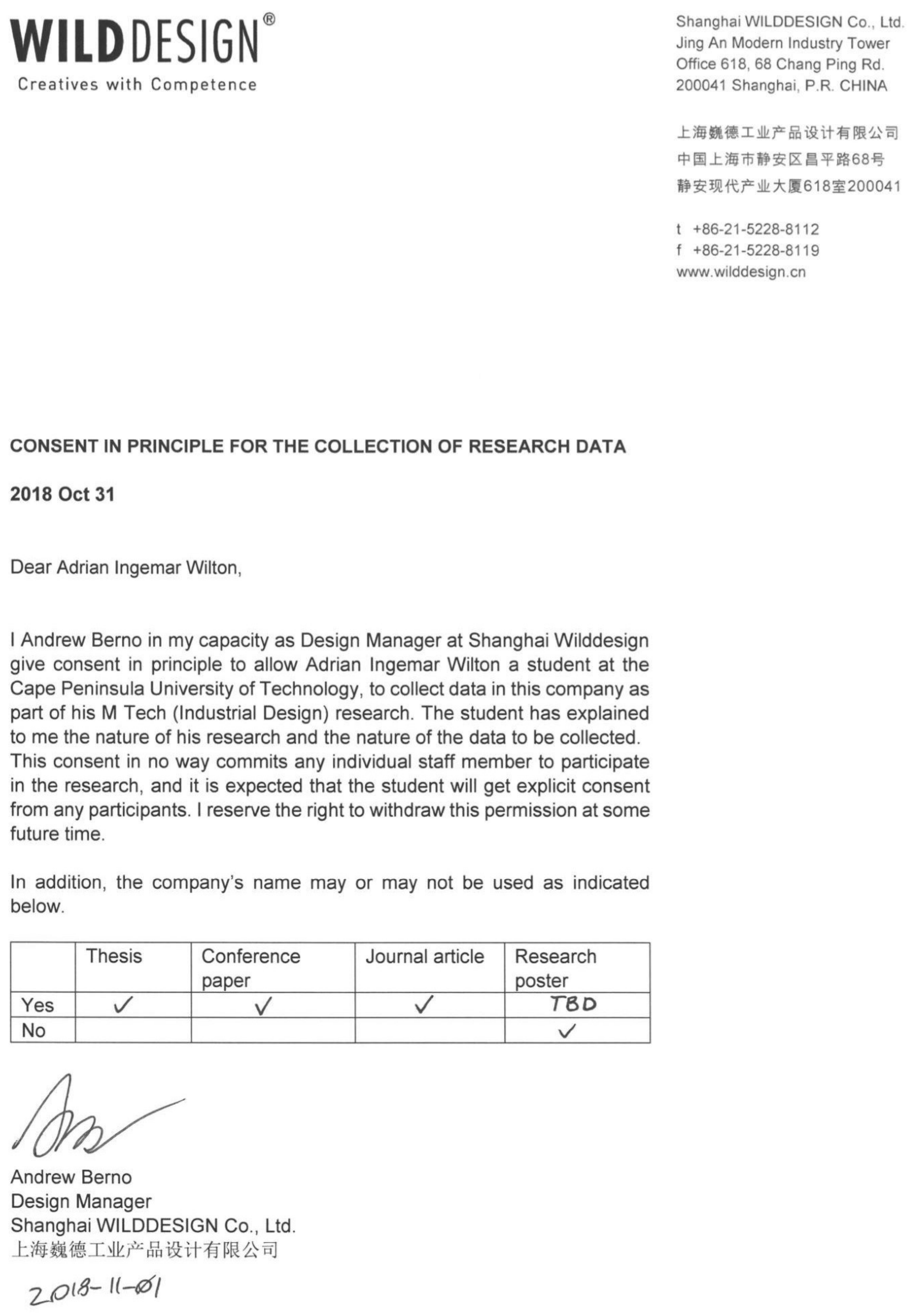
	Thesis	Conference paper	Journal article	Research poster
Yes	✓	✓	✓	✓
No				

DR BRENDAN DOWER

12/06/2018

3rd Floor | Life Orthopaedic Hospital | Vincent Pallotti Hospital | Alexandra Rd, Pinelands 7405
email: garth@capehipandknee.co.za | brendan@capehipandknee.co.za | admin@capehipandknee.co.za
tel. 021 506 5610/50 | fax. 021 506 5619 | PR 0323152 www.capehipandknee.co.za

Appendix L: Ethics consent form – Wild Design, China



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Shanghai WILDDESIGN Co., Ltd.
Jing An Modern Industry Tower
Office 618, 68 Chang Ping Rd.
200041 Shanghai, P.R. CHINA

上海巍德工业产品设计有限公司
中国上海市静安区昌平路68号
静安现代产业大厦618室200041

t +86-21-5228-8112
f +86-21-5228-8119
www.wilddesign.cn

CONSENT IN PRINCIPLE FOR THE COLLECTION OF RESEARCH DATA

2018 Oct 31

Dear Adrian Ingemar Wilton,

I Andrew Berno in my capacity as Design Manager at Shanghai Wilddesign give consent in principle to allow Adrian Ingemar Wilton a student at the Cape Peninsula University of Technology, to collect data in this company as part of his M Tech (Industrial Design) research. The student has explained to me the nature of his research and the nature of the data to be collected. This consent in no way commits any individual staff member to participate in the research, and it is expected that the student will get explicit consent from any participants. I reserve the right to withdraw this permission at some future time.

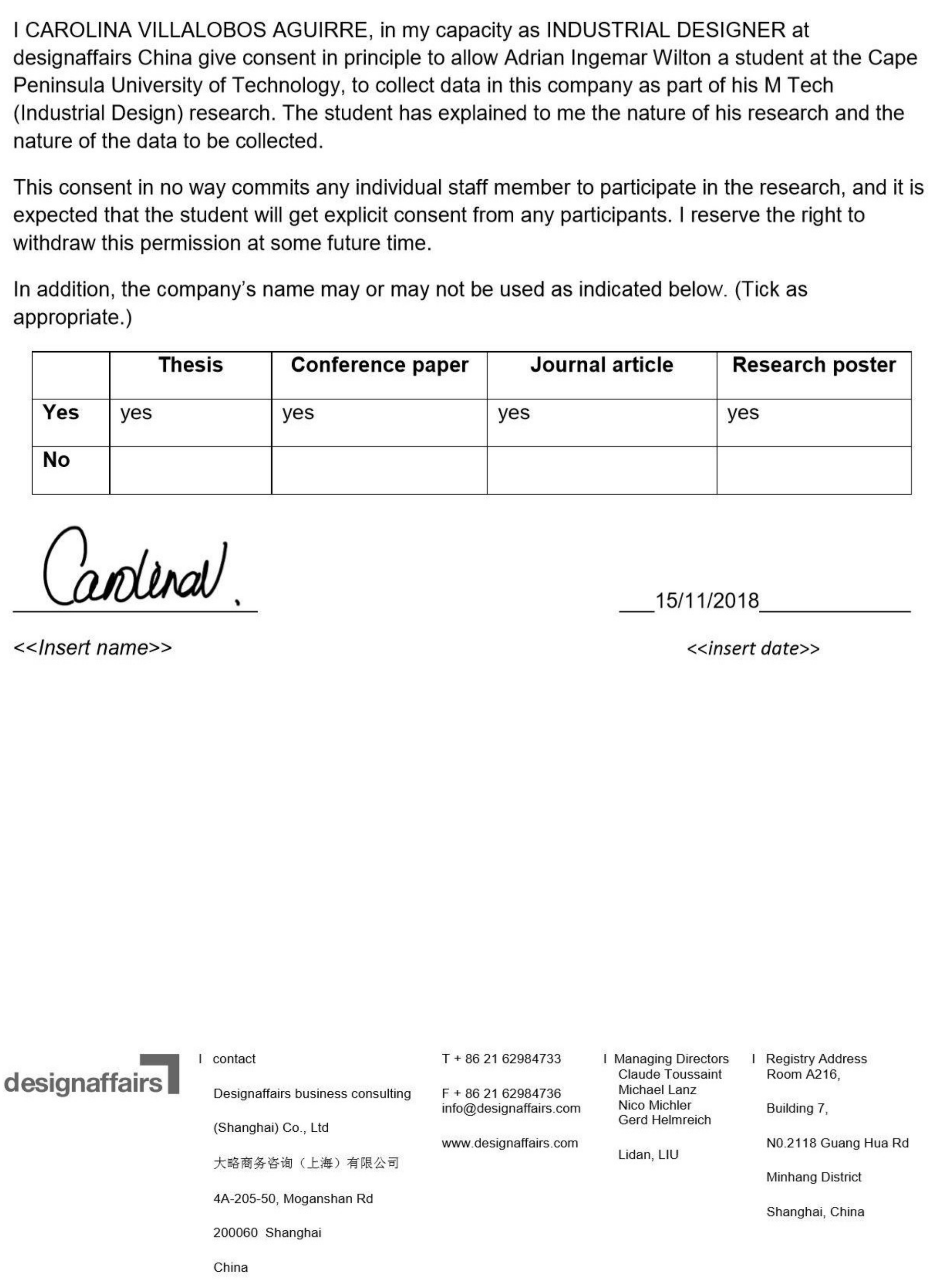
In addition, the company's name may or may not be used as indicated below.

	Thesis	Conference paper	Journal article	Research poster
Yes	✓	✓	✓	TBD
No				✓

Andrew Berno
Design Manager
Shanghai WILDDESIGN Co., Ltd.
上海巍德工业产品设计有限公司

2018-11-01

Appendix M: Ethics consent form – designaffairs, China



I CAROLINA VILLALOBOS AGUIRRE, in my capacity as INDUSTRIAL DESIGNER at designaffairs China give consent in principle to allow Adrian Ingemar Wilton a student at the Cape Peninsula University of Technology, to collect data in this company as part of his M Tech (Industrial Design) research. The student has explained to me the nature of his research and the nature of the data to be collected.

This consent in no way commits any individual staff member to participate in the research, and it is expected that the student will get explicit consent from any participants. I reserve the right to withdraw this permission at some future time.

In addition, the company’s name may or may not be used as indicated below. (Tick as appropriate.)

	Thesis	Conference paper	Journal article	Research poster
Yes	yes	yes	yes	yes
No				

Carolina V.

___15/11/2018_____________

<<Insert name>>

<<insert date>>

contact

Designaffairs business consulting

(Shanghai) Co., Ltd

大略商务咨询（上海）有限公司

4A-205-50, Moganshan Rd

200060 Shanghai

China

T + 86 21 62984733

F + 86 21 62984736
info@designaffairs.com

www.designaffairs.com

Managing Directors
Claude Toussaint
Michael Lanz
Nico Michler
Gerd Helmreich

Lidan, LIU

Registry Address
Room A216,

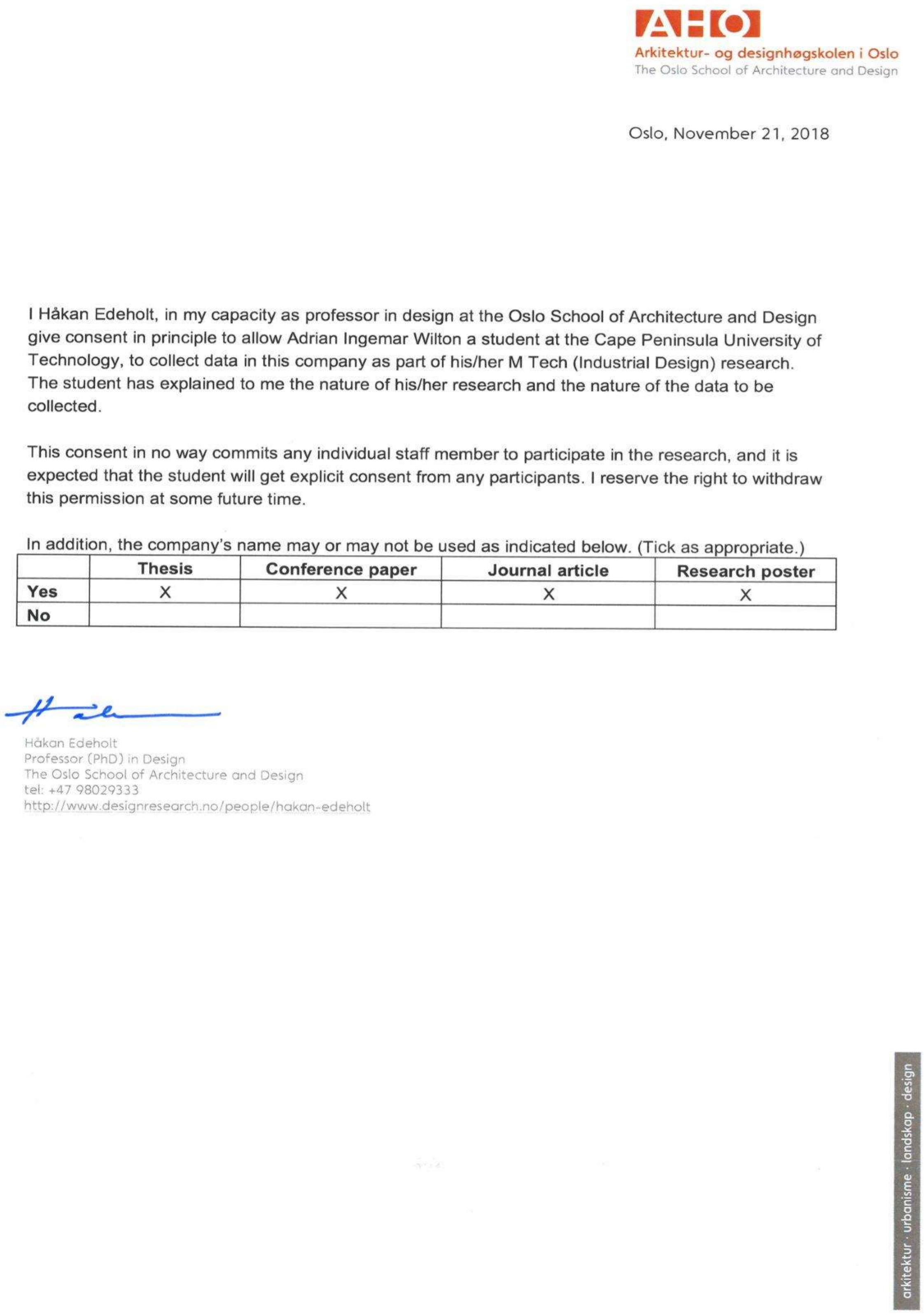
Building 7,

N0.2118 Guang Hua Rd

Minhang District

Shanghai, China

Appendix N: Company ethics consent form – AHO, Norway



AHO
Arkitektur- og designhøgskolen i Oslo
The Oslo School of Architecture and Design

Oslo, November 21, 2018

I Håkan Edeholt, in my capacity as professor in design at the Oslo School of Architecture and Design give consent in principle to allow Adrian Ingemar Wilton a student at the Cape Peninsula University of Technology, to collect data in this company as part of his/her M Tech (Industrial Design) research. The student has explained to me the nature of his/her research and the nature of the data to be collected.

This consent in no way commits any individual staff member to participate in the research, and it is expected that the student will get explicit consent from any participants. I reserve the right to withdraw this permission at some future time.

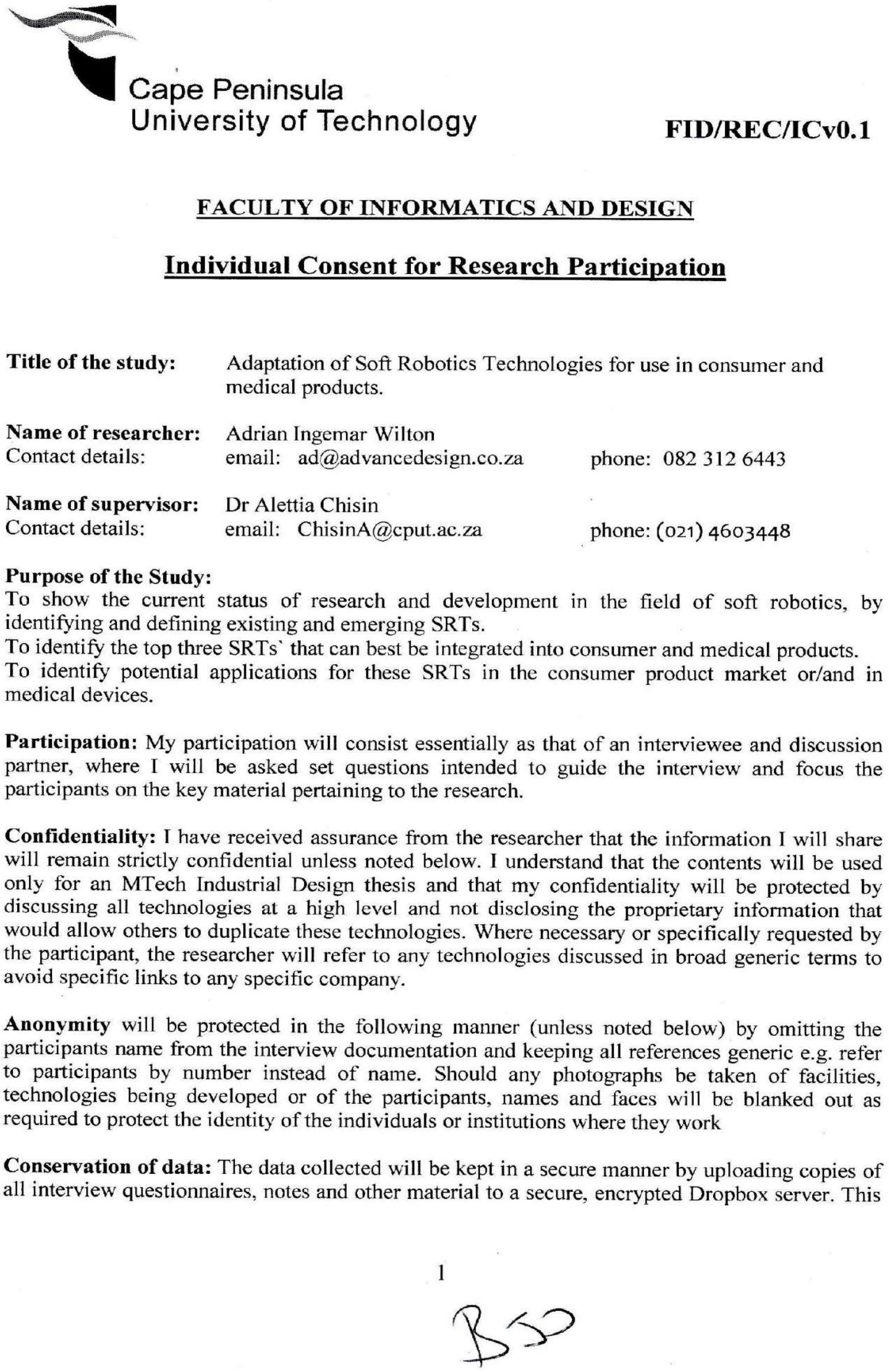
In addition, the company's name may or may not be used as indicated below. (Tick as appropriate.)

	Thesis	**Conference paper**	**Journal article**	**Research poster**
Yes	X	X	X	X
No				

Håkan Edeholt
Professor (PhD) in Design
The Oslo School of Architecture and Design
tel: +47 98029333
http://www.designresearch.no/people/hakan-edeholt

arkitektur · urbanisme · landskap · design

Appendix O: Example individual ethics consent - Brendan Dower



Cape Peninsula
University of Technology

FID/REC/ICv0.1

FACULTY OF INFORMATICS AND DESIGN

Individual Consent for Research Participation

Title of the study:	Adaptation of Soft Robotics Technologies for use in consumer and medical products.	
Name of researcher:	Adrian Ingemar Wilton	
Contact details:	email: ad@advancedesign.co.za	phone: 082 312 6443
Name of supervisor:	Dr Alettia Chisin	
Contact details:	email: ChisinA@cput.ac.za	phone: (021) 4603448

Purpose of the Study:
To show the current status of research and development in the field of soft robotics, by identifying and defining existing and emerging SRTs.
To identify the top three SRTs` that can best be integrated into consumer and medical products.
To identify potential applications for these SRTs in the consumer product market or/and in medical devices.

Participation: My participation will consist essentially as that of an interviewee and discussion partner, where I will be asked set questions intended to guide the interview and focus the participants on the key material pertaining to the research.

Confidentiality: I have received assurance from the researcher that the information I will share will remain strictly confidential unless noted below. I understand that the contents will be used only for an MTech Industrial Design thesis and that my confidentiality will be protected by discussing all technologies at a high level and not disclosing the proprietary information that would allow others to duplicate these technologies. Where necessary or specifically requested by the participant, the researcher will refer to any technologies discussed in broad generic terms to avoid specific links to any specific company.

Anonymity will be protected in the following manner (unless noted below) by omitting the participants name from the interview documentation and keeping all references generic e.g. refer to participants by number instead of name. Should any photographs be taken of facilities, technologies being developed or of the participants, names and faces will be blanked out as required to protect the identity of the individuals or institutions where they work

Conservation of data: The data collected will be kept in a secure manner by uploading copies of all interview questionnaires, notes and other material to a secure, encrypted Dropbox server. This

B

is a professionally managed data server, which provides password access and full encryption of data. This data will remain archived indefinitely on this secure server. The researcher will have sole access to this secure server and encrypted data. The original documents will be scanned and stored on this same server database for auditing purposes.

Voluntary Participation: I am under no obligation to participate and if I choose to participate, I can withdraw from the study at any time and/or refuse to answer any questions, without suffering any negative consequences. If I choose to withdraw, all data gathered until the time of withdrawal will destroyed.

Additional consent: I make the following stipulations (please tick as appropriate):

	In thesis	**In research publications**	**Both**	**Neither**
My image may be used:				✓
My name may be used:			✓	
My exact words may be used:			✓	
Any other (stipulate):				

Acceptance: I, (print name) BRENDAN DOWER

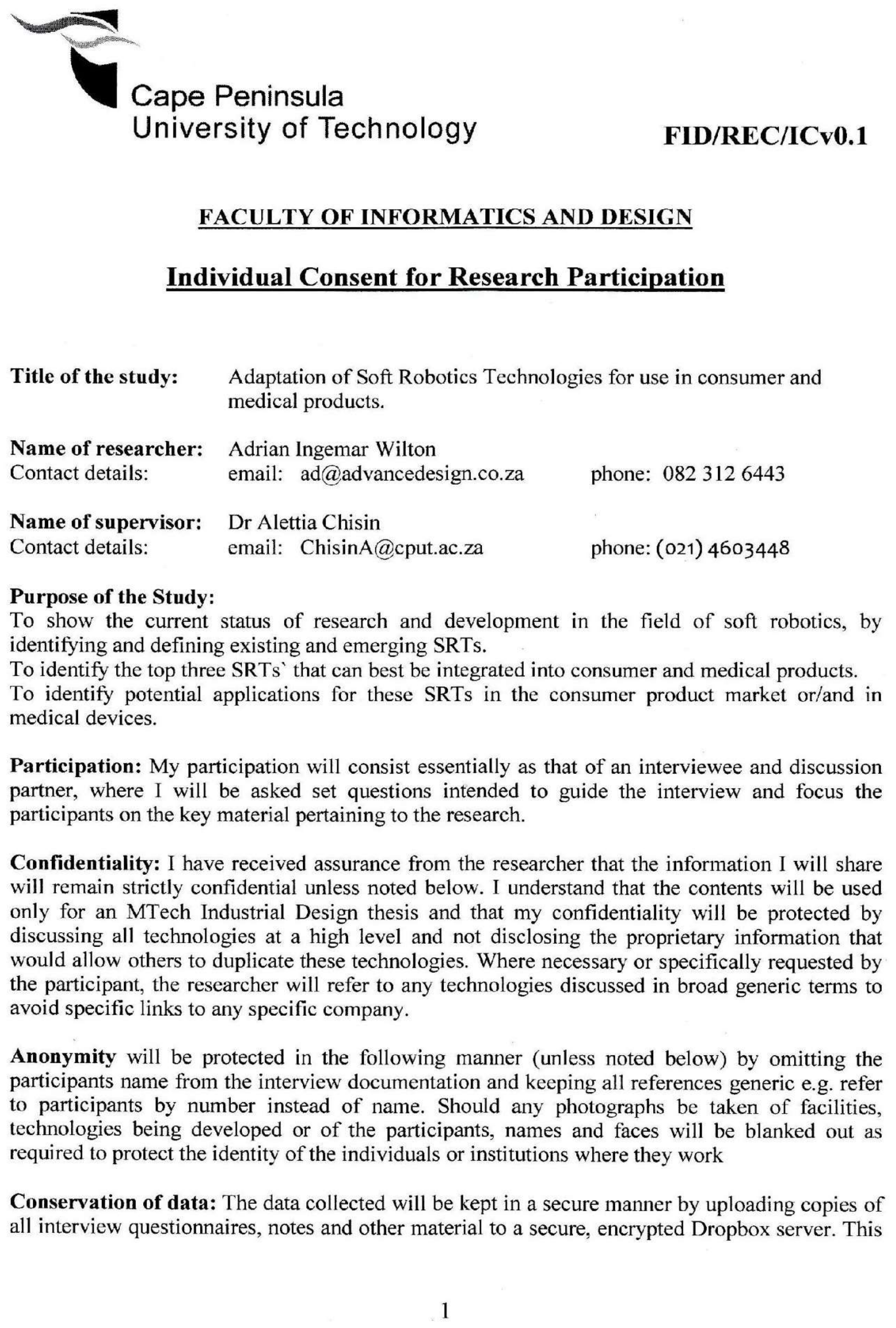
agree to participate in the above research study conducted by Adrian Ingemar Wilton of the Faculty of Informatics and Design, Industrial Design Department at the Cape Peninsula University of Technology, which research is under the supervision of Dr Alettia Chisin`

If I have any questions about the study, I may contact the researcher or the supervisor. If I have any questions regarding the ethical conduct of this study, I may contact the secretary of the Faculty Research Ethics Committee at 021 469 1012, or email naidoove@cput.ac.za.

Participant's signature: ______________________ Date: 19th JUNE 2018

Researcher's signature: ______________________ Date: 12th June 2018 .

Appendix P: Example individual ethics consent – Andrew Berno



Cape Peninsula
University of Technology

FID/REC/ICv0.1

FACULTY OF INFORMATICS AND DESIGN

Individual Consent for Research Participation

Title of the study: Adaptation of Soft Robotics Technologies for use in consumer and medical products.

Name of researcher: Adrian Ingemar Wilton
Contact details: email: ad@advancedesign.co.za phone: 082 312 6443

Name of supervisor: Dr Alettia Chisin
Contact details: email: ChisinA@cput.ac.za phone: (021) 4603448

Purpose of the Study:
To show the current status of research and development in the field of soft robotics, by identifying and defining existing and emerging SRTs.
To identify the top three SRTs` that can best be integrated into consumer and medical products.
To identify potential applications for these SRTs in the consumer product market or/and in medical devices.

Participation: My participation will consist essentially as that of an interviewee and discussion partner, where I will be asked set questions intended to guide the interview and focus the participants on the key material pertaining to the research.

Confidentiality: I have received assurance from the researcher that the information I will share will remain strictly confidential unless noted below. I understand that the contents will be used only for an MTech Industrial Design thesis and that my confidentiality will be protected by discussing all technologies at a high level and not disclosing the proprietary information that would allow others to duplicate these technologies. Where necessary or specifically requested by the participant, the researcher will refer to any technologies discussed in broad generic terms to avoid specific links to any specific company.

Anonymity will be protected in the following manner (unless noted below) by omitting the participants name from the interview documentation and keeping all references generic e.g. refer to participants by number instead of name. Should any photographs be taken of facilities, technologies being developed or of the participants, names and faces will be blanked out as required to protect the identity of the individuals or institutions where they work

Conservation of data: The data collected will be kept in a secure manner by uploading copies of all interview questionnaires, notes and other material to a secure, encrypted Dropbox server. This

is a professionally managed data server, which provides password access and full encryption of data. This data will remain archived indefinitely on this secure server. The researcher will have sole access to this secure server and encrypted data. The original documents will be scanned and stored on this same server database for auditing purposes.

Voluntary Participation: I am under no obligation to participate and if I choose to participate, I can withdraw from the study at any time and/or refuse to answer any questions, without suffering any negative consequences. If I choose to withdraw, all data gathered until the time of withdrawal will destroyed.

Additional consent: I make the following stipulations (please tick as appropriate):

	In thesis	**In research publications**	**Both**	**Neither**
My image may be used:			✓	
My name may be used:			✓	
My exact words may be used:			✓	
Any other (stipulate):				

Acceptance: I, (print name) ANDREW BERNO

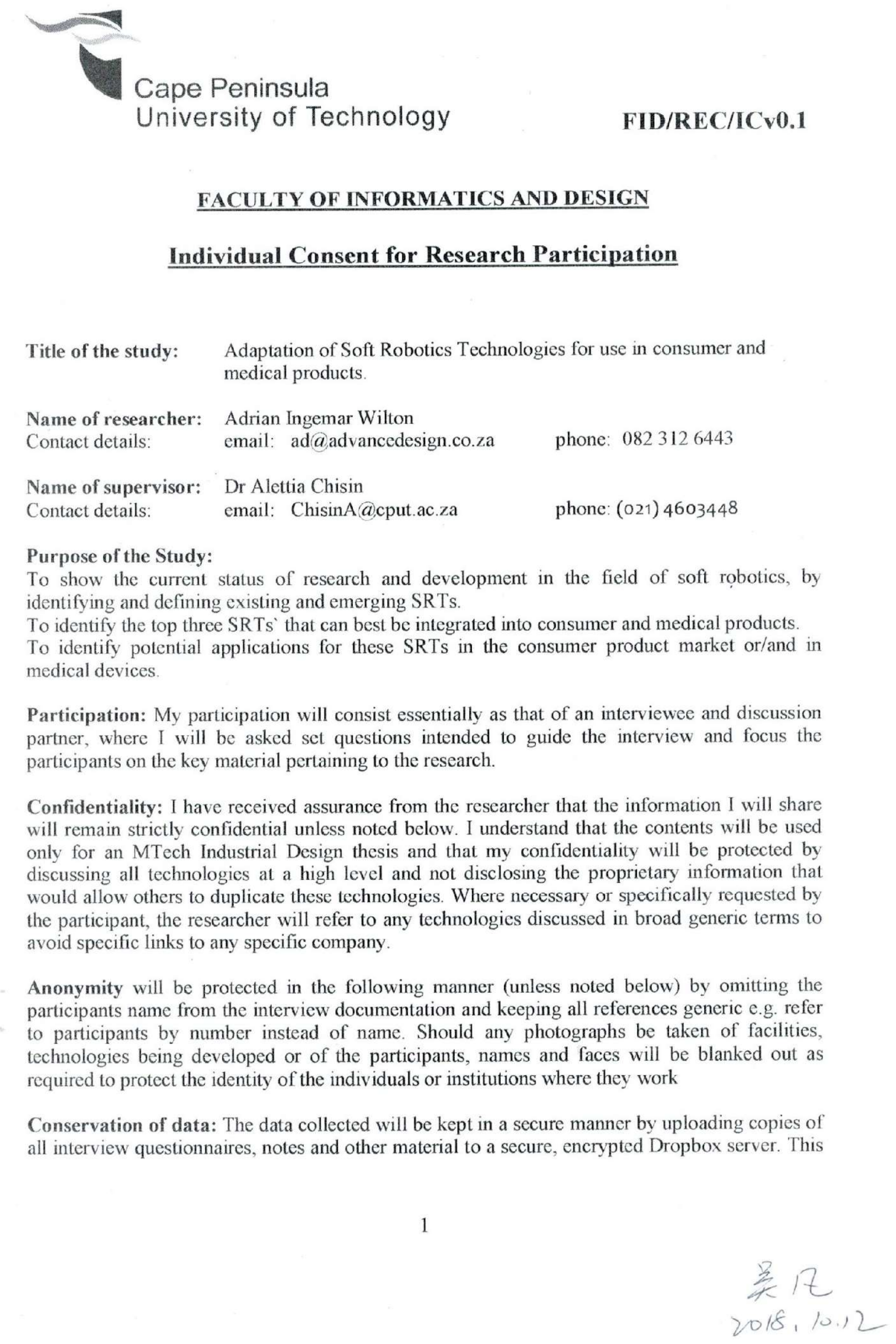
agree to participate in the above research study conducted by Adrian Ingemar Wilton of the Faculty of Informatics and Design, Industrial Design Department at the Cape Peninsula University of Technology, which research is under the supervision of Dr Alettia Chisin`

If I have any questions about the study, I may contact the researcher or the supervisor. If I have any questions regarding the ethical conduct of this study, I may contact the secretary of the Faculty Research Ethics Committee at 021 469 1012, or email naidoove@cput.ac.za.

Participant's signature: ______________________ Date: 2018-11-01

Researcher's signature: ______________________ Date: 12th June 2018 .

Appendix Q: Example individual ethics consent - Wu Fan



Cape Peninsula
University of Technology

FID/REC/ICv0.1

FACULTY OF INFORMATICS AND DESIGN

Individual Consent for Research Participation

Title of the study:	Adaptation of Soft Robotics Technologies for use in consumer and medical products.	
Name of researcher:	Adrian Ingemar Wilton	
Contact details:	email: ad@advancedesign.co.za	phone: 082 312 6443
Name of supervisor:	Dr Alettia Chisin	
Contact details:	email: ChisinA@cput.ac.za	phone: (021) 4603448

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To identify potential applications for these SRTs in the consumer product market or/and in medical devices.

Participation: My participation will consist essentially as that of an interviewee and discussion partner, where I will be asked set questions intended to guide the interview and focus the participants on the key material pertaining to the research.

Confidentiality: I have received assurance from the researcher that the information I will share will remain strictly confidential unless noted below. I understand that the contents will be used only for an MTech Industrial Design thesis and that my confidentiality will be protected by discussing all technologies at a high level and not disclosing the proprietary information that would allow others to duplicate these technologies. Where necessary or specifically requested by the participant, the researcher will refer to any technologies discussed in broad generic terms to avoid specific links to any specific company.

Anonymity will be protected in the following manner (unless noted below) by omitting the participants name from the interview documentation and keeping all references generic e.g. refer to participants by number instead of name. Should any photographs be taken of facilities, technologies being developed or of the participants, names and faces will be blanked out as required to protect the identity of the individuals or institutions where they work

Conservation of data: The data collected will be kept in a secure manner by uploading copies of all interview questionnaires, notes and other material to a secure, encrypted Dropbox server. This

吴凡
2018, 10.12

is a professionally managed data server, which provides password access and full encryption of data. This data will remain archived indefinitely on this secure server. The researcher will have sole access to this secure server and encrypted data. The original documents will be scanned and stored on this same server database for auditing purposes.

Voluntary Participation: I am under no obligation to participate and if I choose to participate, I can withdraw from the study at any time and/or refuse to answer any questions, without suffering any negative consequences. If I choose to withdraw, all data gathered until the time of withdrawal will destroyed.

Additional consent: I make the following stipulations (please tick as appropriate):

	In thesis	**In research publications**	**Both**	**Neither**
My image may be used:			yes	
My name may be used:			yes	
My exact words may be used:			yes	
Any other (stipulate):			yes	

Acceptance: I, *Wu Fan*

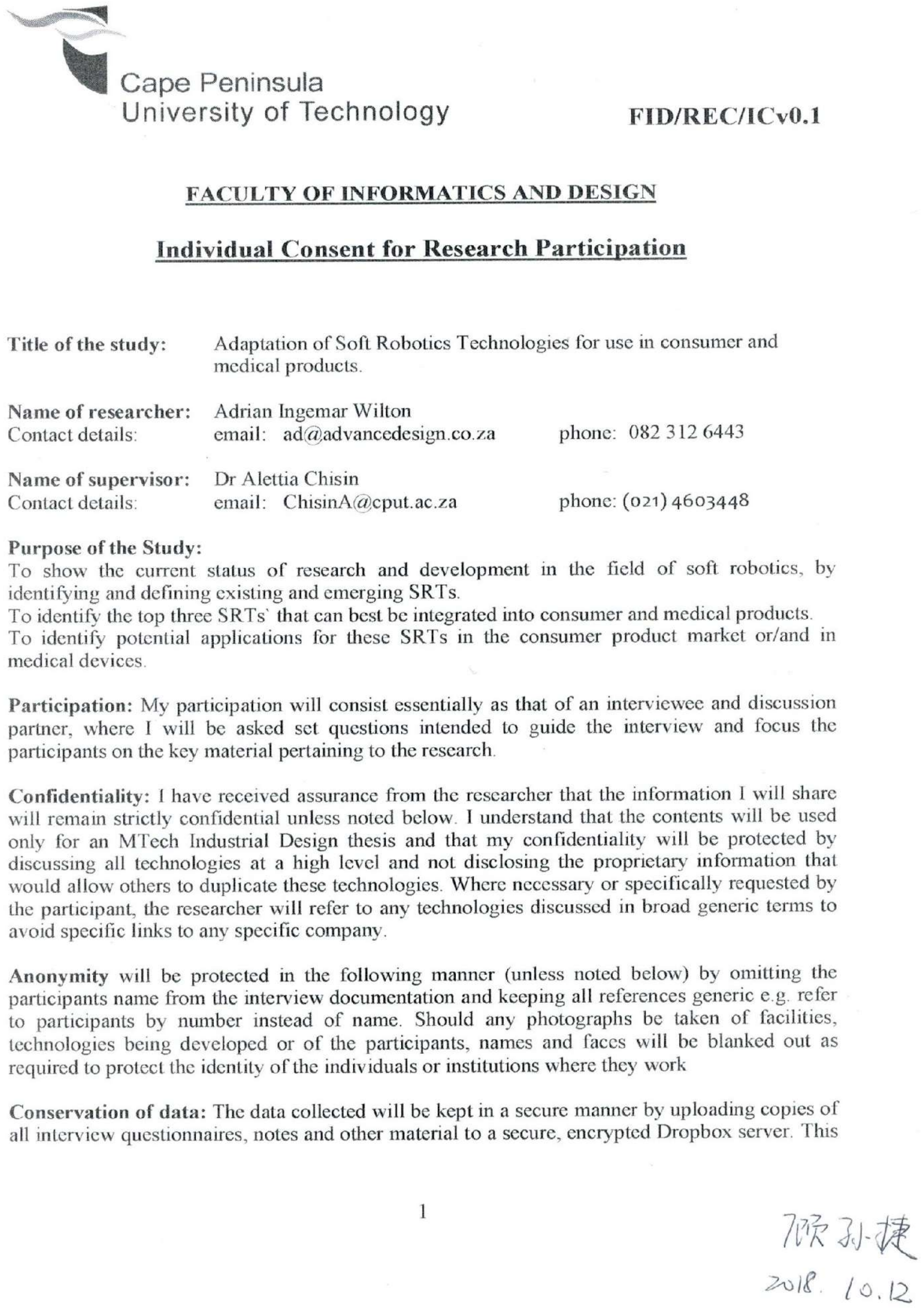
agree to participate in the above research study conducted by Adrian Ingemar Wilton of the Faculty of Informatics and Design, Industrial Design Department at the Cape Peninsula University of Technology, which research is under the supervision of Dr Alettia Chisin`

If I have any questions about the study, I may contact the researcher or the supervisor. If I have any questions regarding the ethical conduct of this study, I may contact the secretary of the Faculty Research Ethics Committee at 021 469 1012, or email naidoove@cput.ac.za.

Participant's signature: 吴 凡 Date: 2018 . 10.12

Researcher's signature: Date: 12th Oct 2018 .

Appendix R: Example individual ethics consent - Gu Sunjie



Cape Peninsula
University of Technology

FID/REC/ICv0.1

FACULTY OF INFORMATICS AND DESIGN

Individual Consent for Research Participation

Title of the study:	Adaptation of Soft Robotics Technologies for use in consumer and medical products.	
Name of researcher:	Adrian Ingemar Wilton	
Contact details:	email: ad@advancedesign.co.za	phone: 082 312 6443
Name of supervisor:	Dr Alettia Chisin	
Contact details:	email: ChisinA@cput.ac.za	phone: (021) 4603448

Purpose of the Study:
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To identify the top three SRTs` that can best be integrated into consumer and medical products.
To identify potential applications for these SRTs in the consumer product market or/and in medical devices.

Participation: My participation will consist essentially as that of an interviewee and discussion partner, where I will be asked set questions intended to guide the interview and focus the participants on the key material pertaining to the research.

Confidentiality: I have received assurance from the researcher that the information I will share will remain strictly confidential unless noted below. I understand that the contents will be used only for an MTech Industrial Design thesis and that my confidentiality will be protected by discussing all technologies at a high level and not disclosing the proprietary information that would allow others to duplicate these technologies. Where necessary or specifically requested by the participant, the researcher will refer to any technologies discussed in broad generic terms to avoid specific links to any specific company.

Anonymity will be protected in the following manner (unless noted below) by omitting the participants name from the interview documentation and keeping all references generic e.g. refer to participants by number instead of name. Should any photographs be taken of facilities, technologies being developed or of the participants, names and faces will be blanked out as required to protect the identity of the individuals or institutions where they work

Conservation of data: The data collected will be kept in a secure manner by uploading copies of all interview questionnaires, notes and other material to a secure, encrypted Dropbox server. This

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is a professionally managed data server, which provides password access and full encryption of data. This data will remain archived indefinitely on this secure server. The researcher will have sole access to this secure server and encrypted data. The original documents will be scanned and stored on this same server database for auditing purposes.

Voluntary Participation: I am under no obligation to participate and if I choose to participate, I can withdraw from the study at any time and/or refuse to answer any questions, without suffering any negative consequences. If I choose to withdraw, all data gathered until the time of withdrawal will destroyed.

Additional consent: I make the following stipulations (please tick as appropriate):

	In thesis	**In research publications**	**Both**	**Neither**
My image may be used:			✓	
My name may be used:			✓	
My exact words may be used:			✓	
Any other (stipulate):			✓	

Acceptance: I, Gu Sunjie

agree to participate in the above research study conducted by Adrian Ingemar Wilton of the Faculty of Informatics and Design, Industrial Design Department at the Cape Peninsula University of Technology, which research is under the supervision of Dr Alettia Chisin`

If I have any questions about the study, I may contact the researcher or the supervisor. If I have any questions regarding the ethical conduct of this study, I may contact the secretary of the Faculty Research Ethics Committee at 021 469 1012, or email naidoove@cput.ac.za.

Participant's signature: 顾孙捷 Date: 12th Oct 2018

Researcher's signature: Date: 12th Oct 2018 .