Wearable Technology: Exploration from the Technical Side

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University of Twente
A Creative Technology graduation project

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Contents

Abstract

This graduation project is about making sensors applicable within the context of wearable technology. The goal of this field is it to integrate technology into body-worn clothing or garment. Market researchers predict this to be one of the emerging trends of the future. Yet, designers for wearable technology encounter a problem: The sensors available are either limited in their reliability or they are very expensive. The idea for this project was to develop sensors, which hold the balance between those two points.

To address this problem the design process for creative technology was used. From several material choices, a combination of carbon fibre embedded into silicone was chosen. The silicone has several desirable properties for the field while the carbon is highly conductive.

Through several iterations, three different designs for sensors out of these materials were refined: one stretch and one pressure sensor and an electrode ring. For the final design of each of those, a manual has been compiled detailing the manufacturing process.

The manuals have been tested by user testing and the resulting sensors were evaluated in regards to their qualitative properties. The outcome was, that the reliability of the sensors is also limited while their other properties, including their material price, were very positive. Therefore, the tests conclude that the here developed sensors do not keep the balance between price and reliability as intended. Further work is needed to improve upon the sensors reliability, but the manuals should made accessible any ways to benefit the designers already.

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Chapter 1

Introduction

Market researchers predicted wearable technology to be one of the emerging markets of the future [1,2]. But in order for designers to develop new products in the wearable technology field, they need to feel comfortable working with several different technologies already in the prototyping phase. The sum of all these technologies make up the tool box for each designer and each single technology can be referred to as a building block within the tool box. One of the essential components for each wearable system are the sensors. These sensors, however, are causing one essential problem for designers: Either the single sensors are already very far developed products, which makes them very expensive, or they are built according to instructions from the do-it-yourself community, which often limits the sensor's reliability. In addition to that, most of people working in that field do not have a background in electrical engineering, which imposes certain limitations on the sensor as well.
The research question this graduation project is tackling is 'What methods or materials could be used for fabricating wearable sensors resulting in a valuable addition to the tool box of wearable designers?'. In order to answer that question, two core sub-questions were identified. First of all, the parameters of interest for sensors in wearable technology need to be identified. Furthermore, the limitations in place by providing a building block to the target group need to be found to ensure that the result is usable for them.
In order to answer this question, the design process for creative technology as presented by Mader et Eggink [3] is used. This design approach allows for the exploration of several ideas while keeping the focus on finding an answer to the research question. The different phases of this approach are also used as for structuring the report. After a first introduction to the field of wearable technology with a focus on the sensors used, the next chapter describes the ideation process. In the following chapters the remaining phases are covered, namely specification, realisation and evaluation phase. The report wraps up with a conclusion evaluating the whole project. As a last part the appendices can be found for content not appropriate within the text.

1.1 Relevance

The trend over the previous decades was to make technology mobile, or in other words make it easy to carry around. When comparing the first mobile phone to any of the flagship smartphones today, it can be seen how far the technology improved in that regard. As a next step, the technology could be taken from being carried around by the user to being actually worn by the user. This is the aim wearable technology designers are working towards. The potential of this field is not only recognized by the anticipating designers, but also by market research firms which predict the field to be one of the emerging markets of the future [1, 2].

In order to bring the market to its full potential, the community of designers needs to work on new products. As a part of the development process, prototypes are used in several different stages throughout the whole process. From building an initial proof of concept up to a high-fidelity (hifi) prototype, they are used to evaluate the feasibility or previous design choices. As it is shown in section 2.2 on page 5, sensors are a crucial part of every wearable prototype or product. This is why it is important to use well working sensors, which are also meeting the requirements for wearability, already in an early stage of the devlopment process.

Chapter 2

Background

This chapter aims at providing the reader with insight in the area of wearable technology and especially sensors. As a first step, the determining factors leading to the wearability of a product are analysed. Consequentially, the parameters of interest in the wearable technology field are given and the solutions for recording them are presented. As a next step, the application areas for wearable technology are introduced alongside examples in order to get an idea in which areas the outcome of this project could be used in the future. In the last part, the factors for adapting the outcome of this project as a tool within the tool box are discussed. This is done to ensure the result of this project is usable by target group later on.

2.1 Wearability

One of the essential tasks when designing a wearable technology system is to think about what criteria should be met for a system to be wearable. Since this is an important issue, there are several frameworks which develop different categories with which wearability can be assessed. Out of all of them, the one provided by Gemperle et al. [4] seems the most promising, since it provides the finest grained categories.
Bryson [5] included wearablity as a part of his demands of the body framework, but notably put it as a subcategory of psychological considerations. This indicates that all the categories have to be understood as each of them is perceived by the user. The categories identified are comfort, durability, sensuality, aesthetic sensibility and reliability. Knight et al. [6] propose, that the wearability of a system should be assessed along three categories only, namely physiological, biomechanical and comfort. A more fine grained set of guidelines for wearability is suggested by Gemperle et al. [4]. A table with all the categories named by each of the authors can be found in table 2.1.

The unobtrusiveness of new technologies , which can be seen as the ultimate objective of wearability, is a trend which has already been predicted in 1991

Knight et al. [6]	**Bryson [5]**	**Gemperle et al. [4]**
Physiological effects	Comfort	Placement
Biomechanical effects	Durability	Form Language
Comfort	Sensuality	Human Movement
	Aesthetic sensibility, appearance , style	Proxemics
	Reliability / Perception of Reliability	Sizing
		Containment
		Weight
		Accessibility
		Sensory Interaction
		Thermal
		Aesthetics
		Long-term use

Table 2.1: The factors regarding wearability as discussed in the literature

by Weiser [7]. In his opinion, the goal for new technological developments is to make the technology disappear. The ultimate aim is that the user can interact with technology without thinking and therefore is able to focus on new, greater goals. Wearable technology is one way in which this prediction can manifest itself further. A product can become as unobtrusive that the wearer does not realize using it any more but it still enriches the life of the user. Examples for how applications of wearable technology can enrich a persons life are to be found in the section 2.3 about application areas for Wearable Technology.
All of these aspects provide insight into which points should be considered when designing for a wearable system or its components. One of the categories found in two papers is comfort, which can also be found broken down further in smaller factors by the remaining author. This is a clear indicator that comfort is essential for a system to be regarded as wearable. Therefore, all its components including the sensors need to be comfortable as well.

2.2 Sensors in Wearable Technology

Each system has three distinguishable categories of components, according to the black box view. Inputs to and outputs from the system are interlinked by a black box, which maps the first to the latter. In the field of wearable technology, inputs are captured by sensors. Since the focus of this project is put onto the exploration of sensors, the existing sensor technologies are investigated. In order to structure the findings, the research conducted by Hanson et al. [8] is used. They provide three distinct categories in which sensors within the wearable technology context can be put. The identified categories are physiological, biokinetic and ambient sensors.

Physiological Sensors

Physiological sensors capture signals of the body which are vital. Andreoni et al. [9] presented in their research the different properties that can be recorded by sensors. For an overview, as well as a diagram, about where on the body the different signals can be captured, go to figure 2.1 on page 7 [9].

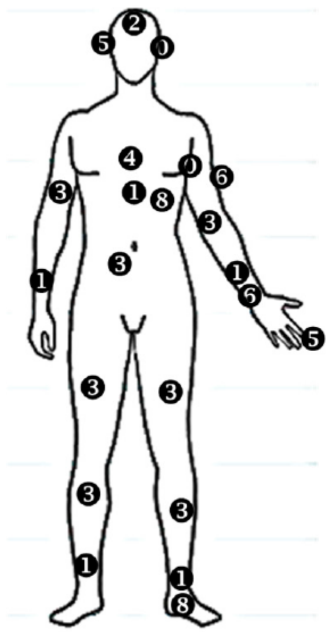
These signals only have a limited meaning in themselves. However, a single or a combination of such signals can be used in order to capture other, higher level, information. Haag et al. [10] for example used a combination of the galvanic skin response (GSR), skin temperature, heart rate, respiration rate and an EMG attached to the jaw for arousal and valence recognition. Their machine learning algorithms were able to classify arousal correctly 97% of the time and valence 90% after being trained. Another higher level feature could be to classify whether a person is stressed or not. Wijsman et al. [11] implemented a classification algorithm based on sensor input or signal's statistical properties of heart rate, GSR, respiration rate and an EMG on the trapezius muscles. As a result they report a correct classification of almost 80% on stress.

Biokinetic sensors

Another central class of sensors aims at capturing the motion of the body. A sensor which is commonly used across the field for that purpose is a strain sensor. In the literature, strain is defined as the deformation of an object [12]. This includes two basic effects of human motion which can be aimed at for measuring. One is the bending at one joint, which can range from a joint as small as on a finger up to the knees or hips. This bending over a limb causes the sensor to stretch, which is a measurable deformation. This stretch can track the actual movement itself up to the extend that the angle of the joint the sensor is over can be determined [6].

A different way to determine motion is to measure the varying amount of surface pressure applied to a certain location of the body as a result of the movement. For this approach, several wearable pressure sensors are attached to the sole of a sock, as it is done by the Sensoria fitness sock [13], so that statements about the weight distribution can be made.

Further approaches for motion capturing, as identified by Shyr et al. [14], are camera and accelerometer based. In order to achieve that by cameras, however, typically there need to be multiple cameras set up locally at a fixed position. The worn parts of such a system normally consist of several reflecting objects which can be tracked by the cameras. But since the cameras need to be set



No.	Signal
0	temperature
1	ECG (ElectroCardioGram)
2	EEG (ElectroEncephaloGram)
3	EMG (ElectroMyoGram)
4	Respiration
5	Blood gas
6	Blood Pressure
7	Interface pressure
8	Resistance

Figure 2.1: Simplified Figure showing where which physiological signals can be picked up on the human body

up, the working radius for such a system is restricted to rooms with cameras installed, which limits the application areas.
Accelerometers, however, can be another possibility for tracking human motion. When one is mounted on each body part of interest in addition to one reference one, these body parts can be tracked properly. One downside of this approach is that the data of each of the accelerometers needs to processed before the biokinetic information can be extracted. Therefore, for a wearable system with multiple of accelerometers, a substantial amount of calculation power is needed.

Ambient Sensors

The third group of sensors is the one of ambient sensors. They aim at capturing the surrounding the wearer is in. Seymour [15] published a list with all the variables relevant to wearable technology which can be found in table 2.2 on page 8.

Most of these are straight forward in regards to the way they can be measured. Light can be measured by a photoresistor, which changes resistance dependent on the light intensity it is exposed to. Sound can be recorded by a normal microphone and the visuals can be recorded by a small camera. Smoke and micro-particle sensors have been widely adopted in smoke detectors in houses, but even those sensors have shrunk to a wearable size [13]. Only in the humidity

Ambient Parameters
Light
Humidity
Sound
Temperature
Smoke
Micro-particles
Visual Properties

Table 2.2: List of the properties of the environment relevant to wearable technology [15]

detection, wearable alternatives have been developed in addition to the small sized sensors available. Miyoshi et al. [16] developed a flexible humidity sensor which consists of a membrane in between two gold layers. They report a fast responsiveness of the sensor which would also make it applicable for measuring respiration rate for example.

Conclusion

To summarize the section an overview of all the properties of interest is provided in table 2.3.

Physiological Properties [9]	**Ambient Properties [15]**	**Biokinetics**
[Body] Temperature	Light	Movement of the Body
ECG	Humidity	
EEG	Sound	
EMG	Temperature	
Respiration	Smoke	
Blood Gas	Micro-particles	
Blood Pressure	Visual Properties	
Interface Pressure		
[Skin] resistance		

Table 2.3: Table of all the parameters relevant for wearable technology

All the ambient properties are nowadays well covered with the developments in the micro-electromechanical systems (mems). This makes new developments of sensors in this category obsolete. Within the physiological properties, medical technology has also developed quite far. For biokinetics, however, the technology is not as mature yet and there are still problems with the current ways of tracking them. In wearable technology, this is most of the time done with stretch sensors applied over joints. But the sensors available to measure the stretch have some problems, which is further elaborated later on in section 4.5. Therefore, this area is chosen as the main focus point for the later sensor developments.

2.3 Application Areas for Wearable Technology

What is still missing in order to bring the whole story about wearable technology together is to show the relevance of the field. In the following paragraph different application areas for such technologies are identified and backed with example products or research. Different taxonomies for application areas within the wearable technology field have already been discussed by other researchers. In this report, the categories used by Pfab [17] ,which in turn are taken from the Beecham Research's [18], website [18] are used.

Business Operation

One of the possibilities in which wearable technology can be fostered within business is by using them for authentication purposes. A research conducted by Mare et al. [19] was aimed at introducing a bracelet worn on the dominant hand within an office environment. Whenever the wearer would interact with a workstation, the movement would also be transmitted from the bracelet to the workstation, in order to authenticate the employee. Installing such a system could make up one of the means for the more secure two-way authentication and be more secure than an authentication by RFID card only. Furthermore, it could make inactivity timeouts at workstations superfluous and therefore improve the usability and security at the same time.

Safety and Security

One example for wearable technology in the safety and security field is the PROeTEX research project [20]. Multiple partners across Europe developed a smart integrated garment for firefighters in emergency situations. The product consisted of two different layers. The inner layer was integrated in a shirt and used to keep track of physiological signals of the firefighter, like the heart rate, respiration rate and amongst the remaining most importantly the skin temperature. The outer layer was integrated in the standard firefighter coat. It included several communication modules, a GPS module for the outdoor position, accelerometers for posture and activity recognition and ambient temperature and hazardous gases. All the acquired data is transmitted in real time to the headquarter of operation in order to assess the risk of each individual firefighter and monitor the run. The developed system was tested on an exercise site with real firefighters.

Medical

One of the possible applications within the health field could be the monitoring of physical exercises for rehabilitation purposes. A system developed by Giorino et al. [21] integrates several strain sensors based on CPC composites into a shirt in order to track the motion of the limb and the thorax. The system then classifies the data from all the sensors in order to give the patient feedback whether the exercises are performed correctly.

Wellness

The increased adoption of smart bracelets on the consumer market offers the wearer more insight into their daily rhythm. One of the measurable properties there is the sleeping duration as well as the identification of different sleeping phases during the night which is for example done by the wristband Jawbone UP3 [22]. On the one hand such data can be collected for research purposes, but on the other hand, research can be used in order to help the wearer finding a healthy sleeping pattern. As a result, such information can contribute to the well-being of the wearer

Sport and Fitness

One showcase product for wearable technology in the field of fitness was developed by the company Sensoria [23]. Their Sensoria fitness sock is equipped with pressure sensors in the area of the sole of the foot as well as with an accelerometer. These socks are then connected to a smartphone application which displays the data gathered there. What these socks offer in addition to the standard feedback on running speed, step counting etc. is feedback on the foot landing technique and cadence [13]. They suggest that such information could be used to identify injury-prone running styles early and by doing so help the user to prevent such injuries from running.

Figure 2.2: The Sensoria fitness sock with the accompanying app showing a heatmap of weight distribution on the foot [13]

Lifestyle computing

Rosales et al. [24] proposed a design of wearable technology to enhance children's free playing behaviour. They developed two different prototypes and tested them amongst the target group. One of the prototypes was integrated in socks, which emitted sound and light as soon as both of the feet carried no more weight. They reported that the system encouraged the children to use gross motor skills during their free play activity. As a final conclusion, they suggest that free play among children could be supported by such wearable devices.

Communication

One of the examples for the possibilities of wearables in communication is the Philips Vibe [25]. It is a necklace which tracks several biometric signals and so determines the emotion of the wearer. This emotion can then either be expressed by the hue the product is light up with or it can be communicated to another necklace. This enables communication to a new extent because there does not necessarily need to be human communication in the traditional sense, but the feelings of the other person can still be perceived over distance. This could enable the wearer to get support from other people without them even having communicated a problem, but the other person could see the emotional state through the device.

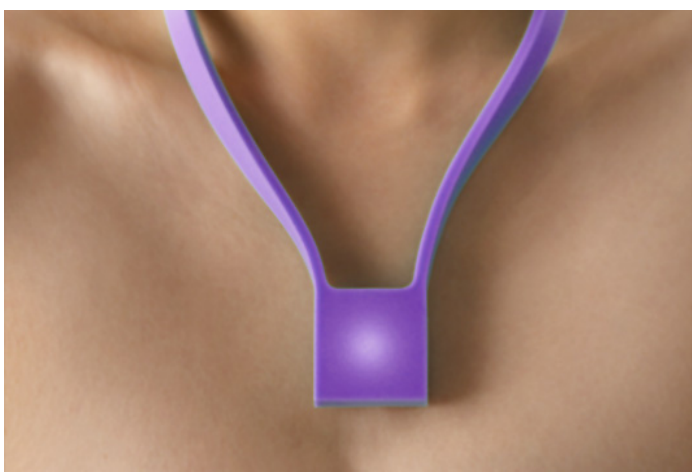


Figure 2.3: The Phillips Vibe necklace emotion sensor showing the emotions of others with the colour of the LED [25]

Glamour

One of the recent examples where wearable technology was used within a glamorous setting was Karolina Kurkova's Cognitive Dress during the annual Met

Gala [26]. This dress had 150 light emitting diodes (LED) included in it. The hue of the LEDs changed according to Twitter Tweets tagged with special hash tags while still keeping the dress in a matched colour scheme. A picture taken from the dress on the evening of the gala can be seen in figure 2.4

Figure 2.4: The Cognitive Dress with embedded LEDs changing colour according to Twitter tweets [27]

2.4 The designers tool box

Any designer wants to achieve a goal with a product. This aim can be decomposed into smaller sub-goals. This is where the concept of the tool box comes into consideration. The tool box provides the designer with means to reach the individual sub-goals and from there ultimately achieve the initial goal. Another term which can be used interchangeably is the skill set of a designer.
The tool box of each designer is the summation of tools or respectively skills. This concept is very broad and therefore not limited by hardware or software boundaries. The proficiency in a certain programming language can be regarded a tool, as well as the ability to build basic electronic circuits. The real challenge is, however, to extend this tool box by new tools. In order to do so, a certain set of requirements has to be met which are explained below.

Affordable: One of the key requirements is that the tool is affordable within the design context in regards to time and price. Any tool which can not provide the a solution within a reasonable amount of time is not a good tool. When looking at the price on the software-side, this can be for instance the initial cost of the software or the prices for API or webservice calls. On the hardware side, this can be the material or component itself as well as the periphery needed to work with it.

Accessible: Another point to be considered when extending the toolbox is that the new tool is actually accessible for the designer. There might be a perfect solution for one problem out there, but when it is for instance patented it is not accessible without added licensing cost. For software as well as for hardware, the designer has to get their hands on it in order to be able to use it. So only if the designer has a way to obtain access, it can be regarded a viable new tool.

Capable: The designer has to have the capability to work with a new tool. Taking a new programming language as an example, it is necessary for the designer to know how to program. Otherwise, the initial cost for learning how to use the new tool might be too high so that it becomes impossible. The designer needs to already posses or learn the capability to use a new tool within a reasonable amount of time.

Documented: Essential for working with any tool are instructions on how to work with it. This is why each tool should come with a well-written documentation or data sheet.

Reliable: It is essential that a solution by a designer keeps working over a longer period of time if not specified otherwise. Otherwise, the effort put into developing a solution to a given problem would be wasted.

Altogether, in order to make any tool available to designers it must fit within the requirements identified above. In case the tool fails to meet one of the requirements completely, it can not be used.

Chapter 3

Methods and Techniques

This chapter gives an overview over methods and techniques applied throughout the project. All these help to ensure a well founded result will be reached at the end of this project.

3.1 Overall design process

During the course of this graduation project the design process for creative technology developed by Mader et Eggink [3] is used. A graphical representation of this process can be found in figure 3.2 on page 17. The process itself consists of four different phases with a fixed deliverable at the end of each of them. The first three phases, named ideation, specification and realization, use a diverging-converging process. This implies that for every phase a set of ideas are explored but over its course weaker ideas are dropped until a final idea is chosen. The choice to use this process is based on the exploratory yet directed nature of it. It allows the designer to explore several different options and ideas but it still helps to focus on developing a prototype or product as an answer to the initial design question.

3.2 Stakholder analysis

One of the essential starting points for getting a better understanding of the surrounding conditions of any potential product or project is a stakeholder analysis. A stakeholder is defined by E. Freeman [28] as "any group or individual who can affect or is affected by the achievement of the [...] objectives". Identifying these as a first step can help to provide a good insight in all the parties tied to the project.

Sharp et al. [30] provide categories to which different stakeholders can be assigned. For this report only three out of the four categories are used - namely users, developers and legislators - because the final category of decision makers

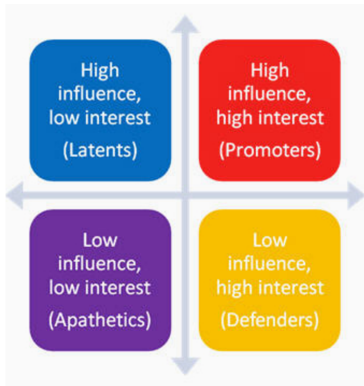


Figure 3.1: Categories of stakeholders in a grid along the axis of influence versus interest [29]

is of importance in an organizational background which is not the case here. In order to analyse the stakeholders further, they are going to be assigned to a quadrant in a grid with influence versus impact on the axis [29]. A visual representation of that grid can be found in figure 3.1. This approach helps to distinguish key stakeholders from the rest since they are the ones which needs have to be taken into consideration at first.

3.3 Personas

Personas are used in order to present different archetypes of users of the system. This allows designers to work without having to interact with the users while at the same time keeping the needs, goals and tasks embodied by the persona in mind [31]. But to avoid only designing for stereotypes, the real target group is still going to stay engaged in the process by using interviews for proving the initial relevance of the problem. In addition to that, the finished product will be tested with users as well. The personas are used as an additional mean to keep designing for the target group and especially parts of it which are not represented in the interviews.

3.4 Requirement analysis with MoSCoW prioritisation

One of the central parts of development is to have a list of requirements with which potential design choices and the final design can be evaluated.
One vital step in the process of requirement engineering is the prioritisation of the identified requirements. For this project, the prioritisation according to the

MoSCoW is chosen. This acronym stands for the different categories of Must, Should, Could and Will Not. Each requirement identified will be assigned with one of these categories resulting in ranking of the requirements according to their importance. This method is chosen because it is quick and easy to perform and still delivers a workable ranked list of requirements [32].
To divide the identified requirements further, they are also split into functional and non-functional ones. The functional requirements are defined to be those that "specify the input to the system, the output from the system, and the behavioural relation between them" [33]. These are the requirements where the decision whether they are met or not is easy because it can be decided by observing the system. For the non-functional requirements the following definition is used: "Describe the non-behavioural aspects of a system, capturing the properties and constraints under which a system must operate" [34]. These are harder to verify in the end because they cannot simply be measured. In order to achieve that participants of user tests are going to be asked to comment on the non-functional requirements. The answers are taken as indications how well the non-functional requirements are met from the perspective of the target group.

3.5 Scrum

For the development process of the sensors in this project, the scrum method [35] originating from software development is used. In respect to the overall design process for creative technology [3], the Scrum method is placed in the specification phase, where the development of the sensor's designs is taking place.
The Scrum process is divided into three phases, the pregame, game and postgame. The pregame phase is used for conceptualizing the idea and an analysis of the context and already existing solutions. Within this project, the outcomes of chapter 2, background, and chapter 4, ideation, are going to provide this initial step. The next phase in the Scrum process is the game phase. Within that phase an iterative cycle of develop, review and adjust is taken. In this project, prototypes of the sensors are developed, then reviewed and the making process adjusted to the findings. The description of the process is described in chapter 5, specification. The postgame phase is realized in this project in the chapter 6 and 7, realisation and evaluation.

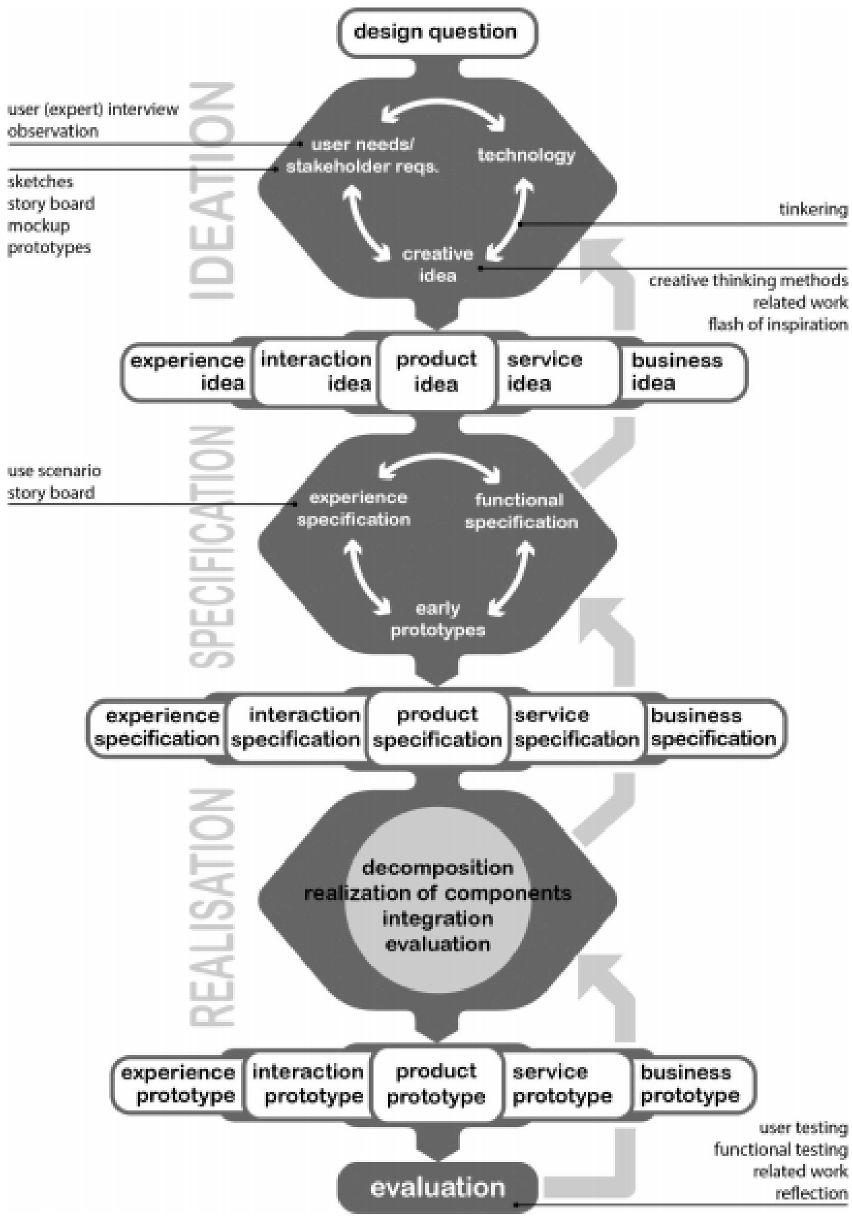


Figure 3.2: Graphical representation of the creative technology design process with potential methods for each cycle in the process [3]

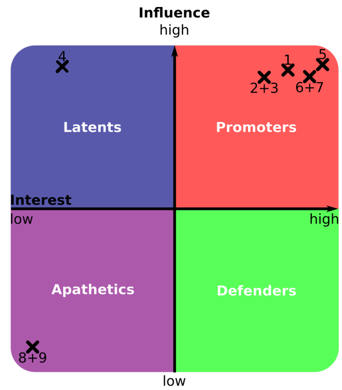
Chapter 4

Ideation

This whole chapter is designated to the description of the process of coming to the final idea of this project. This idea will then be further elaborated on throughout the following chapters.
To begin with, the stakeholders of this project are identified which also includes the target group of this project. To gain more insights into the needs and problems they encounter, interviews are conducted as well as personas written. This, in combination with insights gained already in the Background, culminates in a list of requirements for sensors in the wearable technology.
This list is then used to evaluate the weaknesses of already available commercial sensors as well as the suitability of potential concepts for this project. As a last part the final project idea is discussed more thoroughly.

4.1 Stakeholder Analysis

An overview of the identified stakeholders can be found in figure 4.1 alongside with their assignment to the grid of influence vs. interest. Within the users, a distinction can be made between two different groups. On the one hand, there is the immediate target group. There are of course the designers for wearable technology, as well as creative technologists and students who are working in the same field. All of these groups are highly interested in the results of the project. They are having a high influence since they are the ones using it later on. In contrast to them, there are the potential end-users who are the target group in the second instance since the initial target group designs products for them. It is a fair assumption that the end-user is not interested in the sensors itself, only in the final product made with them. Therefore, it can be said that they have a high influence on the project, but only a limited interest.
As for the developers, the stakeholders within a bachelor project are limited to the researcher as well as the supervisors responsible. All of these have high influence as well as high interest. The direction of the project has to be chosen by the researcher, but it still has to be approved by the supervisors, so the high



Users	Developers	Legislators
1- Designers of WT	5- Fabian Opitz - researcher	8- U.S. FDA
2- Creative Technologists	6- Angelika Mader - supervisor	9- European Union
3- Students	7- Erik Faber - supervisor	
4- End-Users of WT		

Figure 4.1: Table of stakeholders and their assignment to the grid of influence vs. interest

influence is given. And it is of the interest of all members of the developer group to achieve a good project result.
Lastly, the category of legislators responsible are identified. It is important that the user is safe, which is crucial in particular for body-worn technologies. Potential hazards from wearable technology products are for instance electric shocks, burns or chemical reactions. In order to prevent these, the products have to be in compliance with regulatory requirements. General ones are put in place by for example the European union (EU) or especially for medical and wellness products by the United States (U.S.) Food and Drug Administration (FDA) [36]. All the members of this group find themselves in the lower left quadrant. They have close to no interest in the project itself, since they are not actively participating. As for the impact, the test they do are for readily developed products not for single components, so their impact on this project directly is limited. It is largely up to the direct target group to keep the whole product in accordance with the guidelines. But to make it easier for the designers to get approval, the EU and the FDA should be considered a stakeholder.

4.2 Personas of the target group

In order to get a better understanding of the target group, four personas have been written. These represent members of the target group who encounter different problems with sensors for wearable technology.

Persona 1: Layman

Lena Millar is a woman of 28 years living in Berlin. One thing Lena enjoys very much is to sew clothes either for herself or as a special present for friends or family. It all started when her mom helped her designing her very own carnival costume. Back then she was making an owl costume and from there on she took it up as a hobby and is still enjoying it today. Another thing she is very passionate about is to stay active and do sports. Next to going to the gym twice a week, she is also playing tennis with her friends on a regular basis. At the moment she is working in a small start up with a team size of 5 people. They are trying to solve the problem of bad posture when sitting at a desk. Currently they have an early prototype working which they are trying to develop it further to bring it up to a pre-commercial stage. Even though Lena has a background in marketing and communication science, she is also helping to work on the prototypes. Her knowledge about sewing is very useful, but since the team size is so small she is also helping out with the electronics. She visited one workshop in a local fab-lab which covered the basics of micro-controllers and from there she picked it up herself and used the internet to help when she does not know further.

When looking for sensors to test one of the ideas she has had, she found a sensor exactly doing what she wanted but it required to be connected via an operational amplifier (OpAmp) circuit. As she has never worked with one before, she tried to find material on how it works online. But she only found highly technical explanations she did not understand, so she had to continue her search for a fitting sensor.

Persona 2: Workshop supervisor

Rick Geerts is a 35 year old self-employed maker. He has a small workshop at home where he has a laser-cutter, a 3D printer, a lot of tools and much more. He is offering his machines and knowledge for hire to make things for his customers. As a second income, he is also offering workshops at schools, universities or companies in which he helps the participants to bring their own creative ideas to life. One of the topics he is offering workshops on is wearable technology. This field allows people from different backgrounds and technical understanding to work on one idea together while still everyone can contribute to the outcome.

When on such workshop, however, he can only provide the participants with the material he brought with him. Therefore, some ideas were not being able to be made, because he did not bring the right components or the ones he brought did not fit with their shape in the idea.

Persona 3: Industrial Designer

Rosa Berks is a 28 year old woman working as an user experience designer in a small sized company with 20 employees. Originally, in university, she studied

industrial design in one of the more technically oriented programs. She uses these skills to go through prototyping iterations of products she is assigned to. From time to time, she is also using rapid prototyping techniques and working out new prototypes while other team members are conducting tests with users. One of the fields her business is specialized in is wearable technology. This is due to the fact that the old interactions paradigm has to be changed for wearable technology which still has a lot of room for improvements.
When getting further on in the prototyping stages, one of the problems they encounter often is the proper integration of the components into the clothing. They want to hide it so well that the user or wearer does forget about the embedded technology most of the time, but still can interact with it consciously. For that, it is essential that the components have a small form factor or are flexible to follow the movements within the piece.

Persona 4: Wearable technology designer

Marika Rogers is the founder of a small wearable technology start-up. She comes from a textile background but already began to dive into that field when doing her master thesis on smart conductive fibres. After that she worked in the purchasing department of a big fashion company but in her time off work she still kept working on integrating technology into clothing. Five years back, she made her dream come true and founded a startup with a small team of four people to bring the ideas she had and worked on her own so far to the point where they would be ready for the market. The team has grown since and now she is working with ten employees and contractors are added as needed. Currently she is travelling a lot to present one of her prototypes at different trade fairs and companies all around the world to gather more funding and spread the word about her small company.
When prototyping for new products in her company, one problem arises: Getting reliable data from a sensor is expensive. Even if she only wants to try, whether a certain sensor which promises high reliability is applicable in the envisioned use within a project, the price can be several hundred dollars. This is a lot of money, for only trying out if it works. This is why she grew hesitant in introducing new, reliable sensors in her workshop, which might hinder her innovativeness.

4.3 Analysis of interviews

To evaluate, whether designers experience issues with the sensors which are currently available to them, three interviews have been conducted with wearable technology designers. One of the interviewees being Marina Toeters from by-wire.net. She has built numerous clothing based wearable products in which she utilizes her fashion background in order to achieve a high degree of integration in clothes. The second interviewee is Emiel Harmsen, a master student in human computer interaction (HCI). He was just coming back from an internship at sensoree in which he built a prototype tracking several physiological param-

eters in order to determine excitement. The last interview was conducted with Isabella Pfab who is currently working as an intern in the wearable technology design team gathered around Pauline van Dongen. One of her core tasks is to work with sensors needed for the products developed there, so she is a perfect fit in regards to the scope of this project. Transcriptions of all the interviews can be found in Appendix A on page 77.
Mrs. Toeters was reporting that the sensors currently used by her were not causing her any problems. What she describes as way more pressing are issues of wearability, in particular the integration of the components and their rigidity. Mrs. Pfab, however, was of a contrasting opinion. According to her, the trade-off between price and reliability of sensors is always prone to either one of the two sides. Especially for stretch sensors there are, according to her, none available which keep a good balance between these two points. Or in other words, you either have a very expensive reliable sensor or a very cheap unreliable one. This causes problems if an early prototyping stage is left, since the desired reliability of later prototypes goes hand in hand with a need for expensive components. When being asked about problems with sensors, Mr. Harmsen described that his used EKG and breathing sensor worked well, while the skin resistance electrodes caused some problems. Two different setups were tested, one with fabric-based electrodes in the palm of the hand and one with sticky ones in the same location. The fabric-based electrodes showed spikes in the data which should not be present but might be induced through motion artefacts. The sticky electrodes showed a smother progression, but since they are one-time only use, they might be suitable for a research setup but not for products to be sold to end-users.
In conclusion, the outcome of the interviews is mixed. While two interviewees do not report pressing issues with the currently available sensors, the third one sees an immediate problem in the balance between reliability and cost of sensors. This shows, that this problem is experienced by at least a part of the intended target group and is one potential challenge to be tackled in this project. Another point to be taken from the interviews is that the wearability is still an issue to work upon, like the proper integration of the technology into clothing and its rigidity. Therefore, any concept of sensors in this project should aim at improving on these accounts. Another particular problem encountered by one of the interviewees regards the reliability of skin resistance electrodes. Improving upon this point is also one potential direction, in which this project could be heading.

4.4 Requirements

The literature research and methods applied so far lead to one list of requirements. This list is used as a foundation not only to identify any problems already commercially available sensors face, but also to make a well-founded decision for the future direction of this project.
The resulting list of requirements along with their ranking in the MOSCOW

framework can be found in table 4.1. There are four distinct sources from which the individual requirements are obtained. The most important one regards the aim of this project, to develop wearable sensors, so it is crucial that the definition of a sensor is met. In addition to that, there are some desirable properties sensors need to show, which are also added to the list. One example for this is the high repeatability of the sensor. As a next step, to satisfy the target market, the sensor has to be wearable. The categories of Bryson [5] as introduced in section 2.1 are used because it offers clear-cut categories while not depending too much on choices to be made by a designer when developing a prototype. In order to make sure the demands of the target group are met, the third origin of requirements comes from the designers tool box as introduced in section 2.4. Lastly, the point of every research is to solve a problem. Therefore, the last requirement is the relevance of the subject.

Nr.	**Requirement**	**MOSCOW category**	**Obtained trough**
F1	output in response to a specified measurand	Must	sensor definition
F2	high repeatability	Must	qualitative sensor properties
F3	low inference	Should	qualitative sensor properties
F4	linear response	Could	qualitative sensor properties
NF1	comfortable	Should	wearability
NF2	durable	Should	wearability
NF3	sensually pleasing	should	wearability
NF4	aesthetically pleasing	Could	wearability
NF5	accessible	Must	tool box
NF6	affordable	Should	tool box
NF7	documented	Should	tool box
NF8	reliable	Should	tool box
NF9	relevant to the target group	Must	Graduation project

Table 4.1: A list of all the functional and non-functional requirements together with their MOSCOW ranking and their origin

4.5 Analysis of commercially available wearable sensors

Different commercially available stretch sensors have been found from various manufacturers. The stretch sensor has been chosen because it is one of the common ways to track the movement of the body, as described in section 2.2, which is one of the focus points for this project. A discussion of positives and negatives for the different sensors can be found in the section below with a conclusion at the end.

Leap technology's stretch sensor kit

The leap technology's sensor [37] consists of two thin, conductive polycarbonate layers coated with silicone and fabric on both ends for attachment. An image of

Figure 4.2: Leap technology's stretch sensor evaluation kit with two sensors and the interfacing box [37]

it can be found in figure 4.2. It uses the capacitance across the two conductive layers to measure the stretch of the sensor, but can also be used to track pressure or flex. The sensor is very soft which is of great benefit for its wearability. The response of the sensor also seems to be quick and linear in respect to the stretch. However, the sensor also has some serious downfalls. First of all, the price for an evaluation kit is 850€ excluding taxes, which is very high. Using capacitance as a measuring principle results in the need for additional hardware. The output range of the sensor is, according to the provided data sheet, from 2.5nF up to 3.5nF at full stretch. This is too small to be measurable by a micro controller directly, which they solve by providing it in a box. The size of this box is about 6cm x 4cm x 2cm which is pretty big for being attached to the body. This in turn reduces the wearability of the sensor greatly. The last downside is that it is not customizable by the designers, only by the manufacturer. So the sensor can for example not be cut or sewn in the sensing area, only in the fabric ends. If the size of it needs to be adjusted, this can only be done by ordering new customized sensors from the manufacturer, which will very likely be pricey.
In conclusion, this sensor works very well, but also has a few short comings, especially the price and the need for additional hardware.

StretchSense's fabric stretch sensor kit

A very similar sensor to the one of leap technology discussed in the previous section is made by StretchSense [38] which can be found in figure 4.3. Their sensor, however, uses layers made out of conductive fabric instead. This makes the integration of this sensor into a product even easier and the response is linear as well.
But the same negative points apply here, too. The price is with 850$ for an evaluation kit very expensive. The range of the sensor is even smaller, from about 500nF to 800nF, which makes additional hardware necessary again. There are attachment areas on four sides of the sensor, but 2mm on the long side and

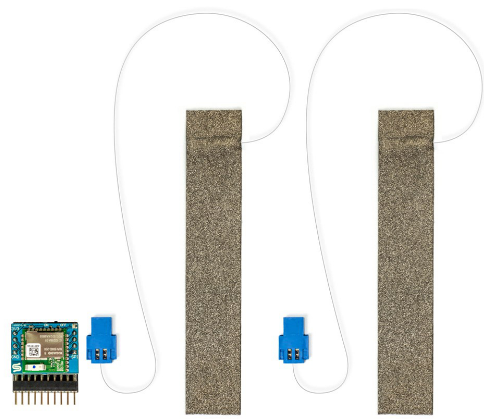


Figure 4.3: StretchSense's fabric based stretch sensor kit [38]

10mm on short sides is not too much space available. The sensor cannot be customized either, since piercing through the conductive layers can render it not usable.
To sum up, the sensor might work well, but the price and the additional hardware are disadvantages again.

Adafruit's rubber band

Another stretch sensor is sold by Adafruit [39] which consist of a round, conductive rubber band as seen in figure 4.4. It relies on measuring changes of resistance rather than capacitance, which enables it to be interfaced to a microcontroller with a simple voltage divider. It is also very cheap in comparison to the already discussed solutions by costing just under 10$ for a full meter of the cord, which can be used to make multiple sensors. It is not a perfectly linear sensor, but the behaviour can be well estimated with a linear function. The cord is also very flexible, which is a necessity for it being used in a wearable technology product.
The shape, however, is not ideal. The circular cross section can be felt even through fabric and on body parts with not a lot of tissue between bone and skin, this could hurt the user when pressure is applied there. An even bigger problem ,also originating in the form factor, is the connection to the wires. The round shape makes it hard to attach both ends to fix points as well, which are required for measuring. To overcome both of these problems, Adafruit delivers the sensor together with two crocodile clamps, which can be attached easily and used to connect wires at the same time. This, however, introduces rigid metal objects to the design which weaken the wearability significantly.
To conclude, this sensor is a cheap and easy to use solution, but still has some problems when it comes to the wearability aspect.

Figure 4.4: Adafruit's conductive rubber cord stretch sensor with crocodile clamps for attachment and interfacing [39]

Stretchable fabrics

Another solution for measuring stretch is made by Eeonyx in the form of a piezo-resistive fabric [40]. When the stretchable fabric is fixed on two ends, the resistance over both ends changes alongside with the stretch. The fabric scores high regarding the wearability, since it is very flexible and does not have any edges like the previously discussed rubber cord. A further advantage is the great potential of customizing the sensor according to ones needs. The fabric can be cut into any shape desired and therefore be adjusted to the project as needed.
There are, however, problems with the Eeonyx fabrics as well. They can only be found in small sample sizes for retail. These are cheap with about 17 pounds [41], but as soon as a designer wants to have larger quantities, the manufacturer has to be contacted. Another problem with the fabrics is the interfacing to the microcontroller. Wires cannot be directly attached to the fabric itself by soldering, so they have to be interfaced in another way. One way to do that is to use press buttons, as can be seen in figure 4.5. This introduce a rigid structure again and can have a negative effect on the wearability. Another solution would be to work with conductive yarn to prevent the rigid structures, but this requires some effort to do, which might be undesirable in early stages of prototyping. A further disadvantage is the wearing out of the conductive coating of the fabric over time, which was mentioned by Isa Pfab in her interview.
To wrap up, sensors based on piezo-resistive fabrics are have benefits, especially regarding their wearability. But they also have problems, in particular their lack of availability with resellers and their longevity.

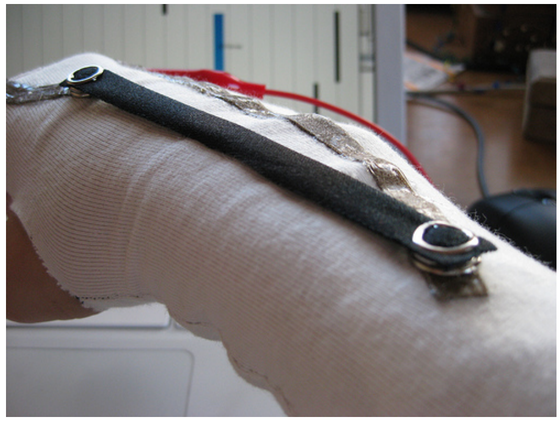


Figure 4.5: Application of the Eeonyx piezo-resistive fabric as a stretch sensor over the wrist [42]

DIY sensors

Another way to implement stretch sensors originated in the Do-It-Yourself [DIY] scene is to use handy craft methods, such as knitting or crocheting, with conductive yarns, as it is shown on the Kobakant website [43]. When a combination of conductive and non-conductive/standard yarn is used, the strain applied to the sensor results in better connections between the conductive fibres and the overall resistance drops. Examples of such DIY sensors can be found in figure 4.6. The resulting sensors are very cheap, since they only require the conductive yarn to work. The easy customizability is also a big plus, since the designer can make them fit their needs. The resulting structures also score hight regarding wearability, since they are only made of yarn.
This approach, however, has a few downsides as well. First of all, the sensor lacks reliability. The reaction of the fibres to a force might not always be the same, which in turn has an effect on the resistance measured. The structure can also wear out over time which can change the response as well. And not only the structure can be influenced over time. The conducting yarn is achieved by adding steel or silver fibres to normal yarn. These metallic fibres can oxidise and disappear over time, which reduces its conductivity. Another point is the problem of connecting the sensor to a micro-controller in a good way. The conductive yarns can not be soldered on, so to connect them, the whole circuit has to be sewn with conductive thread, which requires time. Alternatively, the yarn can be connected to a wire with a press button. This, however, introduces rigid objects again, which should be avoided for a better wearability.
In conclusion, the self-made knitted stretch sensors are cheap, very wearable as well as highly customizable. On the downside, they lack reliability and have some limitations regarding their long-term use.

Figure 4.6: Hand-knitted stretch sensor attached to a stretchable fabric with sewn connections for crocodile clamps [43]

Conclusion

As it is shown above, there are several solutions available to measure stretch in the wearable technology field. Each of the presented sensors have different strong and weak points. The first two sensors work well but are very expensive and require additional hardware to get a signal usable for a micro-controller. The rubber band is cheap and works well, but the form factor has some negative implications for the wearability of the sensor. The piezoresistive fabric and the knitted sensor score high in respect to the wearability, but both have problems in regards to longevity and interfacing with the micro-controller.
A cheap stretch sensor which works well over a long period of time, scores well with the wearability aspect and is easy to interface with a micro-controller is still missing.

4.6 Different concepts as bases for wearable sensors

As the previous section discussed, there are several sensors available but none of them without flaws. The aim of this project is to develop a new sensor which keeps a better balance between price, wearability and reliability.
In order to achieve that goal, several different concepts are explored and evaluated in regard to whether they would provide a better balance between those core requirements. This process is shown in the following paragraphs culminating in the last section dedicated to the final project idea.

Conductive silver ink in an inkjet printer

One year or two ago, a crowdfunding project introduced a pen which contained conductive silver ink [44]. Since silver is a excellent conductor, these pens allow

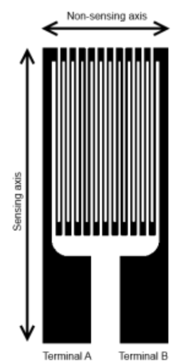


Figure 4.7: Conductive pattern of a strain gauge sensor [46]

one to draw working circuits on paper. With this it is possible to light up an LED when it is connected to a battery via a resistor with drawn lines. This seemed promising for making circuits and upon further research an 'instructable' was found which used such conductive silver ink in a inkjet printer [45]. The circuit is on transparencies from which it could potentially be transferred to another medium, like a flexible rubber film. This would make it promising in regards to the wearability requirements. Furthermore, printing them should allow a certain level of repeatability for the same sensor. One thing, which could be done with such a set-up is to produce a pattern similar to the one of a strain gauge as seen in figure 4.7. Standard strain gauges only allow for a minimal strain exerted onto them. This is why they are mounted on top of aluminium or steel alloy bars when used for measuring pressure [46]. They only bend very slightly even under high pressure, but that is not needed in the wearable technology context. When a similar pattern is, however, printed on a flexible and stretchable foil with the conductive ink, this measuring technique could be applied in a stretch sensor having a larger range than the strain gauges. The foil would also allow it to be easily integrated into wearable technology prototypes or products.

All of that sounds pretty promising, the downfall, however, is the start-up cost. Silver is a pretty expensive material and 100ml of the silver ink cost 350$ [45]. The price per circuit will be lower since you only use a little bit of ink per circuit. But the high initial cost, however, does not meet the requirement of the tool box to be affordable. Therefore, this idea has been dropped.

Carbon nano-tubes and Graphene

Upon an initial scan of the sensors, which have been published in academic papers recently, there was one material reoccurring over and over again were carbon nano-tubes [47]. So the idea came to mind whether one could make the leap and take such materials from the research labs to the design studios. But the limiting factor there is the price. The equipment and materials to grow your own carbon nanotubes is not feasible and purchasing ready-made nano-tubes is expensive as well, ranging from 25$/gr up to 300$/gr [48]. Thus, the pursuit of that idea also proved to be not feasible. Another material also prominent in new sensor research which has the same disadvantage is Graphene.

3D printing for sensor production

Upon some advice from a PHD candidate at the university, the possibility to use the available 3D printers in order to fabricate mechanical sensors was taken into consideration. This idea is, however, weak on multiple points. First, most of the materials which can be printed with a 3D printer are rigid or on the verge of being called flexible. This is already unfavourable for the wearable requirements. Furthermore, mechanical systems are very sensitive. As long as it stays within the boundaries of the use case it might work well, but the washing machine puts an enormous strain on the sensor which also has to be considered for future use.
It would also be possible to skip the suggestion for mechanical sensors but still use a 3D printer. For that it would be necessary to print conductive material, which can for example by achieved by using conductive polylactic acid (PLA) [49]. But with the available one nozzle 3D printers this method presents the challenge that only one material, either conductive or non-conductive, can be printed at the same time. So, if both would be needed, for example one for an non-conductive casing and one for the sensing part, the filament would have to be switched after each layer. This is not very practical and would make the time intensive process even more time consuming. This point especially would have limited sensor design very much. The idea was not pursuit further and dropped because of the mentioned points.

4.7 Final idea: Silicone and carbon as base materials

One carrier material which reoccurred over and over again when reviewing literature for wearable sensors was silicone. This is due the characteristics of silicone which are very desirable in the wearable field. In the following a list is used to comment on some of the properties of silicone.

Flexibility: This is one of the main advantages of silicone. The greater term for the material property of flexibility is called hardness. The measure which is used for expressing the hardness is called Shore. For a better understanding on what materials have which hardness figure 4.8 has been included below.
There is not only one hardness associated with silicone, but it covers a whole range. It can be purchased ranging from 0 Shore A (ShA) up to 90 ShA. When taking the examples from figure 4.8, that would indicate it can be softer than a rubber band or harder than a shoe sole. This point makes it perfect for different uses in wearable technology; soft silicone can

be used for adapting to the body form of the user and keep skin contact while hard silicone can be used for casing sensitive components. But even though silicone can be flexible, it is not likely to tear.

Chemical stability: Silicone is chemically quite inert, so it does not react with a lot of other chemicals. This is important because skin contact is very likely in wearable technology, and sometimes even desired, and the skin is acidic. Furthermore, it is important for withstanding the conditions in a washing machine since next to the mechanical stress the, washing powder adds chemicals to the mix. But that does the silicone no harm.

Uncured consistency: The silicone in its uncured state has an jelly like consistency. This has two major advantages: Firstly, it enables the silicone to be poured into moulds when curing. This allows for great diversity of forms and shapes only limited by the mould. A second advantage of this initial consistency is that other materials can be added in this stage. By doing so, the properties of the materials can be changed. Adding conductive particles for example can change the silicone to be conductive. Since this is essential for making sensors, this will be further elaborated on later on in this chapter. A final advantage is that this consistency allows also for bigger objects to be embedded into the silicone before casting. This could for instance be used to embed an accelerometer into silicone. This would allow the embedded electronics to be protected from direct force, water and chemicals like they would be prevalent in a washing machine and contain them in a non-conductive casing.

Based on the arguments above, silicone shows strong points as a material to be used within wearable technology. To add to that even further, silicone is used in clothing already. It is commonly used to keep clothes in the desired position. It is most of the time used in women's clothing, for instance to keep strapless dresses from moving too much. This point might have a positive impact on the willingness of the end-user to adopt products including silicone-based sensors. The reason for that is that they are already used to the material being em-

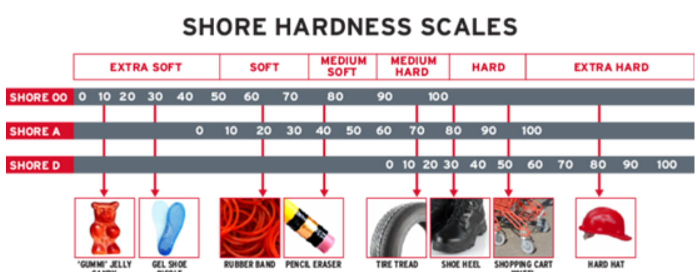


Figure 4.8: An overview of different shore hardnesses and products with similar properties for better understanding [50]

bedded in clothing serving a non-technical purpose. Furthermore, the purchase prices for silicone are very reasonable which is in line with the requirements for the designer's tool box.

As the paragraphs above show, silicone is promising as a material for wearable sensors. But there is one hurdle to overcome in order to make sensors out of it: by default, silicone is non-conductive. Upon searching online for ways to make it conductive, an 'instructable' [51] was found which explained one way to achieve this. It provides instructions of adding short carbon fibres to the uncured silicone in order to change it to being conductive. This sounded very promising since this would offer the possibility to make the sensing part of a sensor out of silicone rather than only provide the casing of it. Further research has been done into carbon fibres, which showed that it is a common material used for model making and therefore easily accessible through online shops. The material also showed several other desirable properties: it is highly conductive, as already indicated, yet very flexible and reasonably priced. In other words, it complies to the requirements previously identified. It was also found, that it is not only available in the short fibres of about 3mm the instructions were using but available as well grounded down to a powder and as a continuous fibre bundle. Especially the latter was of interest in respect to building sensors, because they would offer the possibility to embed conductive structures into the silicone. Depending on how the structure would be embedded, they would offer the possibility to realize several different sensors. One idea, for instance, was to add the fibres all in one direction into the silicone. When this pattern would then be stretched along a perpendicular direction the overlap between the fibres would change. So, measurement across the whole structure should show varying conductance depending on how it far it is stretched and therefore be able to serve as a stretch sensor. Similar concepts have been found in literature, where conductive liquid was embedded [52] or carbon nano tubes [47] into silicone.
In conclusion, the material combination of silicone and carbon fibres presented itself as a very good match in regard to the previously identified requirements. Silicone is already used in clothing and the carbon fibres can be used to either make it completely conductive or embed conductive structures into the silicone. The perceived potential of this material combination for wearable sensors presented itself as big enough to choose this idea to commence verifying it in practice.

Chapter 5

Specification

In this chapter, the development process for three different sensors based on silicone and carbon is shown. For each of the sensors, one stretch sensor, one pressure sensor and one electrode ring, the main problems encountered during the numerous iterations and their solution are described. Each of the sensors has its own section dedicated to it with the problems broken down in them.

5.1 Stretch sensor

As already concluded in section 2.2, the movement of the body is still one area which is can still be developed further. Already existing solutions for stretch sensors are described in section 4.5. But all of them run into problems, so the decision was made to make a stretch sensor based on a conductive carbon fibre pattern embedded into silicone are described.

5.1.1 Fibre pattern

Several prototypes have been made with different structures of the carbon fibres embedded into the silicone. Illustrations of the explored patterns can be found in figure 5.1. The linear pattern and the chequered pattern with a steep angle were the only ones which allowed for a good stretch of the silicone without damaging it. The linear pattern showed a response over a bigger range of stretch so this pattern was preferred in the beginning. However, the connections between the fibres are not very reliable and one late iteration of the sensor showed no conductivity across the leads at all. So it was not very reliable in the sense that it was not clear whether it would work or not. The chequered pattern with steep angles, however, has guaranteed connections and was therefore chosen as the final design.

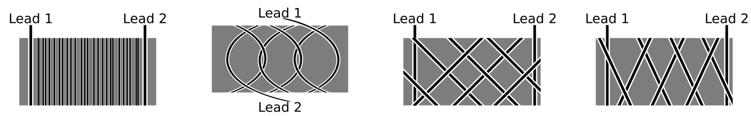


Figure 5.1: Overview over different carbon fibre patterns embedded into the silicone

5.1.2 Wire attachment

Graphics depicting the different stages of the attachment can be found in figure 5.2. At first, only carbon fibres reaching out of the silicone have been used as leads which have been connected with crocodile clamps to electronics or a multimeter. But that is not desirable regarding the wearability of the system. That is why a method has been found to connect carbon fibres with flexcore wires. This is done by twisting the carbon fibre and the individual cores together which leads to a good connection between both. At first, the wire was directly running into the silicone which worked fine for harder silicones. But when softer silicone was used the wire did not have enough stability inside the silicone any more and was pulled out relatively easy which basically destroyed the sensor. This was solved by covering the part of the wire inside the silicone with harder modelling silicone.
To improve the sensor even further it was attempted to bring both leads to the same side by running a very thin lacquered wire inside the silicone from one side to the other. This would make the sensors easier to interface but the thin wire broke easily and cut the silicone inside upon stretch. Therefore, it was not included in the final design.

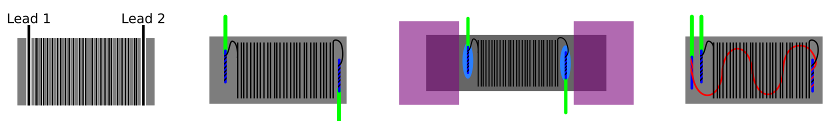


Figure 5.2: Graphics showing the design of the leads from pure carbon fibre up to the in modelling silicone embedded wire-carbon fibre interface

5.1.3 Hardness of the silicone

At first, a ShA33 silicone was used to make the sensors. When such a stretch sensor was shown to a wearable designer she criticized that the force to stretch it was too big. To overcome that softer silicone with a ShA0 hardness was used. But this sensor was too soft and the silicone showed signs of tearing when stretched too far. A mixture of the two silicones with a resulting hardness of about 10ShA showed no signs of tearing while still requiring not lot of force to stretch and was therefore used for the final design.

5.1.4 Attachment possibilities

In the beginning was the stretch sensor only a silicone box with the leads sticking out. But since this is hard to attach to clothes, fabric pieces have been embedded into the silicone on both sides of the stretch sensor. These are held well fixated in the silicone and make the stretch sensor easy to attach to two fix points.

5.2 Pressure sensor

Another way to record biokinetics is not to measure the movement itself, but the resulting pressure of it. This can for example be done on the soles of the feet for step recognition or on the inside of the fingers to determine if one holds something in his hands. Therefore, one of the sensor developments was chosen to be a pressure sensor.

5.2.1 Sensing principle

It was tried to implement the idea of a pressure sensor with changing capacitance between two conductive layers. Some calculations, however, showed that the resulting capacitance is too small to be measured with a micro-controller directly and therefore the idea has been dropped. On another occasion left over silicone from a stretch sensor was made conductive using the carbon powder. The resulting material also changed its resistance when pressure was applied and this idea was developed further in several other iterations.

5.2.2 Ratio of carbon vs. silicone

Different ratios of carbon powder to silicone have been tried. If not enough carbon is added, the cured mixture ends up not being conductive. If too much carbon is used the cured mixuture ends up being brittle. A patent found suggested a ratio of 3:1 of silicone and carbon for it to be conductive. Upon checking such a uncured mixture with a multimeter it turned out to be not conductive. More carbon powder was added and a weight ration from 2:1 proved to be well conductive while still retaining a good amount of flexibility. A test with 1:1 ratio of silicone to carbon powder did not retain the flexibility but got to the point of being brittle. Therefore, a ration of 2:1 seems to be the a good trade-off between the flexibility and the conductivity.

5.2.3 Leads inside the silicone

In order to get a proper interfacing with the sensor to a micro-controller cables have to be used. The initial silicone mixture proved to be sturdy enough to keep simple flex-core wires embedded and also electrically connected. One small problem was that the wires could be pulled out straight of the silicone. Soldering a small hook-like U-turn at the end of the flex-core wire solved that issue.

5.2.4 Moulding principle

The first tries of the pressure sensor were moulded similarly to the stretch sensor. A laser-cut acrylic mould with the central moulding area cut out and filled with the mixture. To make it thinner, the acrylic piece of the moulding area was used to press the mixture down flat. This was a problem for the leads encapsulated in the mixture, since it was then encased in acrylic from all four sides. To get the leads still in there, wholes have been drilled into the sides of the mould to stick the wires through. This made the sensors thinner but, since the wholes cannot be too far off centre in the acrylic, not thin enough. The final solution was to get rid of the encasing mould at all, only a top piece and a bottom plate remain. This allows the wires to be placed freely on the sides. When the top part of the mould is pressed down, the mixture spreads below it perfectly and any excess material oozes out at the sides. This is not a problem, however, since the overflow can still be cut off when cured. This method allowed for sensors to be as thin as 2mm, which could potentially still be improved when thinner wires are used.

5.2.5 Hardness of the silicone used

Different hardnesses of the silicone have been tried to make the sensor as flexible as possible. The initial iteration was made with a ShA33 silicone which gets a bit harder by adding the carbon particles. The results still showed some flexibility, but not as much as desired. To achieve that, the softer silicone with a hardness of ShA0 was used in a later iteration. The result was very flexible, but this came at the cost of not being able to hold the leads with wires inside the carbon any more. They could be ripped out of the silicone easily which makes this not feasible. Another try with ShA10 was done to try to achieve better results. It also shows improved flexibility compared to the initial version, but the concern about the robustness is still there. That is why the Sha33 is the final choice, because it is reasonable regarding flexibility and very sturdy in regard to the electrodes.

5.2.6 Attachment

Since a sole disc of silicone is not easy to attach or integrate into clothing, the sensor has been cast on top of non-stretchable, non-woven perforated fabric. This allows for the sensor to be sewn inside clothing or to be quickly attached with safety pins. The bonding of the sensor and the fabric was good, so it could not be peeled off it. It has also been applied to a stretchable, woven fabric which worked as well. But at the spot the sensor sits on the stretchability of the fabric was gone.

5.3 Electrode ring

During one of the initial interviews, the problem of recording reliable skin resistance data came up. The prototype utilized two reusable electrodes in each hand, but they suffered from motion artefacts. The only better solution found were medical sticky electrodes, which cannot be used again. From this problem, the idea was born to make electrodes embedded into rings to track the skin resistance. Rings can be tight which should allow for continuous contact and they are comfortable to wear. This is why this was chosen as the third sensor, although it is technically not a real sensor.
Another possible application for them could be to track the heart beat if the two rings would be put on different hands.

5.3.1 Mould

The essential part of making the ring is a mould. It was made out of three layers of 6mm acrylic, one base plate and two layers with a circular cut out in the middle called the outer mould. To make the hole of the ring, a round centre piece is pushed into the cut out. A top down view of the mould can be seen in figure 5.3. The first problem is to get a fitting size of the ring, since the fingers vary from person to person. The first mould made a ring with a too tight fit, so the cut-out and the centre piece were made slightly larger. Another issue was to keep the middle piece centred to ensure consistent thickness around the ring. Currently, this is done with holes fitting a tooth pick used for alignment. Later on, the outer shape was changed to not be completely circular any more, but to have a dent at one point resulting in thicker silicone. The wire to the electrode is placed in that spot to allow for increased support.

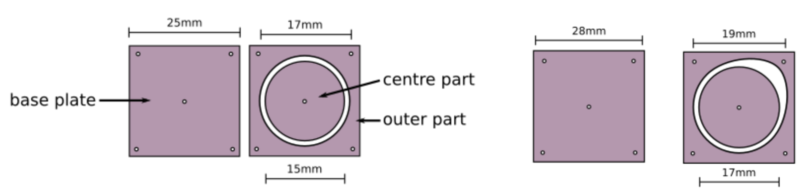


Figure 5.3: Illustrations of the electrode ring mould, the original one and the one with the additional dent

5.3.2 Electrode and Wire attachment

For the electrode, the conductive part making contact to the wearer's skin, the copper mesh available in the workshop was used. An illustration of the different stages can be found in figure 5.4. During the first iterations only the copper mesh was used with the wire soldered on in centre. The mesh, however, did not bond well with the copper properly and got loose pretty quickly. An additional issue was the mesh rolled up around the wire upon soldering and that part was sticking into the centre of the ring. In order to ensure a better bonding to the silicone, the mesh was reinforced by cotton iron-on patches. The wire attachment was also moved to one side of the mesh which allowed it to be inside the silicone. Problems in these versions were lack of bonding between the patch and the mesh as well as patches left and right edges cutting through the silicone. To overcome the later, a string around the central mould piece was used as an attachment method rather than tape. This keeps both edges closer to the central piece and prevent them from reaching through the complete thickness of the silicone. The bonding problem was solved by also sewing the mesh onto the patch rather than only ironing on there. The next weak point was where the wire exits the silicone. The wire can break there easily, especially since the insulation ends around the same point and the exposed cores are especially prone to breaking. To overcome that, the design was changed so that the insulated wire is first running to the bottom of the ring, making a sharp turn there and the stripped wire being soldered to the mesh on the way up.

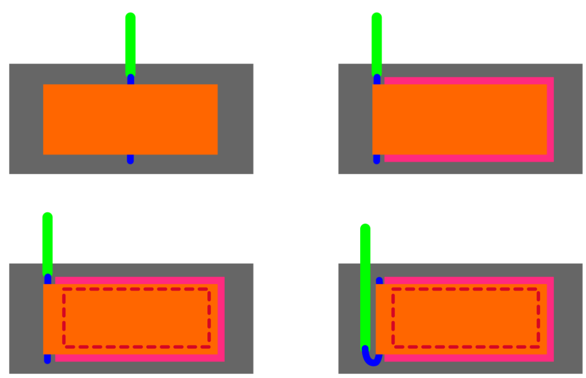


Figure 5.4: Concept figures of the electrode ring throughout the different iterations as seen from inside the ring
Colour code: grey: silicone, orange: copper mesh, green: insulated wire, blue: wire core, pink: patch fabric, dark red: yarn

5.3.3 Higher degree of integration

Two attempts have been made at making an integrated skin resistance solution. This was done by including the resistor for the voltage divider into the ring as well as having two separate patches of carbon mesh the ring. The sketch of the concept can be found in figure 5.5. The idea was only put the ring onto the finger, connect the three outgoing cables to a micro-controller and immediately have the readings without anything else required. This was realized by using thin coil wire which is lacquered with a non-conductive coating. This allowed for the three outgoing leads to be intertwined up to the micro-controller. This idea was, however, not taken as the final design because the connection of the two smaller electrodes to the skin was not very good. It resulted in an unstable signal which is

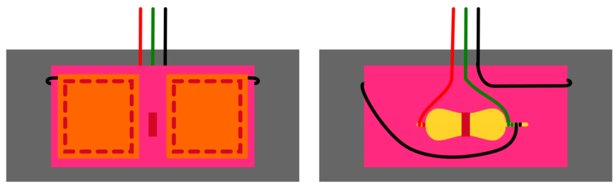


Figure 5.5: Concept of the integrated skin resistance ring
Colour coding: grey: Silicone, orange: copper mesh, dark red: yarn, pink: patch fabric, yellow:resistor, black+green+red: coil wire respectively ground, output and power

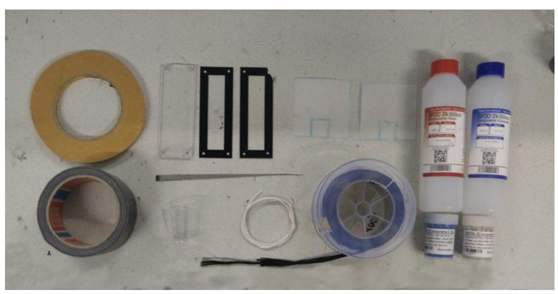
Chapter 6

Realisation

In this chapter, the manuals for the final sensor designs can be found.

6.1 Manual Stretch sensor

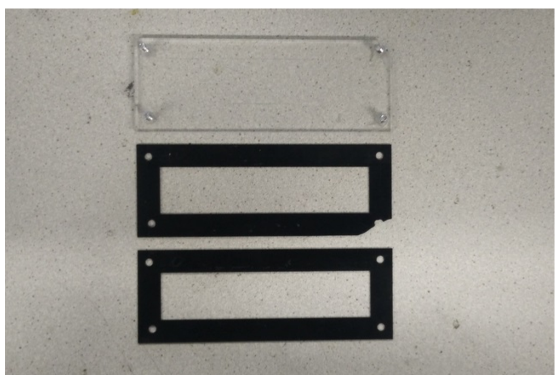
This is the manual for making the stretch sensor out of silicone with embedded carbon fibres.



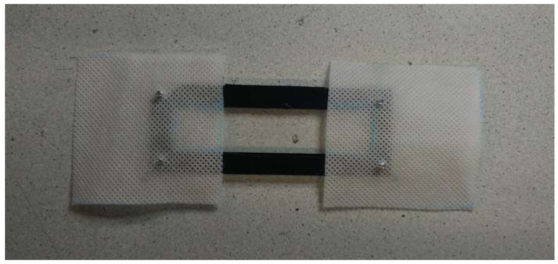
Materials	Tools
ShA08 silicone	Acrylic three part mould
ShA90 modelling silicone	Latex gloves
Perforated non-woven fabric	Small mixing containment
Carbon fibres	Mixing spatula
Thin double-sided tape	Small clamps
Duct tap/thicker tape	Bench vice
Thin flex-core wire	Knife
	Scissors
	Wire cutter

Table 6.1: Table of all the materials and tools needed to make a stretch sensor

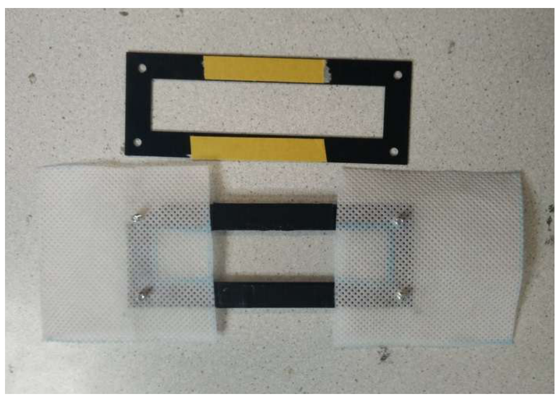
6.1.1 Preparation of the mould



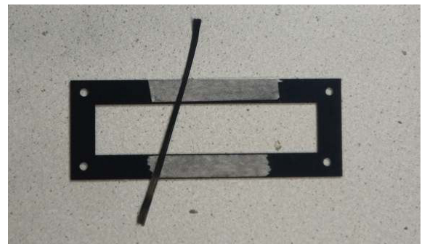
The mould is composed out of three layers, a base plate with 4mm thickness and two moulding parts being 1.3mm thick each with alignment screws. The final moulding area of 90mm x 20mm is cut out of the moulding parts with 10mm spacing on either side.
If the mould is reused, start by removing any tape residue or old silicone from the parts.



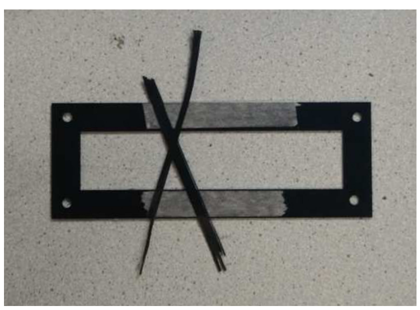
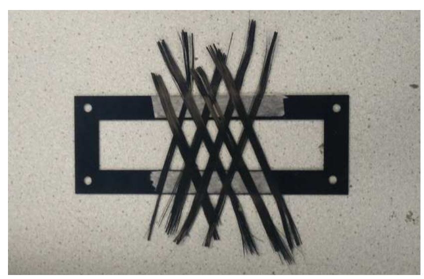
Align the pieces of fabric in such a way that they reach about 1.5cm into the moulding area and make small cuts where the alignment screws go in order to allow them to stick through the fabric.
Use the thick tape to raise the areas of the mould which are not covered by the fabric to prevent the silicone from oozing out there. Raise it to approximately match the the thickness of the fabric. Make sure it is not reaching over the edges of the mould, especially in the moulding area. Cut with a knife if necessary.



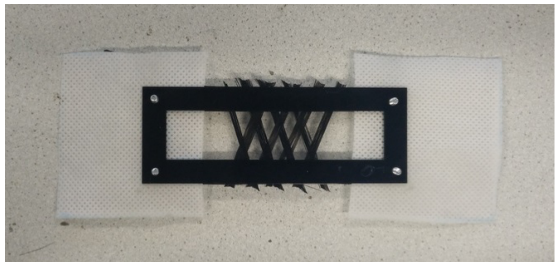
Add double-sided tape to the other piece of the mould around the area which is not going to be covered by fabric. The pattern of carbon fibres is going to be arranged on there and the tape prevents it from moving too much.

!Disclaimer: For working with carbon fibres, gloves are recommended as safety gear!
Now use your hands to make bundles of carbon fibre which are a few millimeters wide when spread flat. Cut the bundle of and arrange it on the double-sided tape with an angle of between 60 and 70 degrees. There should be some space between the fabric of the other part an the first bundle in which the leads will be put later on. Make sure it is pulled straight and does not sag so that they end up being in the middle later on.

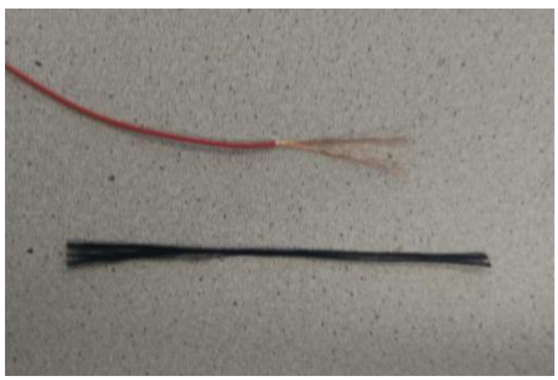
 

Add the next bundle in the same way only mirrored. The angle should still be between 60 and 70 degrees and the intersection with the previous bundle should be well within the moulding area. After that, continue with bundles in alternating direction up until you reach the opposing side of the fabric, but make sure to leave some space for the leads again. The end result should look similar to the second picture.

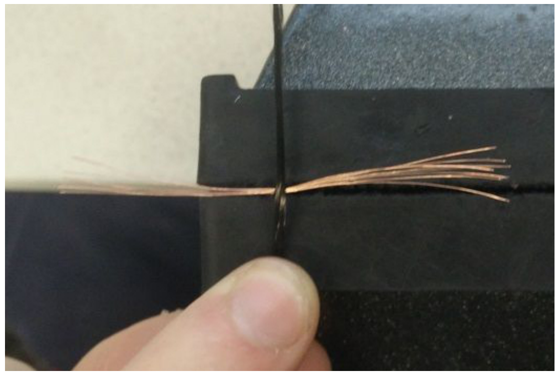


Now cut off the the ends of the carbon fibres bundles outside of the mould with a pair of sharp scissors. If assembled with the other part of the mould, it should resemble the picture above. Note the spaces left on both sides between fabric and the pattern for the leads. After this, the preparation of the mould is finished. Set aside till later.

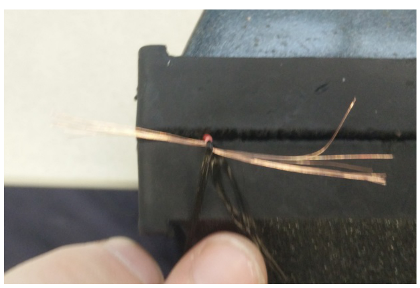
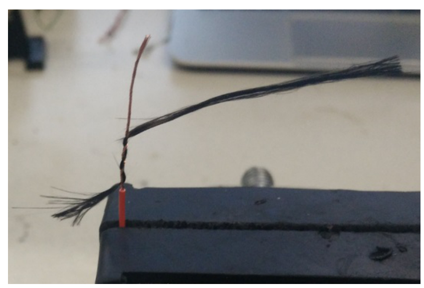
6.1.2 Making of the leads



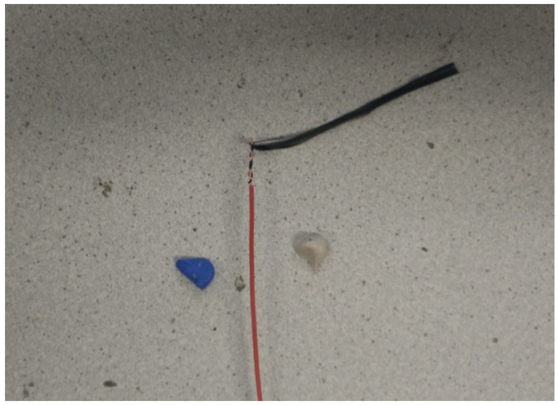
Each lead is made from a piece of flex core wire and a bundle of carbon fibres. These will be intertwined by twisting the into one another. The wire should be about 3cm stripped and the bundle should be three to four times that length. You need two leads per sensor, so this needs to be done twice.



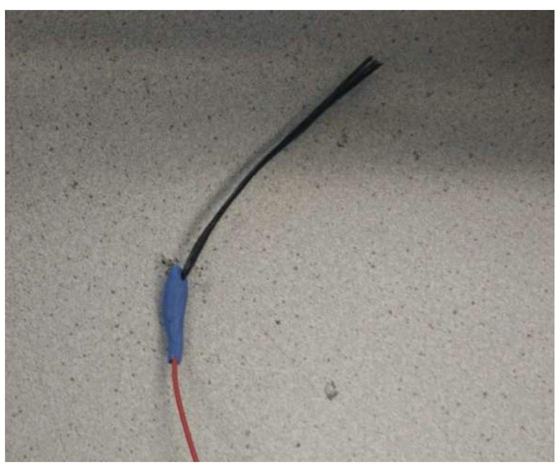
Intertwining them works best with a small bench vice. Put the wire in up to the part where the isolation ends and split it into two parts with about the same amount of cores. Arrange the fibre bundle perpendicular to that in the centre of the wire with one side only being small and the majority on the other. Hold both ends of the fibre bundle and then twist the two set of cores for one full rotation

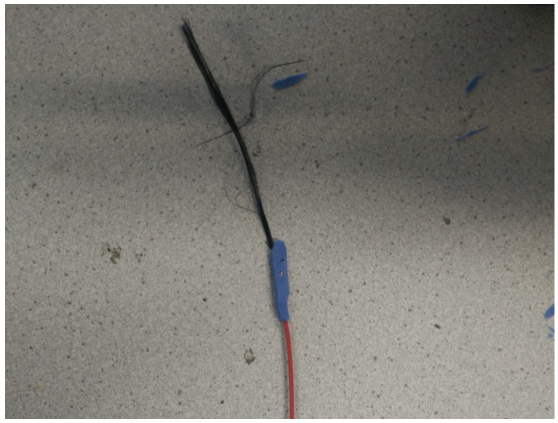
After the first round of twisting, take the long side of the fibre bundle and hold it down on the opposite side. Then twist the two set of cores again by two half rotations. Be careful to turn in the same direction as done before to not loosen up the previous windings. Repeat this two additional times until you have an overall amount of four crossings of the fibres with the wire. Then twist the end of wire while keeping the fibre bundle out of it. The result should be comparable to the second picture. It is important to keep the size of the interwoven part well below the width of the moulding area, skip the last crossing if necessary.



Cut off the short end of the fibre bundle as well as the top part of the wire so that there is still a bit of space between the last crossing and the tip of the wire. In order to give the lead more stability inside the silicone, the intertwined part is covered with a small amount of modelling silicone. Prepare the two components according to the instructions provided along with them.

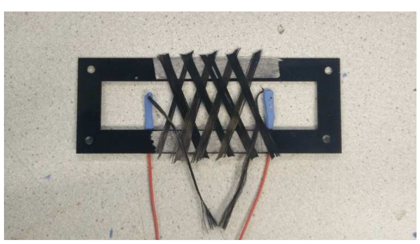


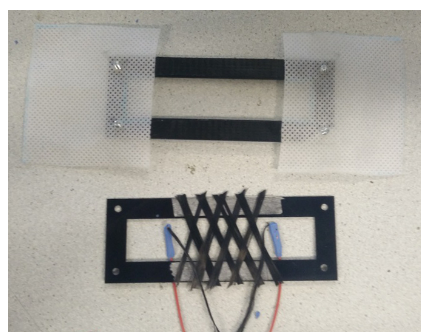
Cover the intertwined part with the silicone. It should not be very loose around the silicone while the size does not really matter since it can be carved with a knife later on. The modelling silicone cures very fast, so do not wait too long.



After the modelling silicone is cured, which takes about 5 minutes, carve away unnecessary material but be careful not to cut the fibre bundle. Especially the thickness should be thinner than the height of the moulding area. It is not really a problem if the wire shows lightly, but again be careful not to cut the intertwined fibres. This concludes the process of the lead.

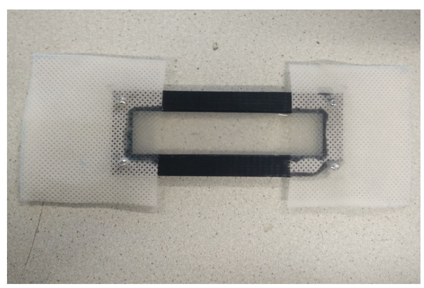
6.1.3 Casting the silicone



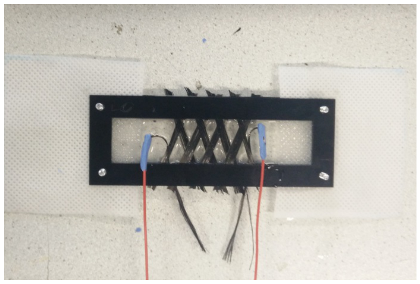
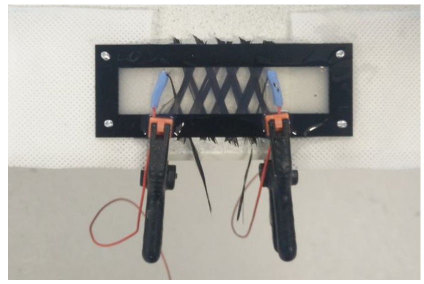


Add the two leads to the part with the already prepared bundle pattern. Make sure the carbon fibres of the leads are on the same side as the pattern while the wires are running on the opposite side. The exact location of either does not need to be fixed yet since this can still be changed later on.

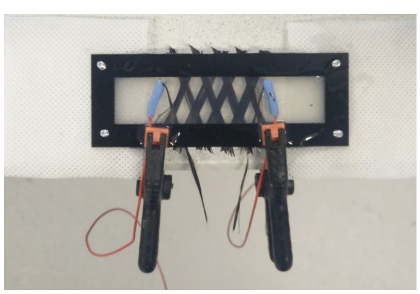
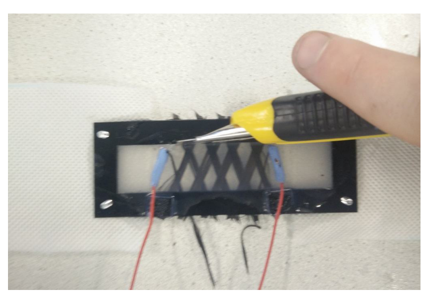
Now mix your liquid silicone together. Based on which brand you are using, you might have to have weight ratios of 1:1 or 10:1. Look at the instructions provided with the materials. Add both components to the mixing containment while metering them with a scale. For the moulding size provided above about 10g of silicone are enough if oozing out is kept at a minimum. Mix them together really good with the spatula.



Remove the fabric if necessary and pour a part of the silicone in the lower part of the mould. The overall level should not rise over this part of the mould. Use the spatula to spread the silicone across the whole mould. A quick blowing over the uncured silicone can help to eliminate air bubbles trapped in the silicone. Then add the fabric to both of the sides again. Make sure to not trap any air below it and lift it up again if necessary. Pushing the fabric gently into the silicone with the spatula helps to get it soaked completely.

The next few steps are crucial. Now add the other half of the mould on top of the filled one. The carbon pattern should face down into the silicone while the wires run out on top. Next, gently go with the spatula over the fibre pattern to remove any air bubbles possible trapped below. Then you can pour more silicone into the mould until the second half is also filled. After that align the leads and their fibre bundles. There should be an intersection between the last part of the pattern and the bundle of the lead at approximately the same level as the pattern intersects which can be adjusted by pulling on the bundle. The part covered in modelling silicone should be in the designated space and as perpendicular to the sensing direction as possible. It also needs to be covered by silicone completely which can be helped by pushing the wire down with the spatula as well. If a lead is well aligned, fixate it with a clamp to hold in place. If both leads are well aligned the sensor needs to cure. Normally, this takes about half a day, but can be sped up to half an hour with the help of a heat gun. At first the silicone will still be very liquid, so it should not blow hard and kept in quick motion at all times. If the silicone got firmer, the airflow can be increased. Also the temperature should not be put too high, in order to avoid damaging the fabric or the acrylic mould. A good rule of thumb was to check with the hand. If the hand could kept 5cm from the nozzle for more than 10 seconds, there was no damage caused by temperature if the hot air gun was kept moving.

After the silicone is not sticky upon touching, continue with the hot air gun for a few more minutes to ensure also the centre is completely cured. Then use a knife to cut along the moulding area. Cut through the patterns carbon fibres, but not through the fabric or the lead wires. Afterwards the sensor can be taken out of the mould. Be careful not to break the thin acrylic when pulling it apart. The sensor is now ready to use.

6.2 Manual pressure sensor

This is the manual for making one of the pressure sensor. An image of all the materials and all non-basic tools can be found in figure 6.1. A list with everything is below in table 6.3.

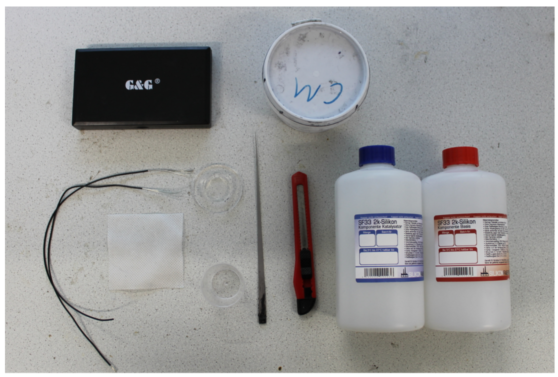
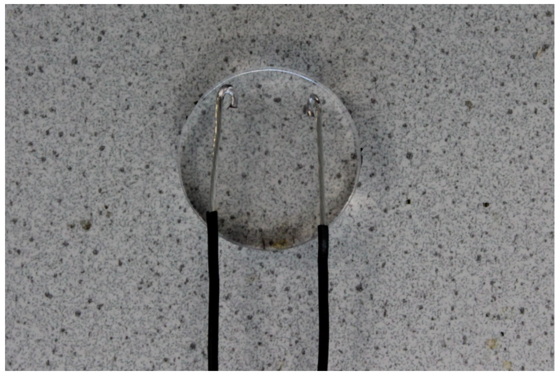


Figure 6.1: Picture of the materials and tools needed for making the pressure sensor

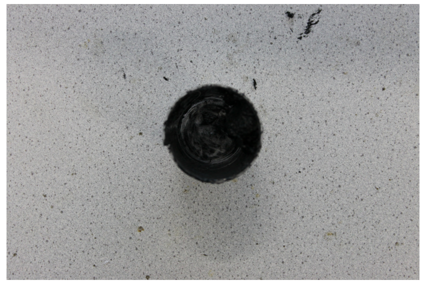
Materials	**Tools**
ShA33 silicone	Acrylic base plate & top disc
Carbon powder	Soldering Iron
Solder	Micro scale
Flex-core wire	Mixing containment
perforated non-woven fabric	Mixing spatula
	Wire cutter
	Knife
	Scissors

Table 6.2: Table of all the materials and tools needed to make a pressure sensor



First prepare the electrodes. Take two pieces of flex-core wire and strip about 3cm on one side and twist it. Now take the acrylic disk, which is going to be the shape of the sensor, and place the wires about where they are going to end up, about 1cm to 1.5cm apart. Bend U-turns into the wire so that the insulation as well as the turn are still on the disk. Now tin these hooks with some solder and the soldering iron to fix them. Then cut off the wire so that only small hooks are left.

Now weigh both the silicone components in the mixing containment with the micro scale. About 1.5g of silicone is more than enough for one sensor. Mix thoroughly with the mixing spatula. Also weigh out the carbon powder. It should be half of the weight of the silicone in order to be conductive.



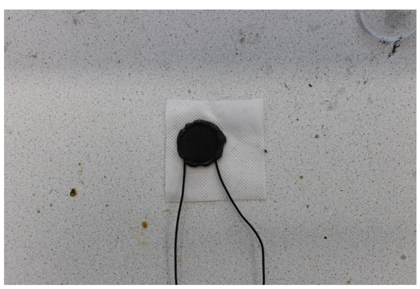
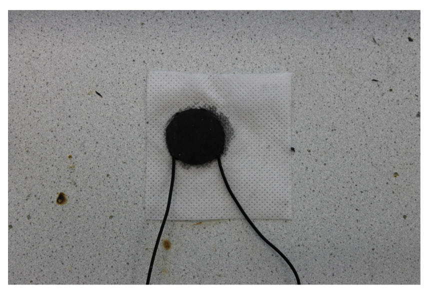
Mix both, the carbon powder and the silicone, together. At first, it looks like a mess, but keep on mixing until all the carbon is incorporated into the silicone and you get an uniform consistency.

Figure 6.2

Put the fabric cut to shape onto the base plate of the mould. Put about three quarters of the mixture onto the centre of the fabric. Spread it a bit and try to approximate the shape of the acrylic disk with it. Then put the leads on top and push them a bit into the mixture.

Use the remaining quarter of the mixture to put on top of the leads and make sure they are covered completely in the mixture. Then put the acrylic disc on top of the mixture and press down. This makes the sensor really thin by letting all the excess material overflow on the sides. Since the mixture is quite thick in its consistency, it can be pushed quite hard to get it as thin as possible.

Now cure the mixture with the help of a heat gun. Be careful to not set the temperature so high that it melts the fabric. A rule of thumb is if the hand can be kept in the direct air flow for more than 10 second a without it being unbearable hot it is fine. Even if the overflown edges already feel hard, still keep going a bit to make sure the centre is also cured. The whole curing time normally takes about 15-20min with the heat gun.

After it is cured, remove the acrylic disk. Use a knife to cut away all the overflown mixture. This can either be done by only cutting away in height or by cutting it in shape. If you want to have it in a nice shape, make sure be careful to not cut the underlying fabric. After that, the sensor is ready to use. Use a multi-meter to determine the zero-level of the resistance to choose an appropriate fixed resistor for the voltage divider.

6.3 Manual electrode ring

This is the manual for making one of the electrode rings.

6.3.1 Materials & tools

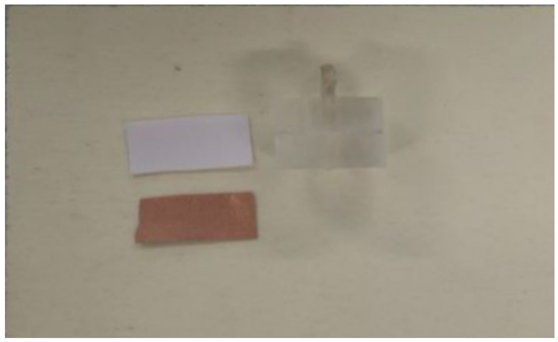
An image of all the materials and all non-basic tools can be found in figure 6.3. A list with everything is below in table 6.3.

Figure 6.3: Picture of the materials needed for making an electrode ring

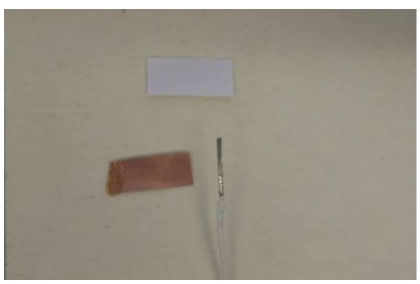
Materials	Tools
ShA33 silicone	Mould
Very fine copper mesh	Soldering Iron
Iron-on patch fabric	Clothing iron
Thread	Mixing containment
Solder	Mixing spatula
Solder flux	Needle
Flex-core wire	Knife
	Wire-cutter
	Scissors
	Micro scale

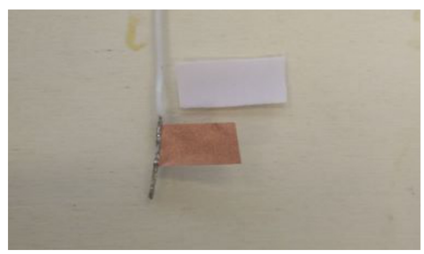
Table 6.3: Table of all the materials and tools needed to make an electrode ring

6.3.2 Preparation of the electrode

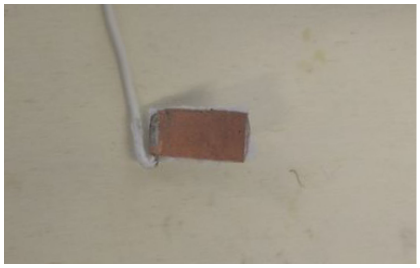


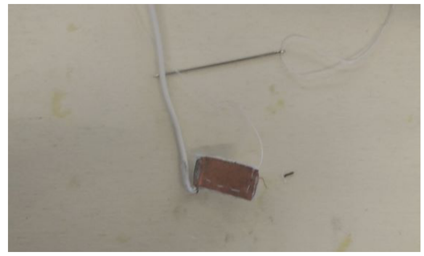
Cut out pieces of mesh and patch fabric. The height of the patch should be a bit smaller that the height of the centre piece. About 1cm x 2.2cm will do fine. The mesh needs to be cut to match that size.



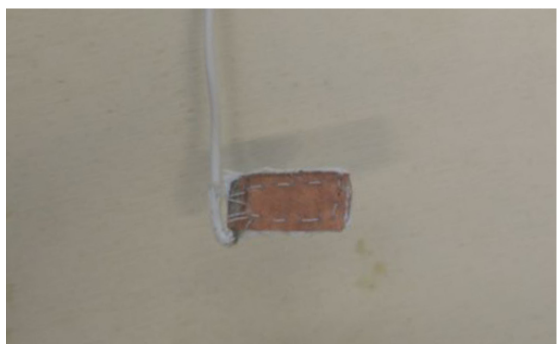


Strip about 2cm of the flex-core wire and tin it with the solder. Add one stripe of solder flux on one short side of the mesh. Then solder the two together close the where the wires insulation ends. Be careful with the soldering iron and the copper mesh, it melts when it gets too hot. Turn the temperature of the soldering iron down if necessary.



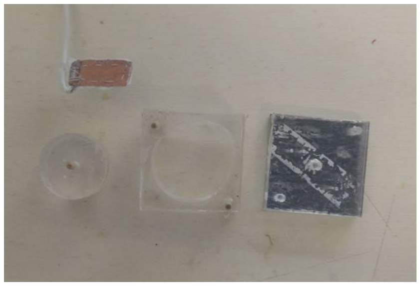
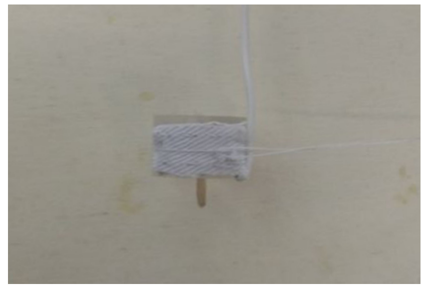


Next step is to bond the mesh and the patch fabric together. Ironing the mesh on the patch helps to get an initial connection. To prevent the wire from breaking later on bend the wire so that it makes a sharp U-turn after the part soldered to the mesh. The mesh does, however, not bond well with the patch. Sewing along the outline of the patch helps to insure they are well connected.

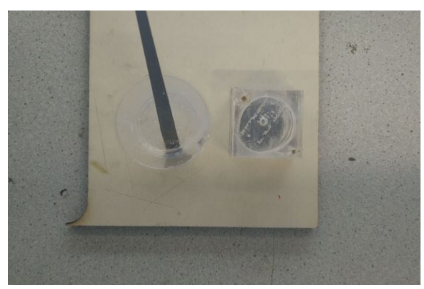


Now you are done with the electrode preparation.

6.3.3 Moulding in silicone

Make sure the moulds are clean and silicone residue from previous castings is removed. Continue by tying the electrode to the centre piece of the mould with the yarn. It is important that this is done tightly because if not the edges of the electrode might reach through the silicone which results in tears. Cut of the remaining yarn close to the nod and push the centring pin so that it sticks out at the opposite site of the cable. Put aside until it needs to be put into the silicone.

Now put the exterior part of the casting area on top of the base plate to prepare it for the casting. Combine the silicone components with the help of the spatula in the mixing containment according to the instructions provided by the silicone and mix them well. About 4g of silicone have been enough for casting one ring. Try to avoid adding to many big air bubbles into the silicone when mixing and pop them if possible with a pointy object, like a needle or the thin end of the spatula used here.

Pour the silicone mixture into the prepared casting area, it should be about half full. Take the centre piece and align it so that the wire is in the location where the silicone is a bit thicker. This provides additional support to the ring. Try to pop any bigger air bubbles again after it is poured in the mould.

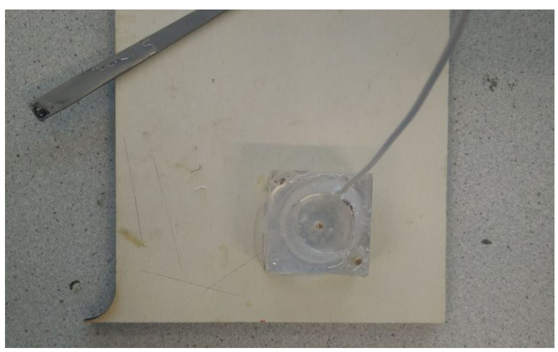
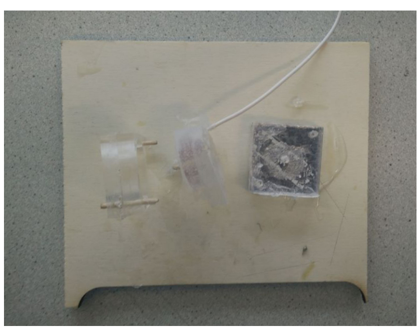


Figure 6.4

Now push the centre piece into the silicone filled moulding area. The centring pin should allow you to keep it in the middle, if it has some play to it make sure to approximately centred by pushing it slightly.

Now it is time to cure the silicone. This can be sped up by using a a hot air gun. Make sure to move it plenty in the beginning to prevent the silicone from being blown out of ring itself. When the top stops to move, the movement of the hot air gun can also be reduced. The overall time for the supported curing is about 25min. Be careful not to take it out too early, the top might be set already but also the middle part of the silicone needs to be done to do so. A good indicator are the small air bubbles in the middle of the silicone; If they are not moving any more when pressure is applied to the top of the mould, give it a few more minutes to make sure it is set completely.

Now take the sensor out of the mould. Remove the base plate first, then push the centre piece out which will take the ring with it. Now carefully push the centre piece out, use knife to score overflown silicone to ease the process if necessary. Then you can clean the ring up with the knife by cutting back all unwanted silicone parts. One last essential step is the removal of the yarn used to attach the electrode to the centre piece. Use the knife to carefully cut into the silicone, where you see the yarn, and then pull it out. Then it can be cut off. Make sure all the yarn is removed where only the silicone is left since it prohibits it from stretching. After that the electrode is done.

Chapter 7

Evaluation

In this chapter, the outcome of this project is evaluated. The results are divided into two main parts: the manuals for the sensor production as well as the resulting sensors from them. Both are tested with the list of requirements provided in section 4.4. First, the functional requirements for the resulting sensors are tested. These can be evaluated by looking at the sensor's output in special tests. To evaluate the non-functional requirements, three user tests have been done, two of which focused on sensor production and one on the sensor's application. All of the test participants have been interviewed afterwards with questions aimed evaluating the non-functional requirements. Transcriptions of the interviews can be found in appendix C while a discussion of the results for each non-functional requirement can be found in this chapter in section 7.2. To show that the sensors can be applied in the context of wearable technology, three application prototypes were done. These can ba found in section 7.3. Lastly, a summarizing conclusion about how well the developments fit the requirements is done.

7.1 Testing of functional requirements

In order to test the functional requirements, tests have been performed with the sensors. The electrode ring is not strictly a sensor, it picks up either the skin resistance or the heart beat from the body. Therefore, it was only evaluated in respect to its interference. Both the stretch and the pressure sensor have additionally been tested for the linearity of their transfer function as well as the repeatability of measurements.

7.1.1 Low interference

A good sensor has a low intereference, or a small impact from other influences than the measurand. This is especially crucial for the electrode ring, since it picks up properties of the body and this has to work well to be useful.

The stretch sensor was influenced by pressure onto the fibre pattern. This, however, cannot be avoided since it relies on changing connectivity between the fibres to measure stretch. When pressure is applied the overlapping fibres get also pushed closer together and the overall resistance changes. But the impact of the pressure was not influencing the signal too much.
The pressure sensor is actually a strain sensor since it relies on its deformation for measuring. Therefore, it is also susceptible to other strains which are stretch and flex. But the problem of the stretch is not applicable if it is put on a non-stretchable fabric. This does not allow the sensor to stretch and eliminates this source for interference. The influence of flexing is, however, very significant. The resistance of the sensor dropped to about half its original value when it was flexed far. This makes it a problem for calibrating it to output a weight, since it could also be flexed.

The inference for the electrode ring is crucial since it only picks up the properties from the body and requires a constant good connection to do so. It has to be noted that the rings have been made to fit the researcher well and the data has been captured with these ones so the tight fit is already guaranteed. The measurement set-up were the two rings put on the index and middle finger and interfaced to the arduino via a voltage divider with a fixed resistor of 680kOhm.
One of the most crucial points when interfacing the ring with the skin was the position of the copper mesh in respect to the finger. The connection between the finger and the mesh was better when turned so that it is located on the inside of the finger. If it was turned around, connecting to the top part, the connection was worse. This can be seen in the left graph of figure 7.1. When it is turned down the value is lower which means the connection is better while the signal is less stable when turned up. This means that the rings have to be tested for a good connection before they can be put to use in a project which limits its possibilities for the being included in an end-user product.
Another point for interference are motion artefacts, which are occurring in this design when the finger is moved. Ideally, the output should stay smooth even when the finger is moved a lot. In the graphs, it can be seen that the impact of the motion is also largely dependent on the right positioning of the mesh. The peaks are way more prominent in the suboptimal position than in the other one. The ripples are still there in the ideal positioning, so even then it is not a perfect mean to pick up skin resistance.

One way to improve on both aspects is to add conductive gel under the ring before measuring, which can be seen in the right graph in figure 7.1. The ring was placed in the suboptimal position for that measurement and from second 0 up to 25 seconds, the fingers have been moved or the ring has been moved. But it can be seen in the graph that the connection is good and the interference resulting from the motion it is minimal. With the gel, a lower resistor might would even be better to have a bigger output range.
Overall, the ring needs to meet certain preconditions for producing useful data: it needs to fit tightly in the first place in order to have chance of connecting

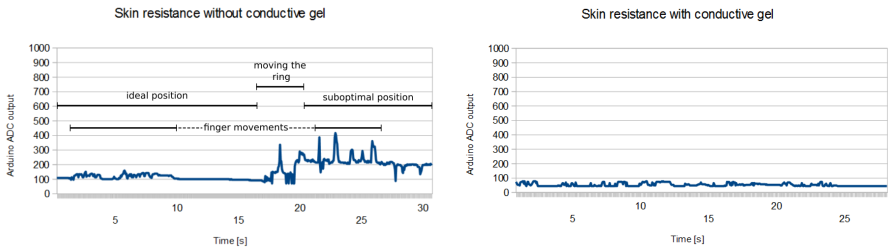


Figure 7.1: Graphs of the skin resistance captured with two electrode rings. The left one is without conductive gel and in two different positions, the right one is with conductive gel

reliably. It also needs to be in the right position on the finger to connect well, only then is the influence of motion artefacts minimized. The second point, however, is not important when conductive gel is used with the ring. Still, the end-user cannot be expected to always arrange the ring in the right way or apply the gel, under the precondition that the ring fits tightly already. This limits it applicability within products.

7.1.2 Linear response

The pressure sensor and the stretch sensor have were put in tests to evaluate their behaviour. A linear response would be desirable in both cases since it allows for an easier calibration of the sensor. Other behaviours require a more complex functions to achieve the sensor calibration.
The set-up for the stretch sensor's evaluation was done by clamping one end to the edge of a table with the other end hanging floating in the air. The weights were attached to the loose end which stretched the sensor. The data used for the graphs was obtained by interfacing the stretch sensor with a voltage divider with a fixed resistor of 1kOhm to an arduino uno.
It can already be seen from the raw data in figure 7.2 that the sensor does not have linear behaviour. Even though the weight addition was done in constant increments of 100g, the drop between the different levels is less and less. This becomes even more obvious when a look is taken at the scattered plot. For the arduino output value, the average of the plateau values for each of the weights was taken. The best approximation was achieved by using a power function with an $R^2 = 0.98$. This shows that the stretch sensor does not have a linear response.
One thing which can also be observed in the raw data is that the output of the sensor was not settling when a weight is attached. The value was constantly shifting down over time, more prominently when the weight is small. This is a problem when the desired parameter to keep track of is not changing often. This is, however, less of a problem for constantly changing parameters, like the circumference of the chest when breathing for example. The pressure sensor was

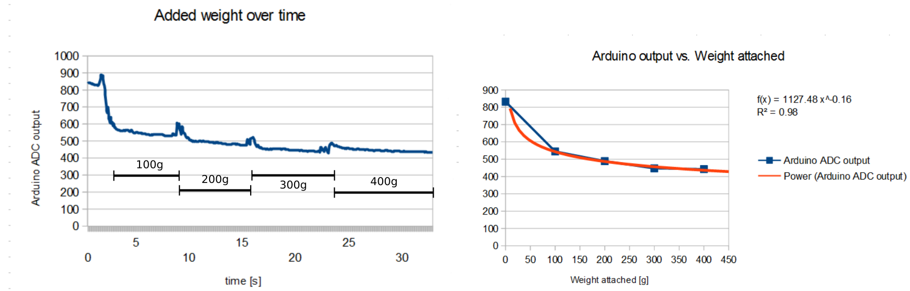


Figure 7.2: Graph of the response of the pressure sensor to incrementally increasing weight and the scattered plot of weight vs. averaged output with a power trend line

evaluated in a similar way. Both the measurement and the resulting scattered plot with the averaged output versus the weight can be found in figure 7.3. The sensor was connected to an arduino with a voltage divider and a fixed resistor of 125Ohm. The weights were stacked on top of the sensor laying on the table. The resulting scatter plot revealed a close to linear relationship between the weight and the output with an R^2 value of 0.88. This leads to the conclusion that the output of the pressure sensor can be considered linear.

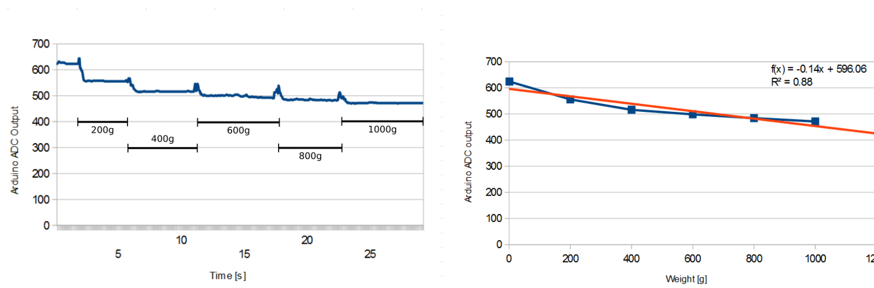


Figure 7.3: Graph of the response of the pressure sensor to incrementally increasing weight and the scattered plot of weight vs. averaged output with a linear trend line

7.1.3 Repeatability

In order to test for the repeatability of the sensor readings, three different weights were attached to the stretch sensor and released again. The results of this test can be seen in figure 7.4. The data shows that the levels were approximately the same for the weight. There are a few outliers, the first 100g weight drops a bit further than the remaining two and a trend of a sinking level across all the iterations for 200g. The first might be due to a set-up difference which happened with the first lifting. The always reducing value for the 200g has to assumed to originate from the sensor. This leads to the conclusion that the repeatability of the sensor readings is limited.

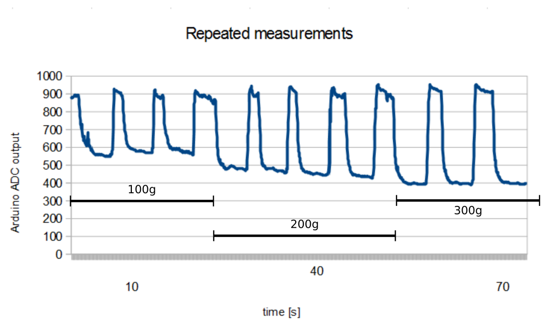


Figure 7.4: Repeated measurement of 100g, 200g and 300g attached to the stretch sensor

A similar procedure was followed with the pressure sensor. Different weights with 200g, 400g and 600g were put on the sensor and lifted again. This was done four times for each of the specific weights. The graph of the resulting data can be found in figure 7.5. It is obvious that there is a noticeable difference in output when the same weight is applied. The last drop of the 200g weight is on the same level as the last drop with the 400g weight. One explanation for the variations could be a shift of the weight which was not totally controlled for in the testing set up. If the centre of gravity moved in respect to the sensor, the output might be influenced and settle on the different levels.
But what can also be observed is that the level of the base level of the sensor is shifting in between the times when no weight is on the sensor. This is also a big problem since it makes it impossible to determine an initial zero level of the sensor.

Overall, the tests of the repeatability for both the stretch and the pressure sensor show that they are poor in that regard. Both have varying outputs with the same input which makes it very hard to make a reliable calibration resulting in SI units, such as stretch in centimetres or weight in grams. Nevertheless, the sensors can still be used for applications where no exact values are necessary. Examples for such applications with the developed sensors are described in section 7.3.

7.2 Testing of non-functional requirements

In order to evaluate if the non-functional requirements are met user testing sessions have been held. Since the focus of the project is split onto two main

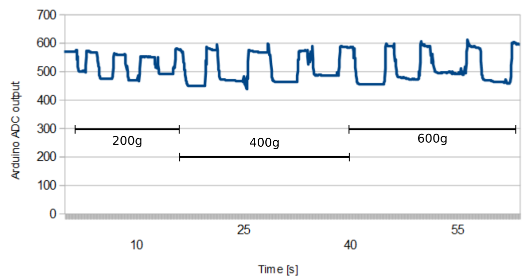


Figure 7.5: Repeated measurement of 200g, 400g and 600g put on top of the pressure sensor

parts, the manuals to make the sensors and the sensors itself, two different kind of testing session have been used. In the one kind, the focus was put on following the manuals and making the sensors. This was done with Emiel Harmsen and Marina Toeters again which were already introduced in section 4.3 for the initial interviews. One user testing session of the other type has been held, focusing on applying the developments in a small prototype. This has been done together with Judith Weda, a human-computer interaction student at the university of Twente. The resulting prototype can be found in section 7.3.1. After all the testing sessions, the participants have been interviewed to gather view on how well the non-functional requirements are met. The transcriptions of these interviews can be found in appendix C and a discussion of the sections below arranged by the origin of the individual requirements.

7.2.1 Tool box

One of the origins of non-functional requirements is the designer's tool box. A discussion of the findings for each individual tool box requirement is done in the section below. A final discussion of all the requirements can be found at the end of the chapter in section 7.4.

Affordable: There are two central factors of the affordability: the price and the time. Therefore, the participants of the user tests have been asked whether they see either of it as justified.Regarding the time needed for the stretch sensor, the participants answered that one hour to one and a half hour would be acceptable for them. There was, however, a huge difference in time needed to make it during the manual testing. It took Marina Toeters about three hours to make the stretch sensor, while Emiel Harmsen made it in 1 hour 15 minutes, only a bit longer than it took the researcher. So it is possible to make the stretch sensor in the time they see as justifiable, but one has to work concentrated at a good pace. It also should be mentioned that there is a learning curve. It might take one longer the first time doing it, but the next time it will be faster. This

makes the one hour goal a realistic one in the long run. The 30 minutes it takes to make the pressure sensor and 60 minutes for the electrode ring where seen as justified by all the participants.
The material prices were perceived as good by all the participants. Each sensor has an initial material cost below 35€ and the cost per sensor being a few euros is very cheap.
To wrap up, the material costs of all the sensors are seen as very good. They time it takes for making a pressure sensor or an electrode ring were perceived as acceptable. For the stretch sensor, the maximum of acceptable time of 1.5 hours can be achieved, but there is a possibility that it takes longer the first few times it is attempted.

Accessible: The materials are accessible, but most of them need to be bought at special retailers which most likely cannot be found locally. This is, however, not a problem nowadays since the materials can simply be ordered in online shops.
The two component platinum cured silicone with different hardness levels can probably only be found in shops specialized on it, but online they are easy to find. The carbon fibre and carbon powder are used for model building, like for radio-controlled planes. Shops for that can also found online. The only remaining special material is the copper mesh, which can be purchased in shops specializing on selling materials for shielding against electro-magnetic waves. All the other necessary materials, like yarn or solder, should not be hard to find.
Summing it up, the special materials, in particular the carbon,the silicone and copper mesh, need to be purchased online in shops specialized in certain fields. The remaining materials are rather standard and should not be hard to find.

Capable: The stretch sensor made by Marina Toeters did not work, but the pressure sensor did work well. Emiel, however, got a working and well looking stretch sensor as well as pressure sensor. Therefore, it is shown that members of the target group can potentially make the sensors, but they need to follow the manual closely. If only one of the intermediate steps is not executed well, it can eventually ruin the whole sensor.
A further point is the ease of interfacing them. Both, the stretch sensor and the pressure one, rely on a resistive change as a measuring principle. By relying on that, they can be interfaced easily with a voltage divider. That only requires a basic understanding of electronics and only one resistor as additional hardware. For the electrode ring, it is dependent on what you aim on reading. Skin resistance can also be done with a simple voltage divider, while an EKG, as a further possibility, requires more signal conditioning.

Documented: The documentation was evaluated by asking the user testing participants if they could follow the manuals on their own without help. Both confirmed that they thought they were able to do so. But Marina

Toeters suggested to use a video rather than text based manual, because one could see the process better and it could also be used to work alongside the video.
The documentation works, but a video might work better as a medium for the manuals.

Reliable: One problem with self made sensors are always slight inconsistencies from one batch to the other. This is for example the case for the resting resistance. Each of the sensors should be checked with a multimeter in order to choose the correct value for the resistor in the voltage divider. These slight inconsistencies also require a separate sensor calibration for each of the sensors, when multiple ones are to be used in one project. This takes time and is not ideal, but sensors perfectly the same are only achievable when manufactured industrially.
Another point to mention here is that the electrode ring is not completely reliably either. When it is put on the finger, it first needs to be checked whether it results in proper readings. It also suffers from motion artefacts induced by varying contact of the conductive area with the skin. Both of these problems can be solved by using a conductive gel but this limits the applicability in consumer products. For that, it would by simply putting it on the finger.
To sum it up, the stretch and pressure sensors suffer from inconsistencies introduced during their production. This limits their reliability to some extend. The electrode ring's reliability is even more limited because it suffers from motion artefacts. It also needs to be checked in the beginning of each use to see whether it makes a proper connection with the wearer's skin.

7.2.2 Wearability

The wearability of the individual developments was assessed by asking the participants to assign a number between 1 and 7 to three out of the four identified requirements. These were aesthetically pleasing, sensually pleasing and comfortable. If the score was low for one point, they were asked where they would potentially see it and would need to change to make that happen. Below, the average numbers for the respective categories for each sensor can be found, an average for the potential scores and comments. The last requirement the participants were not asked to comment on is the durability of the sensors, since they cannot rate it from making them once or using them once. The durability is discussed at the end of this section.

Wearability of the stretch sensor

The stretch sensor received positive remarks in all the categories. The look was rated as being very good. One of the remarks received by all participants was that they would like to avoid the blue modelling silicone for it to look even

better. This is ,however, needed to keep the wire in the soft silicone. This is one point to be taken for future improvements of the stretch sensor.
The sensor rating in comfort and sensually pleasing was also very high. About the negative remark regarding the stickiness of the silicone, there is nothing which can be done about that. That is one of the inherent properties of the silicone, which cannot be changed. The same point is valid for the clarity of the silicone. In regards to the comment that sweating under the sensor could be problematic, there is not a lot which can be done from the sensor's perspective. One way to avoid that could be to not have the sensor attached directly on the skin, but rather on a layer of fabric. This is, however, a choice that is up to the designers using the sensor.

aesthetically pleasing	**6** The fibre pattern in the silicone looks good The blue modelling silicone looks ugly It would look even better with the silicone staying perfectly clear
sensually pleasing	**5** has the sticky fell of silicone sweating under the sensor could be problematic
comfortable	**5** by being so soft it should be comfortable to wear

Table 7.1: Average of the available scores assigned to each category of the stretch sensor and additional comments

Wearability of the pressure sensor

For the pressure sensor, the scores also indicating a good wearability of the sensor. The potential scores show that there is still a lot of room for improvements. The comments are showing some points which are workable, but also some which are not. The bleeding of the silicone through the fabric for example, which was seen as negative for the look of the sensor. This is, however, necessary for the silicone to bond well to the fabric. If the bleeding does not happen, the sensor can simply be pulled of the fabric. The look as well as the comfort of the sensor could be increased by changing the moulding principle. The method letting the silicone overflow to the sides results in small bump around the edges as well as not clearly defined edges. This method allowed for a very thin result, but could be adjusted in future developments to overcome the issues mentioned.

aesthetically pleasing	**4**, with a potential score of **5.66** the bleeding of the silicone through the fabric does not look good using a mould for a cleaner shape would be beneficial would look better with only one wire running into it
sensually pleasing	**4.6** on the fabric side, **4.3** on the silicone side feels like it is breaking apart if flexed too far
comfortable	**3.75**, with a potential score of **4.75** the slightly higher edges around it could be a problem

Table 7.2: Average of the available scores assigned to each category of the pressure sensor and additional comments

Wearability of the electrode ring

The electrode ring is also perceived as wearable as well, but still lacking the aesthetics. The two layers of the mould were not glued together perfectly. The small resulting gap was transferred to all the iterations as a small seam going around the middle. This contributes to perception of the rings not being completely clean. Both the comfort and the sensually pleasing requirements were rated as very high with 6 out of 7. The concern that the ring could cut off the blood flow is a issue that could possibly happen but this is not intended. The ring should be tight to ensure a good connection between the electrode and the wearer's skin but it should not be so tight that it cuts of blood supply to the finger. During trial with different people, it could already be seen that the ring is not the one-size-fits-all type. Designers should offer different sizes of rings or adjust it to their necessary size. This ensures a reliable connection by the ring being too loose at the same time as preventing blood flow problems caused by the ring being too tight.

aesthetically pleasing	**4**, with a potential score of **5** it does not look completely clean with the seam in the middle the wire is to thick to look good
sensually pleasing	**6**
comfortable	**6** if the ring should be worn tight, blood flow to the finger would be a concern it got a bit sweaty under the ring

Table 7.3: Average of the available scores assigned to each category of the electrode and additional comments

Durability

The durability of the developments has not been tested because they have not been put into a long-term use projects or prototypes. This only allows for a speculation of their potential durability. The main material for all three developments is silicone. Silicone can withstand high temperatures and is chemically inert which prevent damage from sweat or washing detergent. Additionally, it does not rip easily and but is still flexible.
When weak points have been noticed during one of the multiple iterations, the design has been adapted to prevent them from happening. One such issue was, for example ,the wire breaking for the electrode ring, which was solved. All of these points do not guarantee the long-term durability, but they show that there it is potentially there and for the issues encountered up to now the design has been adjusted for.

7.2.3 Relevance

In order to determine, if the outcome of this project was relevant, the user testers have also been asked to comment on that point. All of the participants were positive about the relevance of the project. The main points received for the relevance were that the exploration of the combination of materials is valuable as well as the knowledge connected to the materials. Furthermore, it was stated that these sensors could be a stepping stone for further, better developments in the field and ability to customize sensors to the individual needs is an advantage over other commercially available sensors.

7.3 Sensor applications

Another point to evaluate is to check whether the sensors can actually be applied in the context of wearable technology. In order to prove that one possible application for each of the developments has been made. These three prototypes are shortly introduced below.

7.3.1 The angry dad monitor

Testing whether the electrode rings work was a bit of challenge since the they normally record physiological signals which can not be controlled, like the skin resistance or an EKG. This makes it hard to find an application for them containing an interactive element.
During an user test with Judith Weda, however, the idea for the Angry Dad Monitor was born. Inspired by the old fair's love testers, the idea came up to measure the resistance between the rings while they are split on two people. This set-up can then detect when both people have skin-to-skin contact, since only that allows for a conductive path between the two rings. This concept worked out really well and it turned out that it could do more than only detect

a binary touching or not touching. The resistance also depended on how big the touching area is. It made a difference whether it was one finger, a few fingers or the whole hand.
As a possible application for this, the Angry Dad Monitor was thought of. It would allow a dad of a teenage daughter to keep tabs on her while she could watching a movie with her boyfriend for instance. The dad could then detect how much they were touching one another and would get more and more angry the more they do so. This was translated into a graphic of a face, as it can be seen in figure 7.6, which shows the increasing anger of the dad. This could be an innovative new product idea to increase the repertoire of tools for controlling parents.

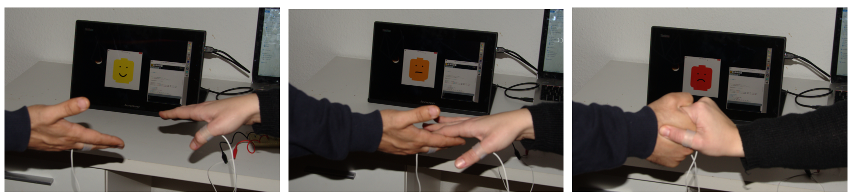


Figure 7.6: Depiction of the dad getting more and more angry the more the two people wearing the rings touch

7.3.2 Step detection

One of the points of the body where pressure is on most of the time during the day are the soles of the feet. When walking or balancing, the pressure always switches from one foot to the other. In order to track this pressure exerted on the foot, the pressure sensor was put in one shoe below the inserted of the shoe, as it can bee seen in figure 7.7. When a look is taken at the output of the sensor, to be found in the same figure, the weight distribution can clearly be recognized. When walking, the sensor reading peaks with each step. Balancing on either of the foots can also be easily recognized by different levels of the sensors reading as well as standing with both feet on the ground. The form factor of the sensor also allows it to be unnoticed, only the wires running are off putting.
With this application, the steps of the wearer could be tracked easily. If multiple sensors would be put in the shoe, it could also work similar to the Sensoria fitness sock as introduced in section 2.3.

7.3.3 Breathing detector

One physiological parameter of interest is the respiration rate as stated in section 2.2. This can for example be used in a sports tracker to keep track of your activity level or to indicate a person's stamina. One of the common ways to track this is strap a stretch sensor around the torso. Possible locations for the sensor are the chest and the around the stomach. With the increasing volume

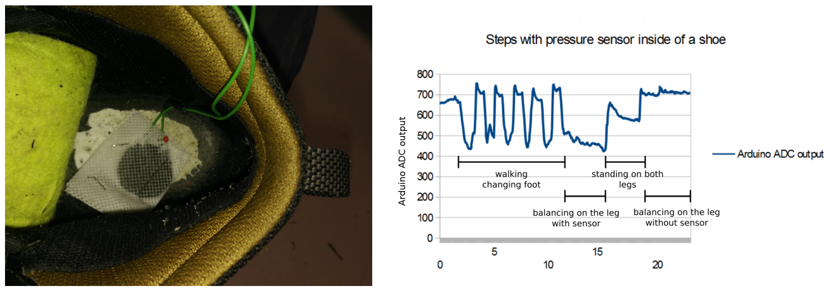


Figure 7.7: The pressure sensor placed under the inserted sole of a shoe and the resulting data recorded with an Arduino

of air in the lungs, the circumference changes with it. This change is then detectable by the stretch sensor.
To evaluate whether the sensor developed here is also suited for this purpose, it was connected to a strap and put around the stomach area. The set-up of the sensor as well as the resulting output tracked with the help of an Arduino can be found in figure 7.8. From the measured change in resistance the breathing pattern can clearly be recognized. This shows that the breathing rate detection is one application which can be achieved using the here developed stretch sensor.

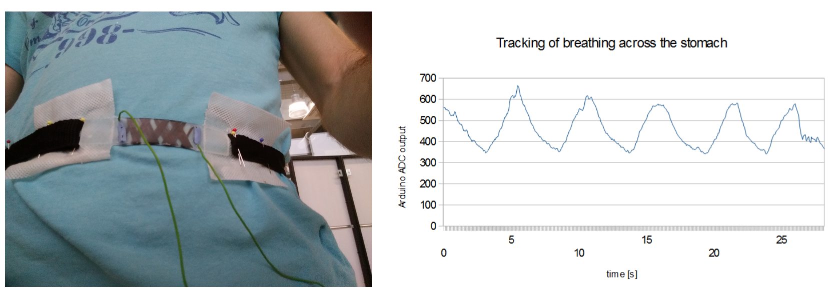


Figure 7.8: The breathing detector setup with the stretch sensor strapped across the stomach and the resulting data captured by an Arduino

7.4 Conclusion

An overview over all the requirements as well as the rating of the individual sensors in the categories can be found in table 7.4.
All the developments had a reaction to the parameter they were designed to track, so the first requirements is met for all of them. But in the qualitative sensor properties, all the developments performed poorly. The only applicable one for the electrode ring is the low interference, which is not given due to the

placement and the motion artefacts encountered. The repeatability of the measurements was poor for both the stretch and the pressure sensor. The pressure sensor suffered from severe interference from flexing, while the stretch sensor is only slightly influenced by pressure applied to it. And for the linear response, only the pressure sensor could be approximated by a linear transfer function, the stretch sensor follows a power function.
Regarding the wearability, the feedback of the participants of the user tests was mostly positive. Only the durability of the developments in a long-term application has not been tested. The pressure sensor scored in all categories well, it was seen as aesthetically pleasing, sensually pleasing and comfortable. The ring did well in the comfortable and sensually pleasing requirements while doing okay in the aesthetic aspect. The pressure sensor was perceived as doing okay in all of the categories.
For the requirements originating out of the designer's tool box, all of the developments are seen as accessible since their materials can be found in specialized online shops. In the score for the affordability, the price as well as the time needed are considered. The price is very low for all the sensors, but the time it takes for making the stretch sensor brings its score down. The pressure sensor does not require a lot of time and the ring is also still reasonable, so they rank better in this category. The documentation was perceived as okay by the target group, they thought they could follow it on their own. The reliability of all the sensors is limited as already elaborated in the functional requirements. Lastly, when asked about the relevance, the participants were positive about it.
To wrap it up, the developments made throughout this project are not perfect sensors. But all of them were considered to be at least wearable by members of the target group. Furthermore, they are able to make them by themselves which is in particular useful if money is more essential than time.

Nr.	**Requirement**	**MOSCOW category**	**Stretch**	**Pressure**	**Electrode ring**
F1	output in response to a specified measurand	M	**y**	**y**	**y**
F2	high repeatability	M	**- -**	**- -**	n.a.
F3	low inference	S	**0**	**-**	**-**
F4	linear response	C	**-**	+	n.a.
NF1	comfortable	S	+	**0**	+
NF2	durable	S		**0**	
NF3	sensually pleasing	S	+	**0**	+
NF4	aesthetically pleasing	C	+	**0**	**0**
NF5	accessible	M		+	
NF6	affordable	S	**0**	++	+
NF7	documented	S		**0**	
NF8	reliable	S	**-**	**- -**	**-**
NF9	relevant to the target group	M		+	

Table 7.4: An overview over all the functional and non-functional requirements, their MoSCoW ranking and the scores for each of the developments

Chapter 8

Conclusion

The last part of the creative technology design process is dedicated to an evaluation and reflection of the work done throughout the project. To do so, the initial research question is evaluated again here: What methods or materials could be used for fabricating wearable sensors resulting in a valuable addition to the toolbox of wearable designers?

The focus of this project was put on the actual development of the addition to the tool box. An evaluation of different material combinations and production methods was already done early on at the end of the ideation chapter in section 4.6. From there on, the materials, which were chosen at the end of the ideation chapter, were tinkered with the aim sensor development. This process culminated in the manuals describing the manufacturing the final design of the three sensors. The resulting sensors are not be perfect ones, but they are still applicable in the field, as the project examples in section 7.3 show. And the manuals offer the target group to manufacture their own sensors according to their needs with a small financial commitment. So, yes the research question has been answered by developing an valuable sensor addition to the tool box of wearable designers.
For the future work, one of the things which needs to be done is to make the developed manuals accessible to the designers. For that, a maker website such as instructables.com would be the right place, since it already has a pool of manuals and people are actively looking for solutions to problems they encounter there. Another point, which came up during two of the testing sessions, was the preference for video manuals. According to the participants, it is easier see how the process is done. It also offers the possibility of working alongside the sound of the video after watching it once or a few times, which makes the diversion of focusing on to the screen to read obsolete. This was not the only insight gained by the user testing sessions; Remarks on further improvements for the design of the sensors have been collected, which could still be realized in the future. For example, the blue modelling silicone introduced to keep the wires in place was perceived as ugly by two participants. Or another issue: the look of the

pressure sensor was described as being unclean as a result from the moulding principle used in the final design. These issues would need further iterations and rounds of tinkering to come up with alternative solutions to the problems solved there, like the thickness or the wires pulling out.

Appendix A

Interview transcriptions

A.1 Marina Toeters - ByWire - 22.09.2016

In your projects, what are the typical sensors you use currently ?

Different sensors for different projects. A short overview of several projects lead to the following list:

- sleep sensor: Hello sleep
- Breathing sensor: Unix-stretch, knitted stretch sensor, stretchable fabric;
- Lumo lift: posture sensor;
- Other sensors: Strain gauge (pressure), thermometer, EKG

Do the sensors work as you intended ?

The sensors currently used work okay. If she would have to compile a list of problems prioritized by severity, sensors in particular would make it in the top 20 at most. Before that, there are more severe problems to be addressed in my projects, like the integration of the components and their rigidity.

What do the sensors cost ?

The costs for the sensors vary largely. A knitted stretch sensor can be made out of conductive thread for a few cents, while other more complex sensors cost her up to 80.

How do you connect the sensors to the wiring ?

The sensors are connected in several different ways. Most commonly used are magnets to snap them together, simple copper wire, conductive silver epoxy glue or mechanical snaps.

What do you use for wiring, conductive thread or flex core wire ?

The conductive yarn is too much of a hassle and too unstable, so flex core wire is used preferably.

Any other remarks ?

A suggestion that came from Marina was to look into printed sensors on top of flexible, stretchable foil. Furthermore, she suggested to take a look into actuation rather than input.

A.2 Emiel Harmsen - Intern Sensoree - 26.09.2016

In your projects, what are the typical sensors you use currently ?

In the prototype developed by Emiel he used following sensors: Electrodes for GSR and EKG, Conductive rubber for stretch to measure breathing and motion determined by accelerometer.

Do the sonsors work as you intended ?

The breating and the EKG sensors worked well. Only the GSR did not work as well. The normal prototype using fabric based electrodes suffered from motion artefacts and were not too reliable. The sticky electrode was way more reliable.

What do the sensors cost ?

Each of the sensors cost at most 10.

How do you connect the sensors to the wiring ?

For connecting the the breating and the EKG sensor, mechanical snaps were used. Otherwise, the standard headers were used within the encasing of the prototype.

What do you use for wiring, conductive thread or flex core wire ?

Only standard wires were used within the encasing and there were no other connections to be made.

Any other remarks ?

The heart beat detection of the polar strap the prototype was mounted on was not too accurate. An own software solution should work better than that.

A.3 Isa Pfab - Intern with Pauline van Dongen - 22.11.2016

A short working version of the problem statement was sent to the interviewee on her request.

How do you perceive the problem of the gap in between DIY-sensors and highly sophisticated ones in wearable technology?

I experience this problem as well, even though it depends on the sensor type. It is especially pressing in stretch sensors. There are the hand-made knitted ones, which work but they lack reliability. If you rely on ready-made products in that domain, which are reliable, it can get pretty

expensive quickly. There is for example the StretchSense sensor [38] which costs 800$ for a simple evaluation kit with some bluetooth. This is a lot for evaluating whether it works for your product, especially in start-up.
And you want it to work already in an early stage of prototyping. I can take my master thesis as an example here, a wearable system giving feedback on the posture. I did user-testing with the developed system for two weeks, in which the product needed to work all the time reliably.
The problem knitted stretch sensors as well as yarn based ones run into is that they wear out after some time of use. You can of course try to produce them industrially, but when asked a company about it, they wanted to have 10,000$ for delivering a sample. One way we experimented to make fabric based stretch sensors more long-lasting was to coat them in latex or silicone. Another way in which we are utilizing silicone currently is to embedded chips into it. For the production of the moulds we are using a 3D-printer. This process is a big step towards the washability of wearables, since the silicone can protect the embedded elements from this hazardous conditions. The downside is that it takes up a lot of time, especially if you are cycling through iterations of moulds. This is why that process is not really applicable in the early stages of prototyping.

Which aspects are you looking at when choosing a sensor ?

First and foremost, the reliability is important. And since we are mostly working with Arduino, the ability to connect it to one is essential as well, preferably even with an already written library. Another essential point is the form factor of the sensor. I worked for example with inertial measurements units and the smaller the chip the easier it is to achieve good wearability. Next, the price is another factor. It is always dependent on the budget of the individual project, but still the price of the sensor has to be reasonable within that boundary. Then the accuracy and the linearity of the sensor are also important. Furthermore, the ease-of-use is also significant. Some fabric-based stretch sensors for example require Opamp circuits in order to read out the sensor which is not desirable. And the amount of pins taken by a sensor should not be too high, especially in bigger projects with several, since the amount of pins is limited.

Which connections are using in between the micro-controller and the sensors, conductive yarn or standard wires?

Conductive thread is not reliable enough for making good connections. Although, there are some available being reliable enough but they are not not sewing-machine compatible. That makes them not worth using for the effort put in. What we tend to use are wires from electrisola [enamelled copper wire] attached with fabric bonding tape. Otherwise, we also use elastic cables, whch are flat and unobtrusive at the same time.
We are barely using any of the normal wires. This is due the problem of cable breaks which tend to happen with these, but not with other ones we use.

How wearable are the products you are making ?

In that field the products we develop are quite far. This is because a large part of the team is coming from a fashion background. Therefore, our products score quite well in regards to comfort, style, everyday use and we also achieve washability for most of them. But the components for some products have limits themself, which are then also ours. Taking our Solar Windbreaker for instance. When making a first test batch, the solar panels proved to be more sensitive than claimed by the manufacturer. Therefore, we had to change the production plan and we ended up attaching the solar panel by hand. But that worked and it was wearable. It is also important that the products are not to sensitive because they are exhibited around the world by different people.

But what still needs to happen in that field is a bit of user education. At the moment, we are a bit careless with our clothing, we crumple it up and throw it in a corner at the end of the day. And wearable technology cannot do that, it will break. The user has to be taught to handle it with some care because it is not a normal piece of clothing, it is special. That is why we send out our products with a manual so to say, to show and make the user aware how to handle it.

Appendix B

Prototype Evaluations

B.1 Electrode ring

Electrode ring: iteration 1

Aim: A ring with a conductive mesh on the inside serving as an electrode which has a reliable skin contact all the time

Materials: ShA33 silicone, piece of copper mesh, wire
a mould was made out of 2 layers of 6mm acrylic.

Process: The copper mesh was cut to a rectangle of about 1.5cm x 1cm. The wire was then soldered onto the middle of the mesh. This combination was attached with tape to the centre piece of the mould. The outer pieces of the mould were put on top of the base plate. Then the silicone was mixed together and poured into the cavity of the mould. Then the centre piece of the mould was pushed down inside the silicone filled cavity forming the ring. To make it cure faster, a hot air gun was used. After that it was taken out of the mould

Insights & Problems: The ring was taken out of the mould too early which lead to extreme structural damages. Upon trying to put on the finger the ring ripped in half. Because this fact renders it unusable the electrode was taken out and reused in the next iteration.
The attachment of the wire on the mesh was hard to do well since the soldering iron also melts the mesh quickly

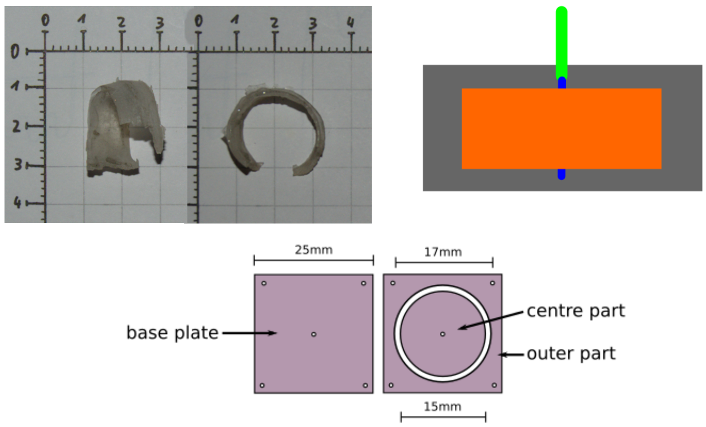


Figure B.1: Iteration 1 of the electrode ring, a concept sketch as seen from inside the ring as well as a depiction of the mould. Note that the outer part and the centre piece are made from two layers of 6mm acrylic glued together to achieve a good height.
Colour code of the concept: grey: silicone, orange: copper mesh, green: insulated wire, blue: wire core

Electrode ring: iteration 2

Aim: A ring with a conductive mesh on the inside serving as an electrode which has a reliable skin contact all the time
Longer curing time than iteration 1 to prevent structural damage

Materials: ShA33 silicone, piece of copper mesh, wire
same mould as iteration 1

Process: The copper mesh and wire attached from iteration was reused. The same procedure as in iteration 1 has been followed with the adaption of a longer curing time to prevent damage.

Insights & Problems: The moulding principle allows for a good ring shape and after some cleaning up it looks good as well.
The centre piece of the mould was not well centred which made one side significantly weaker than the other one (0.5mm vs. 2.8mm)
The ring was a bit too small
The wire attached to the copper mesh pulled it out of the silicone and left it hanging in the middle

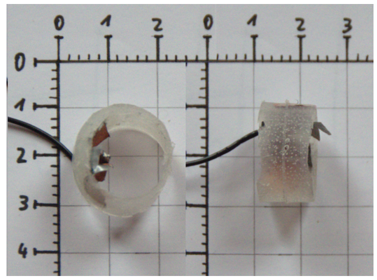


Figure B.2: Iteration 2 of the electrode ring

Electrode ring: iteration 3

Aim: A ring with a conductive mesh on the inside serving as an electrode which has a reliable skin contact all the time
New mould for a bigger, better fitting ring
Paying more attention to the centring of the centre piece

Materials: ShA33 silicone, piece of copper mesh, wire, new mould

Process: The same procedure as in iteration 2 was used with the new mould and more attention has bee paid to keeping the centre piece aligned. The centring worked out well and an consistent thickness around the whole ring was achieved. Also the size of the ring was better and it could be put on a finger well while still being tight for a good contact.

Insights & Problems: When attention is paid to keeping the middle piece centred the ring had a consistent wall thickness all around.
The result out of the new mould was fitting better on the finger. It could be put on without to much of effort and it was tight at same time which is important for a reliable interface between the mesh and the wearer's skin.
The copper mesh is again not bonding well with the silicone and was pulled loose by the wire again.

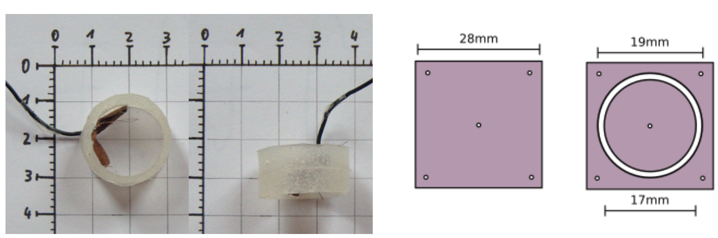


Figure B.3: Fourth iteration of the electrode ring with the new slightly bigger mould

Electrode ring: iteration 4

Aim: A ring with a conductive mesh on the inside serving as an electrode which has a reliable skin contact all the time
Making the mesh bond better with the silicone by using iron-on patch fabric

Materials: ShA33 silicone, piece of copper mesh, wire, iron-on fabric, mould, solder flux

Process: The electrode part was made differently this time. First, the wire was attached on the side of the mesh and not in the centre so that it was more embedded into the silicone. Solder flux was also added on to the copper mesh to make the soldering faster with less chance of actually melting the copper mesh. After the soldering, it was ironed on a piece of the patch fabric only slightly bigger than the mesh. The resulting electrode part was then taped onto the centre piece. The outer mould was filled with the combined silicone mixture and the centre piece was pushed in. It was heated with the hot air gun to speed up the curing process.

Insights & Problems: The silicone bonds well the patch fabric making it a good choice for fixating the copper mesh.
Putting the wire on the side of the mesh was a good idea since the wire is now well embedded into the silicone rather than sticking into the whole the finger should go through.
Demoulding the ring too early resulted in slight structural damages.
The centre piece was not aligned properly which left one side a bit weaker that the other (1.6mm vs. 2.6mm)
A new problem arising from the use of the fabric was that the edges are reaching through the silicone resulting in a cut on the outside. This is a severe structural problem because it introduces weak points to the ring which could potentially tear up if the ring is put on the finger.

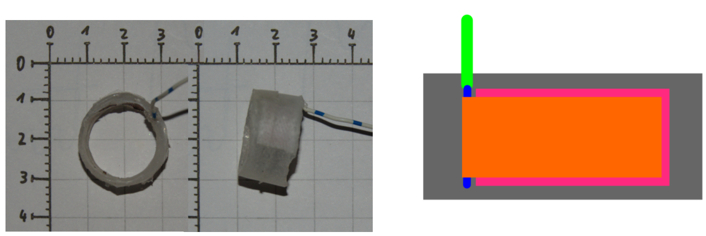


Figure B.4: Iteration 4 of electrode ring and a concept sketch
Colour code: grey: silicone, orange: copper mesh, green: insulated wire, blue: wire core, pink: patch fabric

Electrode ring: iteration 5

Aim: A ring with a conductive mesh on the inside serving as an electrode which has a reliable skin contact all the time.

Materials: ShA33 silicone, piece of copper mesh, wire, iron-on fabric, mould, solder flux

Process: The same procedure from iteration 4 has been followed again with more emphasize on aligning the centre piece. The electrode was also taped more carefully to the centre piece and the silicone was left long enough to cure completely.

Insights & Problems: The ring was well centred with a consistent thickness all around
The problem of the fabric cutting through the ring already encountered in iteration 4 came up again. This needs to be fixed in order to get a structurally sound ring.
The bond between the copper mesh and the iron-on fabric seems to be not good either. The copper got loose and was only held in place by the soldering point to the wire.

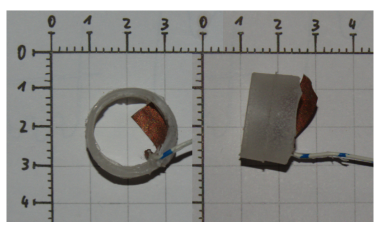


Figure B.5: Iteration 5 of electrode ring

Electrode ring: iteration 6

Aim: A ring with a conductive mesh on the inside serving as an electrode which has a reliable skin contact all the time
Keep the patch fabric closer to the centre piece to avoid the resulting cuts.

Materials: ShA33 silicone, piece of copper mesh, wire, iron-on fabric, mould, solder flux, yarn

Process: The wire was soldered to the side of the copper mesh. The mesh was then ironed onto a fitting piece of patch fabric. To keep it in place later, the sewing machine was used to put a seam around the edges of the mesh. Instead of taping it to the centre piece, it was tied down tightly with a piece of thin yarn. This keeps the edges closer to centre than the tape could. The prepared centre piece was then pushed in the remaining part of the mould filled with silicone. The curing was sped up with the heat gun. After the demoulding the yarn previously holding the electrode in place was carefully pulled out of the silicone.

Insights & Problems: The new way of attaching the electrode worked very well and solved the problem of the fabric cutting through the silicone.
There was too much silicone running out of the outer parts of the mould resulting in not enough remaining to fill the whole ring. Therefore, the ring is in some places around 2mm shorter than it should be.

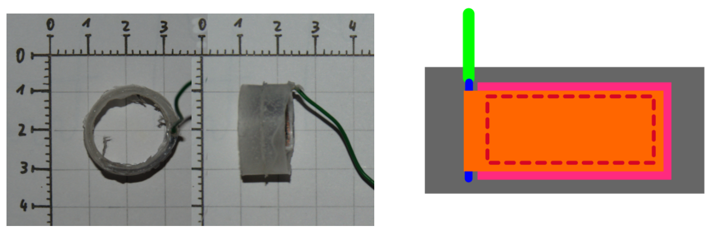


Figure B.6: Iteration 6 of electrode ring and an illustration of the idea as seen from the inside of the ring
Colour code: grey: silicone, orange: copper mesh, green: insulated wire, blue: wire core, pink: patch fabric, dark red: yarn

Electrode ring: iteration 7

Aim: A ring with a conductive mesh on the inside serving as an electrode which has a reliable skin contact all the time.
Reduce the silicone oozing out of the mould

Materials: ShA33 silicone, piece of copper mesh, wire, iron-on fabric, mould, solder flux, yarn

Process: The same procedure as in iteration 6 was followed again with a focus on preventing the running out of the mould.

Insights & Problems: The outcome looked very promising and worked well in a test measuring the skin resistance together with iteration 6.
After some time, the wire broke right at the edge of the silicone. This is a weak point since the wire is not isolated any more and at the same time lacking the support of the silicone. The exposed cores at this point can break easily when they are bent in either direction.

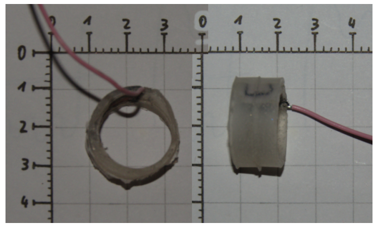


Figure B.7: Iteration 7 of electrode ring

Electrode ring: iteration 8

Aim: A ring with a conductive mesh on the inside serving as an electrode which has a reliable skin contact all the time.
Minimize the weak point of the stripped wire transitioning into the silicone

Materials: ShA33 silicone, piece of copper mesh, wire, iron-on fabric, mould, solder flux, yarn

Process: To overcome the problem, the insulated wire was let run first completely to the bottom with the stripped part starting with a sharp U-turn. The copper mesh was soldered on the bared part of the wire running to the top again. The remaining procedure was carried out as described in iteration 6.

Insights & Problems: The problem encountered with the wire breaking was solved by allowing the insulated wire to go in the silicone.

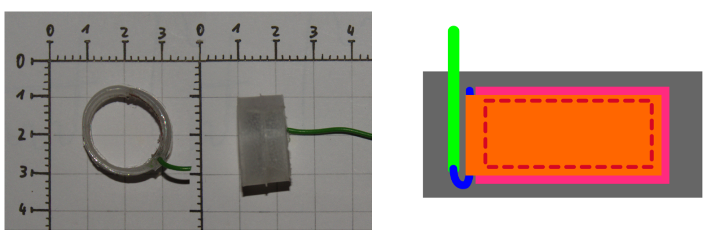


Figure B.8: Iteration 8 of the electrode ring and a graphic of the concept as seen from inside the ring
Colour code: grey: silicone, orange: copper mesh, green: insulated wire, blue: wire core, pink: patch fabric, dark red: yarn

Electrode ring: iteration 9

Aim: A ring with an integrated measuring circuit for skin resistance with 3 leads directly connectible to a micro-controller

Materials: ShA33 silicone, two pieces of copper mesh, very thin coil wire, iron-on fabric, mould, solder flux, yarn, 680kOhm resistor

Process: For measuring the skin resistance with one ring two copper mesh pieces need to touch the wearers skin at all time. A resistor was included as well as fixed resistor for the required voltage divider. All the connections were done using very thin coil wire which is insulated by a coat of lacquer. A coil wire was burnt off and soldered on each of the copper mesh pieces. Each one them was ironed on one piece of patch about 3mm apart. Each of the pieces was then also sewn to the patch. One piece of coil wire later on serving as the power line was soldered onto one side of the resistor. On the other side of it, another long coil wire was attached serving as the output line. the resistor was then sewn to the patch fabric on the opposite side of the copper mesh by doing a few loops with yarn around it. The wires from one of patches was soldered to the resistor's side with the designated output wire. After that, the leads of the resistor were cut off as short as possible. The wire of the other mesh piece was also broad to the other side of the patch, respectively the outside of the ring. This is the ground line of the measuring set-up. All the three outgoing wires were intertwined to make it look like one. Next, the whole patch with everything attached was tied to the centre piece of the mould again. This piece was then pushed into the outer part of the mould filled with silicone and dried using a heat gun.

Insights & Problems: The resistor was to thick for thin silicone wall and pushed the centre piece toward the opposite side. The remaining thickness of the silicone was to thin and the ring not usable. The mould needs to be adapted to allow more space for the resistor inside the silicone.
The thin coil wire is hard to work with.

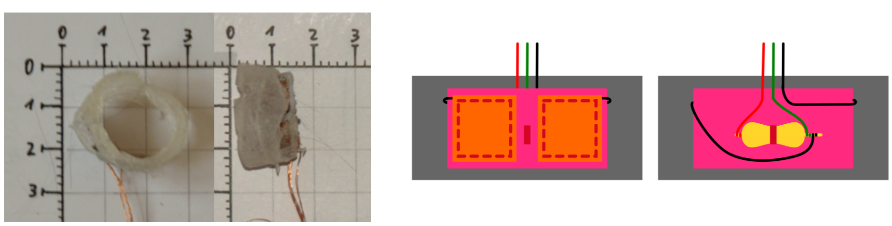


Figure B.9: Iteration 9 of electrode ring and a graphic of the concept as seen from the inside of the ring as well as the outside;
Colour coding: grey: Silicone, orange: copper mesh, dark red: yarn, pink: patch fabric, yellow:resistor, black+green+red: coil wire respectively ground, output and power

Electrode ring: iteration 10

Aim: A ring with an integrated measuring circuit for skin resistance with 3 leads directly connectible to a micro-controller.
Attempt with adapted mould with a dent to have more silicone around the resistor.

Materials: ShA33 silicone, piece of copper mesh, wire, iron-on fabric, mould, solder flux, yarn

Process: The same procedure as in iteration 9 was followed again with changed mould. The centre piece was placed so that the resistor was inside the dent.

Insights & Problems: The adapted mould worked very well, only the remaining leads of the resistor were poking out of the silicone. The rest of the ring was structurally excellent.
When connecting the ring to a micro-controller, the resulting measurement was very unstable. In addition, it suffered greatly from motion artefacts compared to previous measurements with two rings. One explanation for this is the smaller width of the conductive patches. They may make not enough contact any more when moving which has a bad influence on the output.
Due to the unstable output in combination with increased amount of work needed for this ring, it was decided to stick with the not integrated solutions with one big piece of copper mesh.

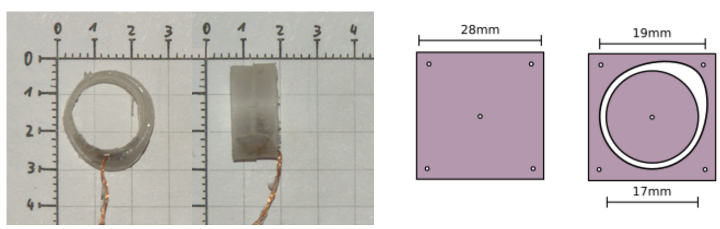


Figure B.10: Iteration 10 of the electrode ring

Electrode ring: iteration 11 & 12

Aim: A ring with a conductive mesh on the inside serving as an electrode which has a reliable skin contact all the time.
In order to improve the structure of the ring, the previously adapted mould was used with the original design.

Materials: ShA33 silicone, piece of copper mesh, wire, iron-on fabric, mould, solder flux, yarn

Process: The same procedure as in iteration 8 was followed again with the outgoing wire placed in the added dent of the mould.

Insights & Problems: This was the final design. It shows great structural integrity and has a reasonable signal stability when worn. An in-depth discussion of this design can be found in chapter 7.

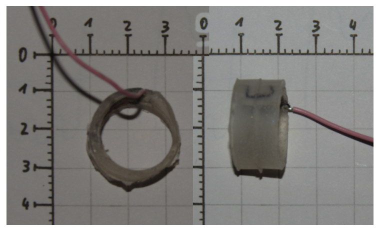


Figure B.11: Iteration 11 & 12 of the electrode ring

B.2 Pressure sensor

Pressure sensor: iteration 1

Aim: Pressure applied onto the sensors changes the capacitance between two conductive layers significantly.

Materials: Copper tape, ShA33 silicone, mould

Process: For this prototype, the stretch sensor mould has been used. The casting was done in three steps. First, a base layer was poured and quickly cured with a hot air gun. On top of this layer, the first stripes of copper tape were put and covered with another layer of silicone. After this one was cured, the second layer of tape was placed on top of the other one. For the last silicone layer, the base plate and lower part of the mould were removed from the already cured bottom and put on top again. In this a third layer of silicone was cast.

Insights & Problems: The capacitance in between two copper layers was not enough to be measured with any of the means available, not even with high-precision precision multi-meter going down to a few nano-Farad. This shows that using a change of capacitance for recording the pressure without any additional special hardware does not work.

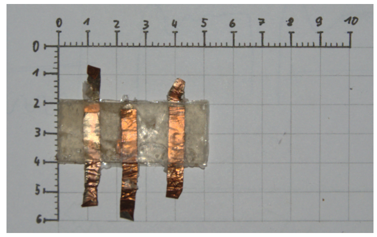


Figure B.12: Iteration 1 pressure sensor

Pressure sensor: iteration 2

Aim: A resistive pressure sensor made from silicone combined with carbon powder

Materials: ShA33 silicone, carbon wire, flec-core wire, mould

Process: First, two wires were stripped for about 2 cm and put through holes at the side of the mould. Next, the silicone was mixed and the carbon powder was added up to the point where a multi-meter showed that the mixture was conductive. Half of it was put into the mould and spread. Then the wires acting as leads were pushed into it and the remaining mixture was put on top. The moulding area was then pushed down with the cut-out piece to force it in a more consistent shape.

Insights & Problems: The resistance across the wires measured with a multi-meter was to big to be detected. The leads might be too far apart from one another or there might be not enough carbon powder in there. To achieve replicable results with the ratio of carbon powder to silicone, a micro scale was obtained to weigh them out.

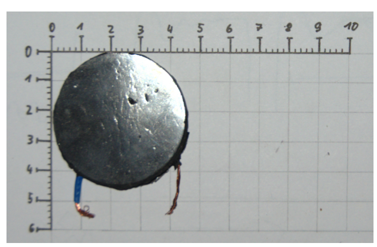


Figure B.13: second iteration of the pressure sensor

Pressure sensor: iteration 3

Aim: A resistive pressure sensor made from silicone combined with carbon powder

Materials: 7.3g of ShA33 silicone, 3.7g of carbon powder, flex-core wire, mould

Process: The mould was prepared by inserting the leads into the holes on the side which are 1cm apart. The silicone was mixed and weighed at 7.3g. A patent reports a carbon content of 15-40% for making silicone conductive. Therefore, an initial carbon content of 25% or 1.8g was chosen to begin with. The check with the multi-meter showed no conductivity yet, so another 0.9g or 12.5% were added. It still was not conductive and another 0.9g of carbon powder was mixed in bringing its ratio to 1:2 in respect to the silicone. This was conductive, so half of the mix was put into the mould, the wires were pushed into it and the remaining mixture was put on top. Then the moulding area was compressed with the cut-out.

Insights & Problems: The resulting sensor is 20mm ⌀ x 6mm with the leads coming out in the middle. The form factor is not ideal with the extreme height and the edges, one point for further improvements is to make it flatter.
The sensor was measured with a multi-meter and it showed a good response when pressed. This shows that this material combination has potential when the form factor is improved.

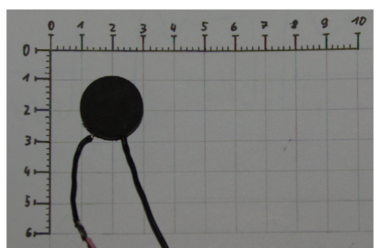


Figure B.14: Iteration 3 pressure sensor

Pressure sensor: iteration 4

Aim: A resistive pressure sensor made from silicone combined with carbon powder
Make the sensor thinner

Materials: 3g of ShA33 silicone, 1.5g of carbon powder, flex-core wire, adapted mould

Process: To achieve a thinner result, new holes were drilled into the mould lower than the previous ones. They were again spaced about 1cm apart and the wires were inserted . The silicone was mixed together and the carbon powder was added to it. Next, the mixture was put on top of the leads into the mould. The central cut-out was pushed onto the moulding area to reduce the height and shape the sensor consistently. After that, the hot air gun was used to speed up the curing process.

Insights & Problems: The resulting carbon sensor had dimensions of 20mm ⌀ x 4mm. With the holes for the wires moved down the sensor also becomes a bit thinner than previous versions.
Not putting the mixture below and above the leads resulted in the leads not being covered in the mixture and sticking out. This is a severe problem and the old way of putting the mixture below and on top of the silicone does not have that problem.

Pressure sensor: iteration 5

Aim: A resistive pressure sensor made from silicone combined with carbon powder
Getting the leads completely covered in the mixture.

Materials: 2.6g of ShA33 silicone, 1.3g of carbon powder, flex-core wire, mould

Process: The same procedure from iteration 4 was followed again with the adaptation of putting silicone below and above the leads.

Insights & Problems: The resulting sensor had the dimensions of 20 mm ⌀ x 3.5mm. This is again a bit thinner again than the previous iterations but it is still to thick to be comfortably worn in a place where pressure is applied, for example then hands. This in combination with the high stiffness of the mixed signals makes it not wearable in the end.
The two leads were sticking out again, even though only slightly at the ends. Maybe the mixture was not well split in between the two castings or they pushed through it. Closer attention should be paid to making them stay in the silicone all the way.
The range of the sensor was ranging from 1Mohm to 5Kohm as determined with a multimeter. This is not ideal for a voltage divider because this range makes it difficult to choose a fixed resistor for the interfacing. An eye should be kept on future iterations, if this problem arises again.

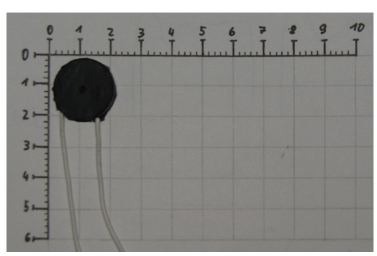


Figure B.15: Iteration 5 pressure sensor

Pressure sensor: iteration 6

Aim: A resistive pressure sensor made from silicone combined with carbon powder
Making the sensor thinner to get to the point that it can be considered wearable.

Materials: remaining mixture of iteration 5 with 2.6g of ShA33 silicone and 1.3g of carbon powder combined, flex-core wire, acrylic disc & base plate

Process: In this iteration, not a mould for the casting was used but rather two pieces of acrylic. A bit of the mixture was put on the base plate and spread out a little bit imitating the shape of the acrylic disc. The stripped wires were then put on top of that about 1.5cm apart from one another and some more mixture was put on top of them to cover them in the silicone. Next, the acrylic disc was put on top and pushed down. This resulted in some of the mixture overflowing on its sides but it allowed to make the sensor really thin. After curing it with a heat gun, the overflown mixture was cut away with a knife.

Insights & Problems: The result of the adapted casting method is a sensor with the dimensions of 26mm ⌀ x 1.6mm. This thin layer of silicone carbon mixture is still flexible and less bulky than the previous versions. Regarding the wearability, this sensor is way better than all the previous iterations and should be applicable in a wearable prototype.
The range of the resulting sensor was much better compared to the last one ranging from 1Kohm idle to about 500ohm when pressed. Upon a test with the arduino and pressing the finger on the sensor it could be observed that there is a some overshoot when it is pressed and released quickly. This might be because of the slight stickiness of the material and it sticking to the finger when released. When the sensor was covered with some fabric, this problem did not persist. For long-term use, this might also be less of a problem since the stickiness of the silicone goes down over time.
The measurements further showed that it does not only measure pressure, but also other strains such as flexing. So it is not a strict pressure sensor if not put on a solid surface but it might open up possibilities into other sensor applications as well.

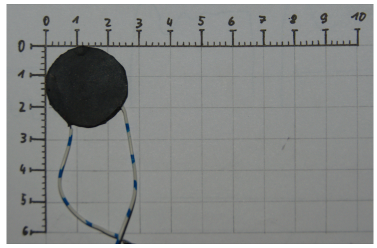


Figure B.16: Iteration 6 pressure sensor

Pressure sensor: iteration 7

Aim: A resistive pressure sensor made from silicone combined with carbon powder
Embedding two pairs of electrode for differential measurements

Materials: 4g of ShA33 silicone, 2g of carbon powder, twisted lacquered wire, acrylic disc & base plate

Process: The same procedure as described in iteration 6 was used but with 4 leads instead of 2.

Insights & Problems: The concept of using differential measurements between the 2 pair of leads was flawed from the beginning. When pressure was applied, both pairs of electrode were effected equally which renders taking the difference useless.

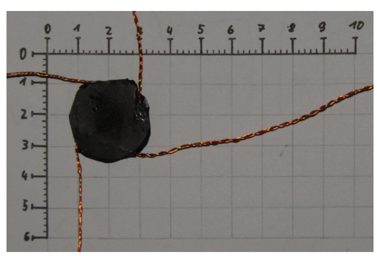


Figure B.17: Iteration 7 pressure sensor

Pressure sensor: iteration 8

Aim: A resistive pressure sensor made from silicone combined with carbon powder
Using softer silicone to get an even more flexible result and potentially an increased output range.

Materials: 2g of ShA00 silicone, 1g of carbon powder, flex-core wire, acrylic disc & base plate

Process: The same procedure as described in iteration 6 was used again with the softer silicone.

Insights & Problems: The resulting sensor was softer, but due to this the material could not hold the leads any more. They were ripped out of the material when the two acrylic pieces were removed. This problem was not occuring in the previous iteration using the harder ShA33 silicone. Therefore, this one is going to be used further at the expense of limited flexibility.

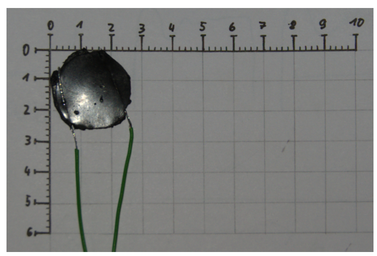


Figure B.18: Iteration 8 pressure sensor

Pressure sensor: iteration 9

Aim: A resistive pressure sensor made from silicone combined with carbon powder
Applying the sensor on top of fabric to allow for easy attachment and integration in wearable technology prototypes.

Materials: 1.5g of ShA00 silicone, 0.75g of carbon powder, flex-core wire, perforated non-woven fabric, acrylic disc & base plate

Process: First, the silicone was mixed together and the carbon powder was added. This was mixed thoroughly until a thick, smooth consistency. Next, the fabric was put onto the base plate and about three quarters of the mixture were put on top of the fabric. This part of the mixture was spread evenly to the approximate shape of the acrylic disc. Then the leads were put in there spaced about 1.5cm apart. The remaining mixture was used to cover the top of the wires with silicone and as a next step the silicon disc was put on and pushed down. After, it was cured with the help of a heat gun and the silicone edges resulting from the overflow were cut off.

Insights & Problems: The resulting sensor was very thin and flexible again. It bonded well to the fabric used and worked quite well. This sensor was used for the evaluation in chapter 7 and also for the step detection application in section 7.3.2.

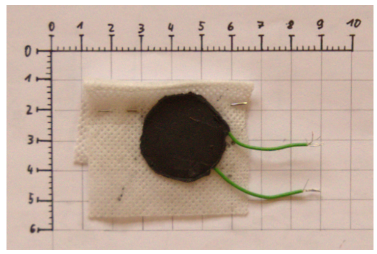


Figure B.19: Iteration 9 of the pressure sensor

B.3 Stretch sensor

Stretch sensor: iteration 1

Aim: A resistive stretch sensor by embedding carbon fibres into silicone.

Materials: ShA33 silicone, carbon fibres, 3 credit cards for the mould

Process: A mould was made with three old credit cards. In two of them a centre piece what cut out with a knife measuring 6.5cm x 2.5 cm. The third one served as the mould base plate. The carbon fibres were arranged in between the two moulding pieces so that they end up in the middle of the sensor. The silicone was poured on top of the stacked form and then fast cured under a heat lamp. After the curing, the long carbon fibres were cut besides some at either end to act as the leads of the sensor.

Insights & Problems: sensor dimensions: 65mm x 25mm x 2.5mm
Testing the sensor with the help of multimeter and crocodile clamps showed that the resistance increases from 2kΩ to 6kΩ when it is stretched.
This shows that the concept of embedding carbon fibres in silicone works and more iterations are made to investigate the possibilities further. The arrangement of the fibres should be improved since they are clustered together and alternative patterns might also change the properties. The material still stretches nicely perpendicular to the alignment of the fibres. There is also some force required to stretch it but it is still acceptable.

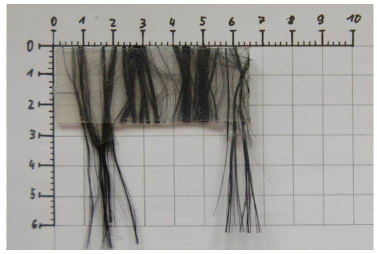


Figure B.20: Iteration 1 stretch sensor

Stretch sensor: iteration 2

Aim: A resistive stretch sensor by embedding carbon fibres into silicone. Using a mould laser cut out of acrylic to make the stretch sensor

Materials: ShA33 silicone, carbon fibres, acrylic mould

Process: A new mould was made with the laser cutter and 3mm thick acrylic. In order to keep the sheets of acrylic aligned small holes were drilled in the edges fitting tooth picks which worked well. More fibres more evenly spread were used in comparison to the first iteration. To do so, the fibres were fixated with Scotch tape to one part of the mould to allow for easier alignment. The process was otherwise kept the same.

Insights & Problems: sensor dimension: 40mm x 20mm x 6mm
Along with the thickness the force necessary to stretch the sensor also increased to a level which is not acceptable. A new mould which has a thinner casting area is needed for the following iterations.
The finer pattern of the fibres did not allow the gel-like silicone poured on top to penetrate easily, which resulted in big pockets of air trapped below the fibres.The process needs to be adjusted to prevent that.

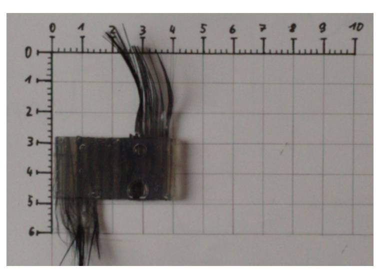


Figure B.21: Iteration 2 stretch sensor

Stretch sensor: iteration 3

Aim: A resistive stretch sensor by embedding carbon fibres into silicone. Have a thin, stretchable sensor come out of the adapted acrylic mould.

Materials: ShA33 silicone, carbon fibres, adapted acrylic mould

Process: The new mould was cut from acrylic being 1.3mm thick which is less than half compared to the previously used on. The carbon fibres were attached to the bottom of the top part of the mould with scotch tape. This time, the silicone was poured twice. Once with only one mould layer on top of the base without any fibres present. The second layer of the mould which has the fibres attached is put on top. This makes sure that the fibres end up on the already poured silicone with no air trapped below. Then another layer of silicone is poured and the curing was sped up under a heat lamp.

Insights & Problems: resulting sensor dimensions: 50mm x 25mm x 2.6mm The result of the adapted process is good, only the air bubbles trapped inside the silicone are remaining. Testing it with a multimeter, however, showed that the resistance is changing a lot when it is held at both sides varies greatly with the pressure applied to the end (30kΩ to 12kΩ) and with a constant pressure applied upon stretching the resistance decreases (12kΩ with pressure to 6kΩ with pressure and stretch). The large influence of the pressure in the ends needs to be improved. The decrease in resistance rather than an increase, as observed in iteration 1, might be due to the increased amount of fibres, but this needs to be tested further.

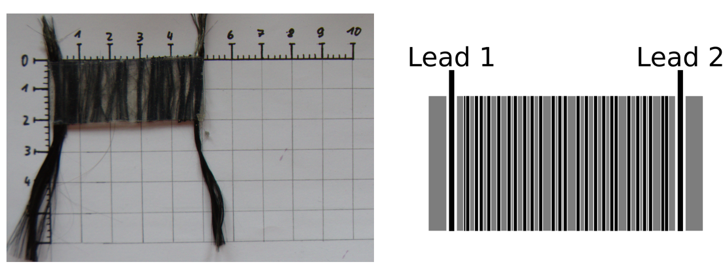


Figure B.22: Iteration 3 stretch sensor

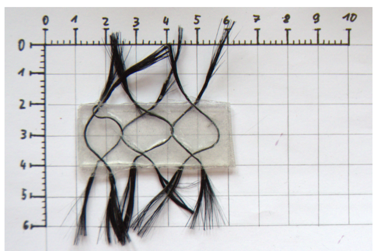
Stretch sensor: iteration 4

Aim: A resistive stretch sensor by embedding carbon fibres into silicone. Evaluate the alternate double-v fibre pattern

Materials: ShA33 silicone, carbon fibres, mould

Process: The procedure was similar to the one used in iteration 3, only the pattern was replaced with the twisted carbon fibres arranged in the double-v shape.

Insights & Problems: resulting sensor dimensions: 50mm x 25mm x 2.6mm The twisted fibre bundles curled up and ended up partly sticking out of the silicone. But more severely, this pattern hinders the material from stretching which makes this patter useless for stretch sensors.



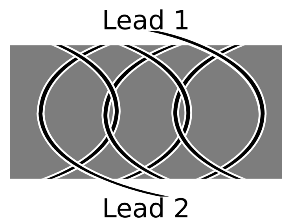


Figure B.23: Iteration 4 stretch sensor and the desired pattern design

Stretch sensor: iteration 5

Aim: A resistive stretch sensor by embedding carbon fibres into silicone. Evaluate the alternative pattern with fibre bundles alternating at a 45 angle

Materials: ShA33 of silicone, carbon fibre, mould

Process: The procedure of iteration 3 was used, this time with pattern bundles at angled at 45 alternating in direction. For the leads, a straight carbon fibre bundle was put at either end

Insights & Problems: resulting sensor dimensions: 50mm x 25mm x 2.6mm This pattern prohibited the material from stretching into any direction which renders it useless as a stretch sensor. The reason is assumed to be the thick fibre bundles as well as the 45 degree angle.

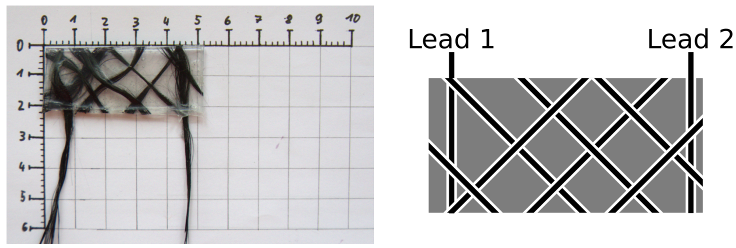


Figure B.24: Iteration 5 stretch sensor and the desired pattern design

Stretch sensor: iteration 6

Aim: A resistive stretch sensor by embedding carbon fibres into silicone. Evaluate the alternative pattern with fibre bundles alternating at a 65 angle

Materials: ShA33 silicone, carbon fibres, mould

Process: The procedure from iteration 3 was used over again with different pattern of thinly spread carbon fibre bundles alternating at a 65 angle.

Insights & Problems: resulting sensor dimensions: 50mm x 25mm x 2.6mm
The resulting sensor could be stretched opposed to other patterns. The range of resistance was determined with a multimeter to be about 1kΩ at rest and around 500Ω when stretched which would be good for a voltage divider.
One problem that has not been tackled yet is the interfacing. All the measurements so far have been done by using crocodile clamps to put on the carbon fibre leads. This, however, is not good for a later use, so another way to interface it needs to be found.
When presented to wearable designer, the remark was made that the force required to stretch the sensor was high. So, a less hard silicone of ShA00 was ordered to reduce the force necessary. For a hardness reference take a look at figure 4.8 on page 31.

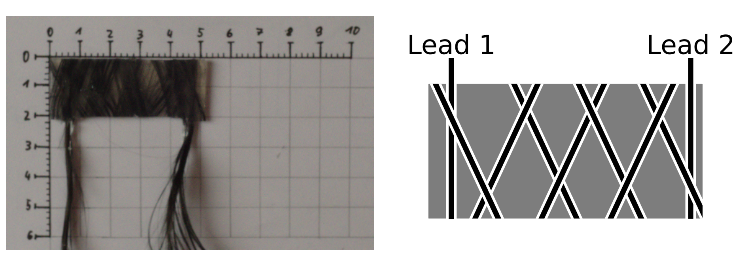


Figure B.25: Iteration 6 stretch sensor

Stretch sensor: iteration 7

Aim: A resistive stretch sensor by embedding carbon fibres into silicone. Include flex-core wires for the leads rather than only carbon fibres for easier interfacing

Materials: ShA33 silicone, carbon fibres, mould, flex-core wire

Process: The pattern of the previous iteration worked well, so this one was chosen again. The wires are arranged at a steep angle of about 65 in alternating direction. In order to incorporate the flex-core wires in the design, the ends have been stripped and the cores were twisted with carbon fibre intertwining it them. The pattern was put on the bottom of the top part of the mould with double-sided tape. The bundles intertwined with the wires were added at either side of the pattern. The first level of the mould was filled with silicone, the second level put on top of that with the wires running on top. Then the top part was filled with silicone as well and all was cured with the help of a heat gun.

Insights & Problems: resulting sensor dimensions: 50mm x 25mm x 2.6mm
The method for the leads worked quite well. It makes interfacing with a micro-controller much more easy.
One issue was that the stripped wire was running out of the silicone and the insulation only started after a short gap. This is a point where the wire could easily break. A fix for that would be to let the wire isolation reach into the silicone.
The range of the sensor determined with a multimeter was around 2kΩ at rest and 1kΩ stretched.

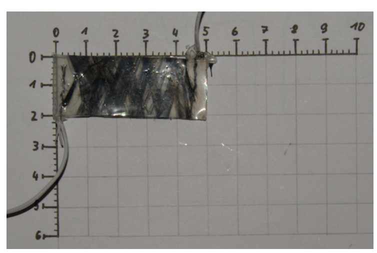


Figure B.26: Iteration 7 stretch sensor

Stretch sensor: iteration 8

Aim: A resistive stretch sensor by embedding carbon fibres into silicone. Prevent the weak point of the wire by letting the isolation run into the silicone

Materials: ShA33 silicone, carbon fibres, mould, flex-core wire

Process: The straight patter as used in iteration 3 was used again in combination with the flex core leads from iteration 7. Attention was paid, that the wire insulation was reaching well into the silicone.

Insights & Problems: resulting sensor dimensions: 50mm x 25mm x 2.6mm The obvious weak point at the edge of the silicone was successfully eliminated with insulation reaching into the silicone.
The carbon fibres were spread a little bit thin which results in a high resistance. The range was determined by a multimeter to be starting 15kΩ at rest up to 8kΩ when stretched. In comparison to the steep-angled pattern, the range of stretch was greater over which the resistance still changes. This would be is preferable and is therefore used further on.

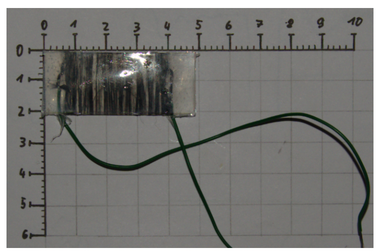


Figure B.27: Iteration 8 stretch sensor

Stretch sensor: iteration 9

Aim: A resistive stretch sensor by embedding carbon fibres into silicone. Using a softer silicone so that the sensor requires less strength for the stretch. Bringing both leads to the same side by using coil wire.

Materials: ShA00 silicone, carbon fibres, flex-core wire, very thin coil wire

Process: As mentioned in iteration 6, a softer silicone was used in order to reduce the force required to stretch. Another desirable property of the sensor would be to have both leads at the same side of the sensor to simplify the interfacing. But since it relies on a change of resistance across the sensor, it has to be connected on either side. To overcome that problem, an idea was to run a thin coil wire inside the silicone from the one side to the other. The lead on the one side would, so to say, be rerouted to the other side. To achieve that, coil wire was used on the one side twisted with the help of some cut-off flexcore cores to the carbon fibre and on the other end connected to an outgoing flexcore wire. To still allow the silicone to stretch, the coil wire was run in a sinus-like patter. Arranging this small construct was too problematic in uncured silicone, so first layer of the mould was cured in advance. Then the coil wire construct was added with the last layer of the mould including the carbon fibres. Then the second part of the mould was filled with silicone embedding the rest in the middle of it.

Insights & Problems: resulting sensor dimensions: 50mm x 25mm x 2.6mm The softer silicone is really easy to stretch with almost no force needed. But it was actually to soft, the silicone showed cracks after some time. For the next iterations, the silicone should be made a bit harder by mixing in some of the harder silicone.
Another problem of this softness is that the wires running into the silicone are not held in there. They can be very easily pulled out in comparison to the ShA33 silicone where this was no problem at all.
The construction with the coil wire in the silicone is very fragile and the wire embedded applies additional internal strain on the material. It is such a big struggle to build and embed the fragile construct that the costs outweigh the benefits and this will not be pursuit further.

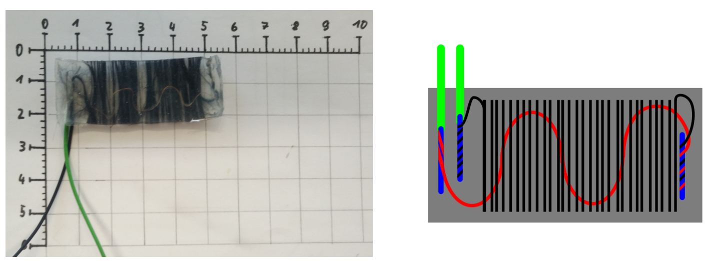


Figure B.28: Iteration 9 stretch sensor including a concept sketch colour coding: grey: silicone, green: flex-core wire, blue: wire cores, black: carbon fibres, red: coil wire

Stretch sensor: iteration 10

Aim: A resistive stretch sensor by embedding carbon fibres into silicone. Using a softer silicone so that is still durable
Cover the leads in modelling silicone to keep them secured in the softer silicone Embed fabric pieces at both ends into the siicone to allow for easier attachment and integration in prototypes

Materials: ShA08 silicone, carbon fibres, flex-core wire, modelling silicone, bigger mould, perforated non-woven fabric

Process: For the integration of the fabric, a bigger mould has been cut. The fabric was cut to pieces of 70mm x 70mm. In order to make sure the wire held into the silicone, the leads as introduced in iteration 7 were covered with some modelling silicone, since silicone sticks well to itself. After the curing time of the modelling silicone, it was cut in shape to fit within the sensor. The linear pattern of carbon fibres as well as the carbon of the electrodes was attached to the upper part of the mould with double sided tape. For making the silicone slightly harder, three quarters of the ShA00 silicone were mixed with one quarter of the ShA33 silicone. When different hardnesses are mixed, the result is in respect to their ratio, so for this sensor it it $00ShA * 0.75 + 33ShA * 0.25 = 8.5ShA$. After pouring the resulting mix in the first layer of the mould, the pieces of fabric were put on either side and then next layer with the carbon fibre pattern and the leads was put on top. Then the mould was filled up with silicone and fast cured with the heat gun.

Insights & Problems: resulting sensor dimensions: 90mm x 25mm x 3mm plus the fabric on either side
The sensor turned out to be non-conductive across the leads and therefore not usable at all. Somewhere in the linear pattern, there is no connection made. To not be relying on this randomness for the final design, the steep angle pattern should be used. This one has a smaller input range, but it guarantees a connection.

The silicone had a good softness to it. It was hard enough to not rip and be durable while at the same time being significantly softer than the original ShA33 silicone.

The fabric pieces are held very well inside the silicone and worked out perfectly. One thing to fix with the fabric was the small resulting gap between the first and the second layer of the mould, where a lot fo silicone was running out.

Covering the leads in modelling silicone was also successful. They were nicely embedded and were not easy to pull out.

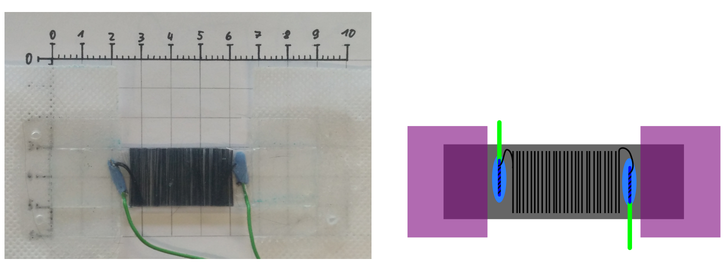


Figure B.29: Iteration 10 stretch sensor including a concept sketch colour coding: grey: silicone, green: flex-core wire, blue: wire cores, black: carbon fibres, light blue: modelling silicone, purple: fabric

Stretch sensor: iteration 11

Aim: A resistive stretch sensor by embedding carbon fibres into silicone with attachment possibilities on either side.

Materials: ShA08 silicone, carbon fibres, flex-core wire, modelling silicone, mould, perforated non-woven fabric

Process: The procedure from iteration 10 was repeated with the only change being the different carbon fibre pattern.

Insights & Problems: resulting sensor dimensions: 90mm x 25mm x 3mm plus the fabric on either side
This sensor turned out really well. It is good to touch, does not need to much force for stretching, has the fabric for attachment on either side and the wires do not easily come out. The input range is not as big as with the linear pattern, as expected, but it is working for sure.
Only negative point was, that the heat gun was set a bit too hot which started melting the fabric on both sides outside the mould.

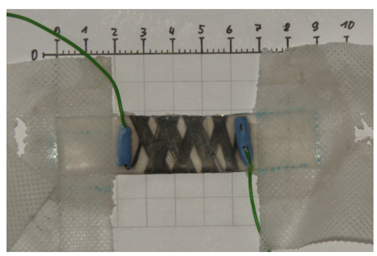


Figure B.30: Iteration 11 stretch sensor

Stretch sensor: iteration 12

Aim: A resistive stretch sensor by embedding carbon fibres into silicone with attachment possibilities on either side.

Materials: ShA08 silicone, carbon fibres, flex-core wire, modelling silicone, mould, perforated non-woven fabric

Process: The procedure from iteration 11 was not changed, only more caution paid to the temperature of the heat gut.

Insights & Problems: resulting sensor dimensions: 90mm x 25mm x 3mm plus the fabric on either side
This sensor looks really good and also feels nice. There are no negative points to mention with this sensor.
This is the sensor used for testing the functional requirements in chapter 7.

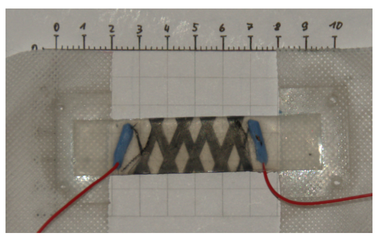


Figure B.31: Iteration 12 stretch sensor

Appendix C

User evaluation closing interviews

C.1 Marina Toeters

Would you use the sensors in the development of your products? Why (not)?

> I could see myself using these kind of materials. But I would only see them under specific circumstances in a niche market. One improvement for me would be if they could be made to stick on the fabric directly. That would make it easier.
> But I like the look of the stretch sensor, it looks very stylish. I would like to see them even more transparent in the long term, that would improve it even further

How would you rate their wearability? Rate them along the categories aesthetically pleasing, sensually pleasing and comfortable from 1 to 7 with 1 being the lowest?

	Stretch Sensor	Pressure Sensor
aesthetically pleasing	**6** the fibre pattern looks really good but I do not like the look of the blue modelling silicone It would look even better if the silicone stayed perfectly clear rather than getting a bit cloudy over time	**5**, potentially **6** the bleeding is a bit off-putting. A mould resulting in a consistent shape would make it better
sensually pleasing	**2** I do not like the sticky feel of the silicone	**6** on the fabric side, a **5** on the side of the silicone
comfortable	**4**	**4**, but could be potentially **6**

Another important point for me regarding the wearability is the integrability of the sensors. The fabric where the silicone bleed into it is not good to sew with the machine. The mechanism moving the fabric forward in the machine fails to grip onto the silicone which makes it hard sew with it.

Do you think you would be able to follow the instructions of the manual without help?

In principle yes, but I am a designer, so I am a bit turned off by the graphical design of it and the visuals. I would also prefer to see each of the steps in a bulleted list rather than a single paragraph to make it easier to follow. I would also like to see a picture of the finished sensor in the beginning to have an idea what I am working towards. The starting picture with all the materials is a good idea.

I personally prefer video tutorials. Information can be easier transferred by the image and comments at the same time. If I first watched the tutorial I can also work alongside only using the commentary which allows me to keep the focus on my work.

Do you think the time it takes to make them is justified? Do you think the price for the materials is justified?

	Stretch Sensor	Pressure Sensor
time	One hour to one and a half hours would be okay for me but only if the bleeding is not an issue any more and it can be easier integrated into fabric	Yes, for the 40min it showed good results
price	For prototyping very easily, if it is further integrated also further down the line Time is of the essence for me, if I value my time at 100€/hr the material costs are not that much of a price factor	

Would you say the outcome of the project is relevant to the wearable technology field? .

For sure, you explored the materials and their combination for the wearable field. And you gathered knowledge on techniques, for example the connection between the wires and carbon fibres.
I personally still prefer the textile sensors simply for their lovely feel. But your sensors could be usable in products which need to look innovative or sports products. The silicone looks fancy and that is important there.

C.2 Judith Weda

Would you use the sensors in the development of your products? Why (not)? .

Sure. I would actually prefer pre-manufactured ones, but if they are expensive, then for sure.

How would you rate their wearability? Rate them along the categories aesthetically pleasing, sensually pleasing and comfortable from 1 to 7 with 1 being the lowest? .

	Stretch Sensor	Pressure Sensor	Electrode ring
aesthetically pleasing	**7** looks very good	**5** looks good	**4** not displeasing
sensually pleasing	**6** sweat might be a problem and it is a bit sticky	**4-6** depending on how you use it	**6** pretty good
comfortable	**6** looks pretty soft and should be comfortable to wear	**3-4** the edges around are a bit of a problem	**6** got a bit sweaty below

Do you think the time it takes to make them is justified? Do you think the price for the materials is justified? .

	Stretch Sensor	Pressure Sensor	Electrode Ring
time	1 to 1.5 hours would be acceptable for me personally	30min are perfectly fine	1 hour is still okay
price	All the material costs seem pretty good to me		

Would you say the outcome of the project is relevant to the wearable technology field? .

Definitely. The availability of sensors improved over the course of the last years, but it still has to look good. Otherwise you have to hide the sensors or put a lot of effort into making it look good. Your's already look pretty good. And the stretch sensor is also easier to integrate compared to the rubber cord with the clamps at the ends. Another big advantage is the customizability of the sensors. You only have to get the cheap materials and then I can fit them to my needs. And the stretch sensor looks really good, I actually prefer it over the sensor from stretch sense.

C.3 Emiel Harmsen

Would you use the sensors in the development of your products? Why (not)? .

For stretch sensors, I prefer the conductive rubber band. It is more reliable and this stretch sensor takes more time to make. But it looks pretty cool. If you are designing something to look cool or artsy, this one would be better. If you would put it on a muscle for example with some lights behind it shining through, it could look really cool.
I also would not use them for proper measurements, there I would something else. Taking the pressure sensor for instance: tracking walking may work with this one but it cannot measure the exact weight of the person. If I wanted to do that I would choose a flex sensor, since it can do that and is thinner. It is always hard to achieve something like that with self-made sensors; their advantage lies in their customizability.

How would you rate their wearability? Rate them along the categories aesthetically pleasing, sensually pleasing and comfortable from 1 to 7 with 1 being the lowest? .

	Stretch Sensor	Pressure Sensor	Electrode ring
aesthetically pleasing	**5** it looks good but the blue part is ugly	**2**, potentially up to **6** Should look cleaner and with only one wire coming out of it	**4**, but could be up to **6** It does not look completely clean now with the seams The wires running to it are not nice and are too thick
sensually pleasing	**7**	**3** ideally, you should not feel it at all seems to break apart if flexed to far	**6**
comfortable	**-** I do not want to rate that since it is only applicable in the finished product		**6** feels comfortable although i would be concerned about the blood flow to my finger if it is tight

Do you think you would be able to follow the instructions of the manual without help?

Yes, I made one mistake with the pattern now but if I would make them on my own I would put more research in how they work. Then such an error would not happen.

Do you think the time it takes to make them is justified? Do you think the price for the materials is justified?

	Stretch Sensor	Pressure Sensor	Electrode Ring
time	One hour would be okay for me	The 30 minutes needed are quite good for a pressure sensor	One hour is reasonable
price	All the prices are very reasonable		

Would you say the outcome of the project is relevant to the wearable technology field?

Yes, it is very relevant. Even if they are not the best sensors, it is good to research. The findings could also be an inspiration for better things. It is

also relevant to know what did not work.
The pressure sensors available are quite expensive while yours are quick and easy to make. I see myself using them in my future projects

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