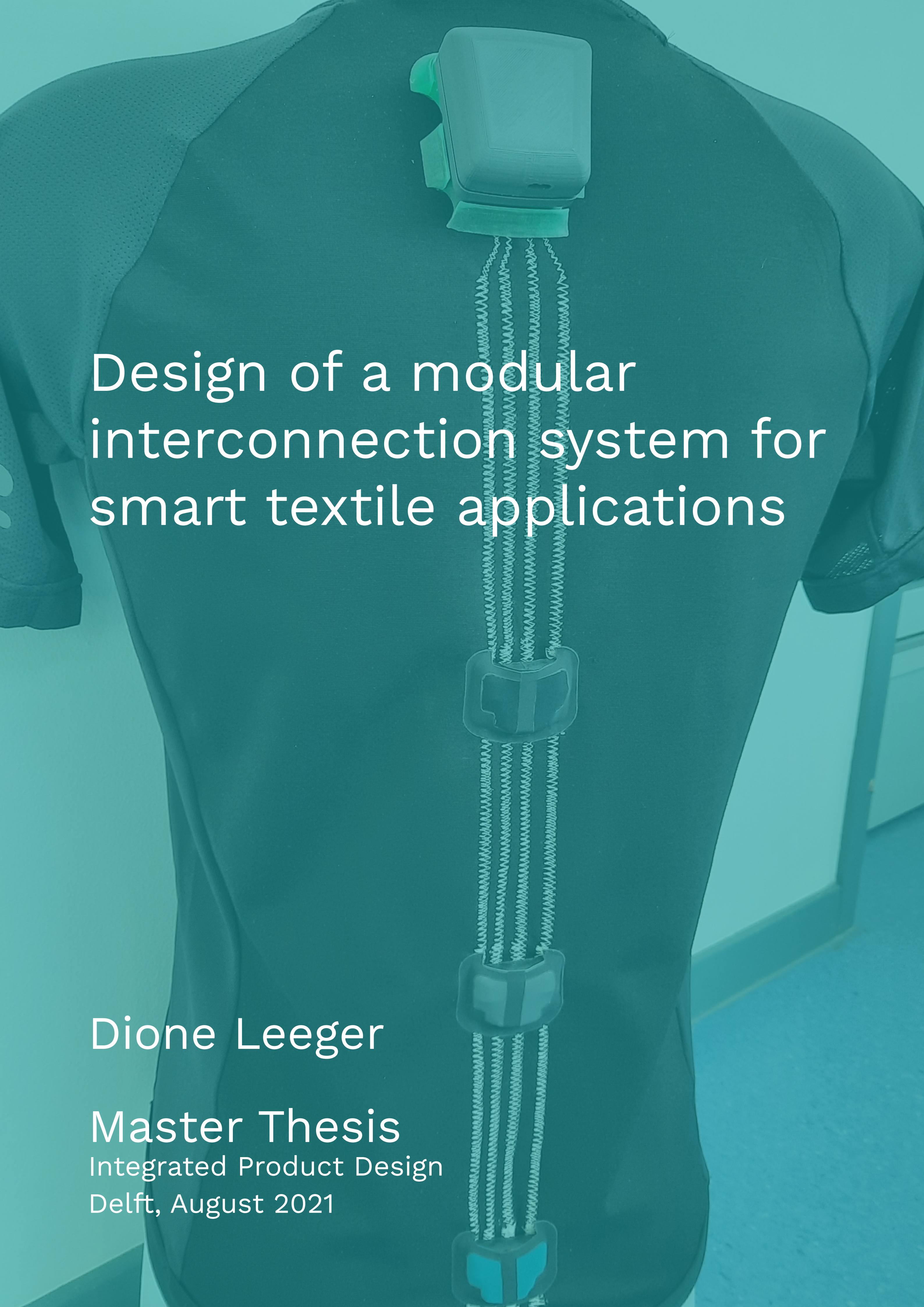

Design of a modular interconnection system for smart textile applications

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Master Thesis

Integrated Product Design

Delft, August 2021

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Glossary

Acronyms

AC= Alternating Current

AHRS = Altitude and heading reference system, also known as a compass system.

B2B = Business to Business, a market strategy where companies make money by selling products to other companies.

B2C = Business to Consumers, a market strategy where companies directly sell products to consumers.

CE certified = Conformité Européenne certified. All products sold on the European market should adhere to these standards, or else trading them is not allowed.

DC = Direct Current

ECA= Electrical Conductive Adhesives

EMC= Electromagnetic Compatibility, one of the tests which a product including electrical components should pass to get CE certified. The general rule is that the product should not disturb other products in its environment and should not be disturbed itself by other products in its surroundings. (D. van Elteren, personal communication, March 3, 2021).

ERM = Eccentric Rotating Mass, a type of haptic feedback vibration motor that spins an unbalanced mass to create vibrations.

FPC = flexible printed circuits

FFC= Flexible flat cables

I^2C-bus= Inter-Integrated Circuit bus

IMU = Intertial Measurement Unit

IoT = Internet of Things

IP-Code = Known as the Ingress Protection, which says something about the level of protection of the construction of the product and/or of electrical components inside a product. It's standardised according to the IEC 60529 norm (IEC, 2001).

LRA = Linear Resonant Actuator, a type of haptic feedback vibration motor where a magnetic coil pushes a mass up and down to create vibrations.

NCA= Non Conductive Adhesive

MNB = Mission Navigation Belt, one of the products of Elitac Wearables that allows soldiers to navigate through haptic feedback.

PCB = Printed Circuit Board

PTTC = Plastic Threaded Chip Carrier

Terms

Haptics = "Haptics is the science and technology of transmitting and understanding information through touch." - Ultraleap (2021a, par. 1)

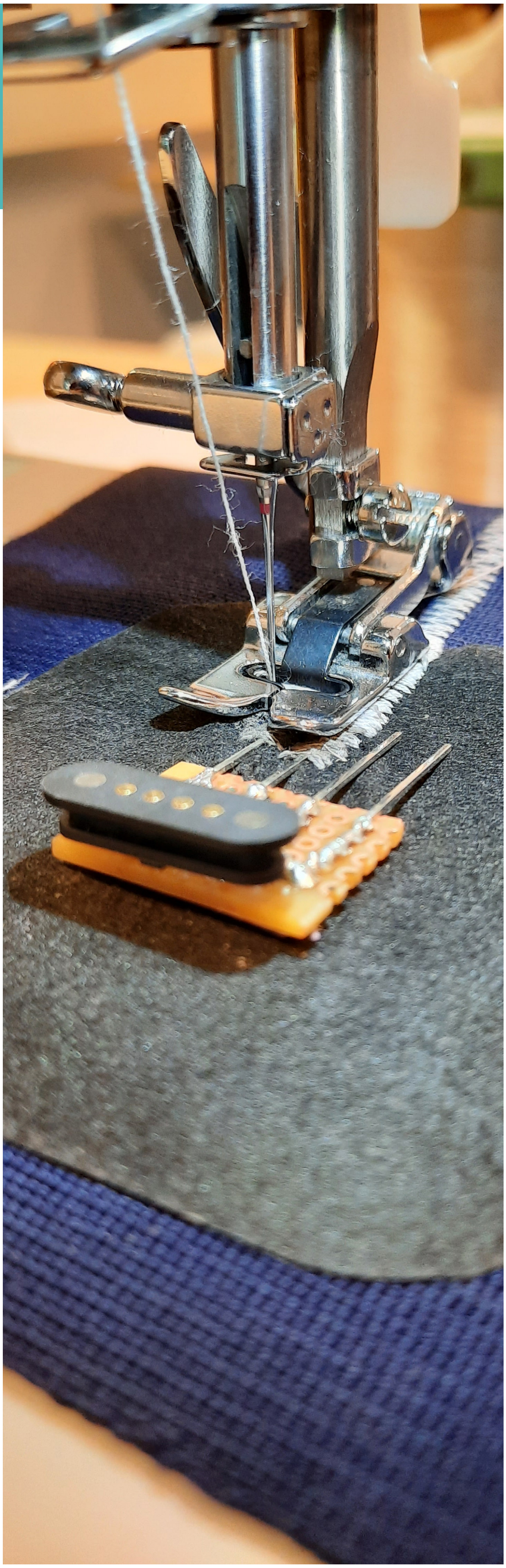
Haptic feedback = "Haptic feedback is the use of touch to communicate with users" - Ultraleap (2021b, par. 1)

Interpolation = The creation of a virtual vibration motor, on a location where no vibration motor is placed, created by adjusting the vibration strengths of vibration motors in its surrounding.

Smart textiles = "Can be described as textiles that are able to sense stimuli from the environment, to react to them and adapt to them by integration of functionalities in the textile structure. The stimulus as well as the response can have an electrical, thermal, chemical, magnetic or other origin." - van Langenhove et al. (2007, p. 106).

Tactor = Short for tactile actuators, which are devices that can create motion that allow electronic devices to transfer information to the user through their sense of touch (Motola-Barnes, 2019). In this report, when referring to a tactor module this will be a small electrical device that includes an ERM vibration motor and a driver to enable haptic feedback.

Wearables = "Also known as wearable technology, is a category of electronic devices that can be worn as accessories, embedded in clothing, implanted in the user's body, or even tattooed on the skin. The devices are hands-free gadgets with practical uses, powered by microprocessors and enhanced with the ability to send and receive data via the Internet. " Hayes (2020, par. 1).



Abstract

This graduation project set out to design a modular interconnection system for smart textile applications for Elitac Wearables, that is widely implementable, robust, durable, cleanable, cost-effective, more integrated in the textile carrier and ergonomically to wear.

The Double Diamond Design Process methodology of the Design Council (2015) is adjusted to a 4 phase Diamond Design process to guide the process towards a final embodiment design.

Phase 1. Understanding the problem
In this phase the focus lies on finding the key challenges Elitac Wearables is facing when designing smart textile wearables. The challenges identified are: the lack of proper integration of electronics & the textile carrier, and no robust and durable (inter-)connections. Furthermore, cable management poses a real challenge as classic electrical wiring is used. A fourth challenge is the cleanability and waterproofing of designs, allowing them to be laundered by users. Also, products are not fit for mass production due to the lack of scalable production processes, the availability of parts for longer periods of time and high prices.
Next, market research is conducted, showing that the development of wearables is increasing, electronics are become more and more integrated in the textile carrier and the most important electronics are removed before washing. However, the standard of washing is still often a delicate hand wash and air drying without wringing. All findings were summarised in a problem definition and a program of requirements & wishes.

Phase 2. Finding building blocks for haptic feedback systems
Technology literature research and practical tests are conducted to select technologies that can help solve the problems found in design phase one. The technologies are rated on mechanical properties, conductive properties, processability, stretchability, flexibility, durability, and costs. High potential technologies I selected during this research are: flat cables, conductive yarns, conductive textiles & conductive inks for power and data transport. Interesting electrical connections are: the lamination process described by Krshiwoblozki et al. (2012), conductive glue and conductive yarn. The same goes for the following integration techniques of textiles and electronics: tapes, lamination, piping & tunnels, overmolding, sewing pads and knitting pockets. Moreover, pogo pins, snap buttons, conductive Velcro and the ball point pocket connector were all considered to be good candidates for removable connectors.

Furthermore, in this study, the solution has been divided into four modules:
• Module A. The tactor, containing an ERM and a driver PCB;
• Module B, The power & data transport, interconnecting all electrical modules;
• Module C. The main controller, containing the micro controller and power supply;
• Module D. The textile carrier, made of stretchable and breathable materials that makes the technology wearable.

Phase 3. Mounting haptic feedback systems to garments
With the input form phase 2, multiple concepts are generated of which two are eventually chosen by Elitac Wearables for further development and prototyping. The first concept is based on conductive yarn knitted pockets and conductive Velcro as connector. The second concept implements sewn conductive yarn traces and a pogo pin connector. First tests show good data reliability and launderability properties. In the end a hybrid version of the two concepts is developed as final design in phase 4.

Phase 4. Embodiment design of the haptic feedback system

The final embodiment design implements a power and data transport system consisting of 4 non-isolated sewn conductive yarn traces to enable I^2C communication, see Figure A1. The waterproof and overmolded tactor module integrates 4 conductive strips. These are pressed against the conductive yarn traces, ensuring the electrical connection, by placing them inside tight pockets on the textile carrier. The main control module is connected through a magnetic male pogo pin connector. An overmolded landing spot with the female pogo pin connector acts as easy attachment point for the main module.
A functional prototype is presented and able to power 3 tactor modules at the same time. User tests show a high level of comfort, but also room for improvement of the interaction when placing the tactor modules inside the pockets and the size of the main module.

Evaluation

When reconsidering the goal of this graduation project (the design a modular interconnection system for smart textile applications for Elitac Wearables, that is widely implementable, robust, durable cleanable, cost-effective, more integrated in the textile carrier and ergonomically to wear), the design fulfils most of the requirements. The final design scores well on the following design drivers: ***widely implementable, scalable, cost effective and cleanable.*** The modular system can be used as a ***design tool*** for future smart textile wearables, as the location of the conductive yarn traces, the main control module, the number of tactors and their placement can be varied as desired. Moreover, the design builds on the strengths of Elitac Wearables, as it implements currently used electronics, materials and production processes that are well-known to the company. The modular design also leaves room for easy reuse/replacement/possible repair of electronics, extending the use phase compared to some previous design of Elitac Wearables that fully embed the electronics in the textile carrier. This also creates new opportunities when it comes to B2C business model strategies (e.g. a subscription based service). Furthermore, most of the materials implemented can be laundered at a 30 degrees Celsius delicate machine wash. However, the ***robustness and durability*** of the design is ***still questionable*** when it comes to ***corrosion*** of conductive yarns caused by artificial sweat. The wire fragmenting is also something that will need to be prevented in future designs. Moreover, the ***ergonomics*** of a prototype of the design is rated to be comfortable during user tests as it does not restrict participants in their movement and the electrical modules are barely noticeable. What still needs to be improved is the placement of the tactors inside the pockets and the size of the main module.

All in all, the final embodiment design seems to have reached the goal of this master thesis, with some improvements to be made on the robustness & durability and ergonomics in the future.

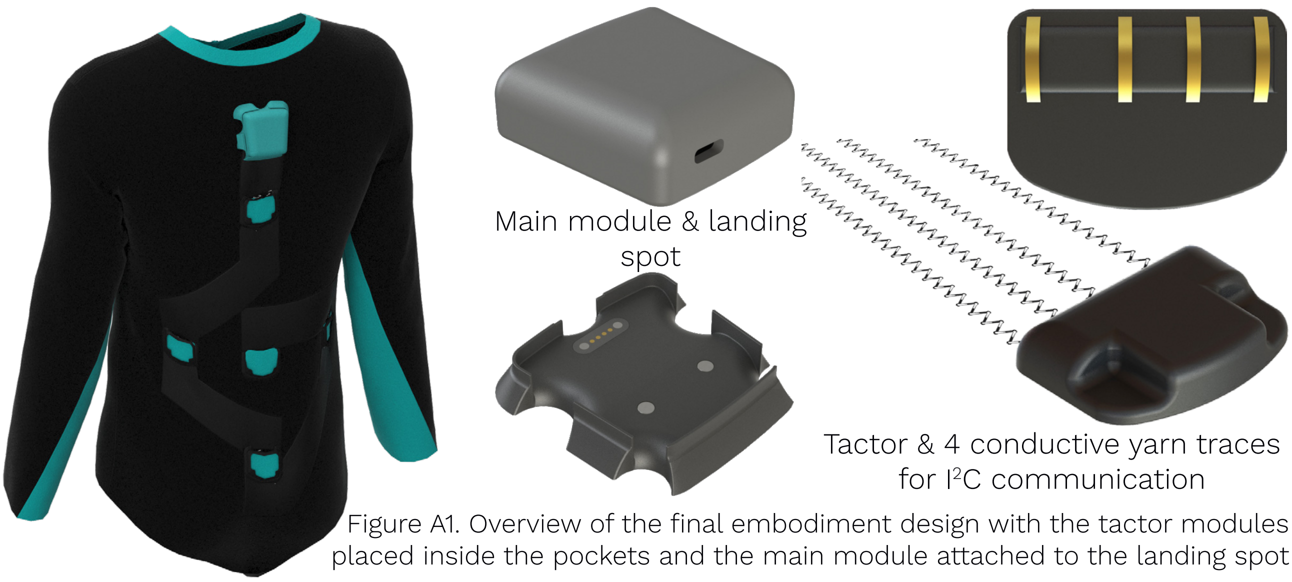


Figure A1. Overview of the final embodiment design with the tactor modules placed inside the pockets and the main module attached to the landing spot

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Introduction

The goal is to get a basic understanding of the project as a reader, to set a foundation before diving into more details.

In chapter 1, the project is explained together with the scope and the general report layout (paragraph 1.1). Then, in paragraph 1.2 the company is introduced, followed by an explanation of the design approach in paragraph 1.3. In addition, the principles of haptic feedback and a system component analysis can be found in paragraph 1.4 & 1.5 Finally, in paragraph 1.6, the general challenges of the smart textile wearables market found in literature are discussed.

1. Introduction

1.1 The Project

The use of ***smart wearables***, ***wearable devices that can actively sense, process and react to data collected***, is becoming more and more popular in the ***healthcare & medical, industrial, defence*** and ***sports sectors***. According to Buchilly (2018) the overall wearables market was good for 113,2 million shipments in 2017, and is expecting a growth of 222,3 million shipments in 2021. Smart wearables are not only used to ***monitor people's health***, but also have real potential to ***improve everyday life***, ***facilitate more effective trainings*** or ***increase the safety of working conditions*** amongst others.

Currently, smart wearables are worn more and more closely to the body, in order to collect, react and store real-time biometric & movement data. To ***facilitate ergonomic wear*** and ***ease of use***, smart wearables are becoming more ***integrated in textile carriers***, creating ***smart textile wearables***.

The integration of electronics and textiles is creating difficulties material wise, as ***hard, rigid and vulnerable electronics have to be integrated in, durable, stretchable, flexible and washable textiles.*** Moreover, the ***scalability of technologies*** used and the ***industrialisation of the fabrication processes*** are challenging according to Kirstein (2013). Cherenack & Van Pieterson (2012) continue to argue that the electronics industry still dominates product development. Next to this, clothes are considered to be a ***fashion item***, making it important to find a ***balance between functionality, ergonomics*** and ***aesthetics*** (Cho et al., 2009).

Elitac Wearables is a specialist in developing haptic feedback wearables and garments for the health, safety/professional and sport sectors. They develop products made from a textile carrier on which a sensor, vibration motors and a control module is placed to provide haptic feedback to its users. Their products are developed for research and R&D purposes (e.g. on human motion) or to provide haptic feedback to a specific target user in a context. An example of a research product is the ScienceSuit (see Figure 1), a unisex shirt that allows users to place a string of in series chained vibration motors (tactors) and a control module at a preferred location on the body. Whereas the BalanceBelt, shown in Figure 2, is an example product that provides haptic feedback to a target user. It helps people with a severe balance disorder to gain back their balance.

Even though the current products of Elitac Wearables are designed to do their job well, the company wishes to improve and innovate the technology used and integrate the textile carrier with the electronics more in future designs. Allowing them to pioneer further in the technological trend of smart textiles and wearables for professional/commercial use, while also maintaining a competitive advantage over rivalling companies.

This report therefore presents a research into the creation of a haptic feedback technology system for Elitac Wearables, that can be widely implemented in textile carriers for different use cases. The goal is to create:

"The ***embodiment design*** of a ***modular, widely implementable, cleanable*** & ***cost-effective electronics design***, that is more ***integrated*** in the textile carrier and remains ***ergonomically*** to wear on the body"

There are ***three levels of focus*** defined and the order in which they appear determines the level of importance:

1. The embodiment of a robust, durable, scalable & widely implementable technology

↓

2. That is integrated in the textile carrier

↓

3. And is cleanable

The following will be considered to be inside of the project scope: The wiring (power & data supply), electrical modules (vibration motors, control module), the (inter-) connection between modules & the textile carrier and the cleanability of the system. Furthermore, for the final feasibility demonstrator the type of textile wearable has to be determined. The location on the body, its material, the configuration and number of tactors used have to be designed. Moreover, the ergonomics and aesthetics of the design will be included to create desirable product. Finally, the viability, of the technology design will also be addressed.

What is considered out of the scope is: Vibration patterns, data processing & visualisation (user interface) of the sensors , the sensor design with its connected PCB together with firmware.

The sensor to be integrated in the final demonstrator is an IMU, also known as an Inertial Measurement Unit, that can determine an objects orientation in space.

A great opportunity of the project is to try and apply in practice research previously done on robust electrical interconnections and integration of electronics with textiles. This can decrease the time it takes for these innovative new technologies to go to market so the world can hopefully profit from them faster commercially.

The original project brief can be found in Appendix A1.

Figure 1. ScienceSuit (Elitac Wearables, 2021).

Figure 2. BalanceBelt (Elitac Wearables, 2021).

Report layout

This report will present the process towards the creation of this robust, scalable and durable technology system. In the first part of the report Introduction (chapter 1) the project, approach, the company and basics of haptic feedback will be discussed to give the reader a kicks-start in understanding the concept of haptic feedback and the company we are designing for.

Phase 1.

In chapter 2 the company Elitac Wearables will be assessed by taking a look at use-cases and applications of products in paragraph 2.1. Moreover, in paragraph 2.2 a summary of the results from internal interviews are discussed, explaining the main challenges Elitac is currently facing when designing haptic feedback wearables.
Chapter 3 focusses more on market research, where a brief trend analysis of the smart wearables field is given in paragraph 3.1. In addition, a state-of-the art of smart textile wearables can be found in 3.2, together with an analysis of competing products and the cleanability in paragraphs 3.3 and 3.4 respectively.
Next, in chapter 4, the important ergonomic factors are presented that need to be taken into account during the design phase.
Chapter 5 presents a brief summary of all the insights gathered during the company, market, cleanability and ergonomics research.
Based on these findings, chapter 6 presents a detailed problem definition in the form of a problem tree. This allows us to break down the problem in small parts, to make the overall problem more specific and tangible.
Finally, in chapter 7, the design drivers and the program of requirements and wishes are presented in paragraphs 7.1 and 7.2 respectively.

Phase 2.

The goal of this phase is to dive deeper into interconnection technologies necessary to solve the problems defined in phase 1.
Chapter 8 therefore presents the technology research about wire connections for power and data transport (8.1), electrical connections (8.2,), integration techniques of electronics and textiles (8.3) and removable connections (8.4). In addition, modular electronics are explored in paragraph 8.5 for inspiration.
Chapter 9 describes initial test of ERM motors used by Elitac Wearables in paragraph 9.1. Resistance tests and corresponding calculations are presented in paragraph 9.2. Moreover, a conductive yarn demonstrator is presented in 9.3, followed by a conductive velcro and ink test in paragraphs 9.4 and 9.5.
Chapter 10 presents a categorisation of the modules to be designed in the solution.
Chapter 11 summarises the general conclusions of phase 2.

Phase 3.

The goal of the third phase is to develop concept solutions and build prototypes for testing and validation.
In chapter 12, two out of five concepts are presented: Conductive yarn knitted pockets and conductive velcro in paragraph 12.1 and Sewn conductive yarns & pogo pins in paragraph 12.2
The prototypes and insights are elaborated in chapter 13. Where paragraph 13.1 describes the electronics and 13.2 & 13.3 the two concept prototypes.
Chapter 14 is al about evaluating the concepts, as paragraph 14.1 investigates the launderability of conductive yarns, 14.2 the current versus heat tests, 14.3 analyses the data reliability of both concepts and 14.4 presents a weighted criteria method & design choice.
Chapter 15 finalizes phase 3 by presenting the overall conclusions.

Phase 4.

In this last part of the report, the goal is to present and evaluate the Final Embodiment Design of the modular haptic feedback system solution.
First, in chapter 16 the case study Gait Keeper will be introduced on which the final design is inspired. Followed by an aesthetics design in chapter 17.
The final design of the solution is presented in chapter 18, which is divided in a feasibility (18.1), viability (18.2) and desirability (18.3) part.
In chapter 19, a final functional demonstrator is presented together with user tests and an artificial sweat test.

Chapter 20 presents the final evaluation and limitations of the design. In chapter 21, the final conclusions and recommendations are presented for future optimisation of the design.

1.2 The company Elitac Wearables

In this chapter the problem owning company, Elitac Wearables, is analysed. The main goal is to empathize with the company in order to create a problem definition in the define stage.

Figure 3. Logo Elitac wearables (2021).

Elitac Wearables was founded in 2012 and focusses on the development of ***wearables***, with a specialisation in ***haptic feedback technology*** and the ***integration*** of ***electronics & textiles***.

Vision & Mission

Elitac wants to add real value, by improving the safety, the performance or the quality of life of their users. This mentality is also strongly visible in their mission:

> *" With our wearables, we want to help improve the daily lives of at least one million people before 2035 " - Mission*
> *(Elitac Wearables, 2021a, par. 1)*

Market sector

Elitac Wearables develops wearables for the ***medical, safety, defence*** and ***sports sector*** (See Figure 4). They work closely together with partners to develop an idea into a commercially viable product. In order to keep a competitive advantage and be part of new technological developments, they constantly invest in research.

Figure 4. Market sectors of Elitac Wearables

Product categories

Elitac Wearables has two distinctive product categories when it comes to their product portfolio: Upper body garments and Belts that provide haptic feedback to its user.

Upper body garments

Shirts, tops and vests can be found in the upper body garment sector. In Figure 5 an example of the such an upper body garment is given: The Cycling Shirt

This shirt is used by athletes to make their trainings more effective. A heart-rate sensor measures the heart-rate and 3 vertical vibration motors provide feedback on this. Moreover, 4 vertical vibration motors provide navigation info to the athlete. The product was developed together with Byborre and is fabricated through knitting. The user is actively and dynamically moving when wearing this product. (Elitac Wearables, 2020a)

In Figure 6 another shirt can be found, the SmartShirt (Elitac Wearables, 2020b). This product can track the movement of an athlete with precision, so they can optimise their game.

Belts

Elitac Wearables has developed two types of belts: The Mission Navigation Belt together with the Netherlands Ministry of Defence and the BalanceBelt developed in collaboration with Maastricht University Medical Center+ among others.

In Figure 7 the BalanceBelt is shown, which helps balance disorder patients by tracking their body position and balance and providing them with correctional haptic feedback (Elitac Wearables, 2021b).

Conclusions

Elitac Wearables is technology company specialised in the development of ***haptic smart wearables*** and works in the ***healthcare, safety, defence and sports sector.*** Their product portfolio consists of two main categories: ***belts and upper body wear.***

Figure 5. Cycling Shirt (Elitac Wearables, 2020)

Figure 6. SmartShirt (Elitac Wearables, 2020).

Figure 7. BalanceBelt (Elitac Wearables, 2021).

1.3 Design Approach

The design approach of the project is based on the Double Diamond Design Process (Design Council, 2005), which consists of 4 stages Discover, Define, Develop and Deliver. This methods helps to go from a general problem to a specific problem statement and solution in a project.

During this graduation project, the design approach was adjusted from two to four diamonds, as shown in Figure 8. The four phases presented now are: Understanding the problem, Finding building blocks for haptic feedback systems, How to mount haptic feedback systems to garments & Final embodiment design of the haptic feedback system.

Phase 1: Understanding the problem

The goal of the first design phase is to empathise with the problem owner Elitac Wearabes and get to a solid problem definition and design criteria for the solution. Therefore, qualitative research was conducted through interviews with company employees of Elitac Wearables, to get a better insight of the problems they are currently facing. In addition, market research was performed to determine the state-of-the-art of smart textile wearables and competing products. Moreover, challenges in literature were analysed, to see how general problems Elitac Wearables is facing are. Also the cleanability and ergonomics of smart textile wearables is researched. Based on all these findings, a problem tree was created with sub-problems , design drivers, a program of requirements & wishes.

Phase 2: Building blocks for haptic feedback systems

The goal of the second design phase was to research and select solutions for sub-problems defined in phase one. An extensive technology research was conducted, giving valuable ideas for interconnections and power & data transport mediums. All potential solutions were benchmarked on durability, conductivity and processability amongst others. Furthermore, resistance tests and calculations were performed with vibration motors, to help specify design parameters such as the maximum allowed circuit resistance and current.
Moreover, small prototypes of power and data carriers such as conductive yarn, ink and Velcro were created to test the feasibility of these technologies for application in smart textile carriers. This phase is finalised with an all round conclusions summarizing the highest potential technologies.

Phase 3: How to mount haptic feedback systems to garments

The goal of the third phase was to use the high potential connection technologies found in phase 2, and generate a variety of concepts. These concepts were in turn evaluated together with the company, and two were picked for further development. The two concepts were prototyped and evaluated on launderability , data reliability & producibility amongst others. Finally, a weighted criteria method helped to select the concept with the highest potential: a hybrid version.

Phase 4. Final embodiment design of a modular haptic feedback system for textiles

In this fourth an final phase the goal was to optimise the chosen concept of phase 3 and translate this into a complete embodiment design. Three pillars were used to present the design; feasibility, desirability and viability. In the feasibility aspect, technology, materials and the production processes involved discussed. Viability talks about potential business cases and costs. Desirability present different application possibilities of the technology. The chapter then continues by presenting a final prototype, which was tested on data & power reliability, durability and wearability. Overall conclusions and recommendation finalize this thesis.

Discussion

Changing the Double Diamond Design Process to a Four Diamond Process was necessary due to the number of problems found. Multiple sub-problems were identified, during ***phase one,*** of which not all were directly related. Turning general ideation into a challenging task. Therefore, the ***second phase, Finding building blocks for haptic feedback systems,*** was added to the design approach. This allowed for the analysis of available technologies that could solve sub-problems. These sub-solutions were evaluated, and the high potential ones were used as building blocks to generate concepts during the ***third phase, Designing haptic feedback systems.*** This additional third phase allowed for more extensive prototyping and evaluation of concepts. Making it possible to develop the two concepts equally, which resulted in a well-argued choice. This also created room for innovative experiments such as knitting pockets or overmolding with silicone on textiles.
In ***phase four, Final embodiment design of the haptic feedback system***, there was room for detailed information on production, costs, applications and business potential. Resulting in a complete system design that can be implemented in the future.

The Double Diamond Design Process is presented as linear, however it must be stressed that a creative design process is never linear. Going back and forth between stages is normal and healthy. The report is presented as linear as possible, though the reader must keep the above stated in mind while reading.

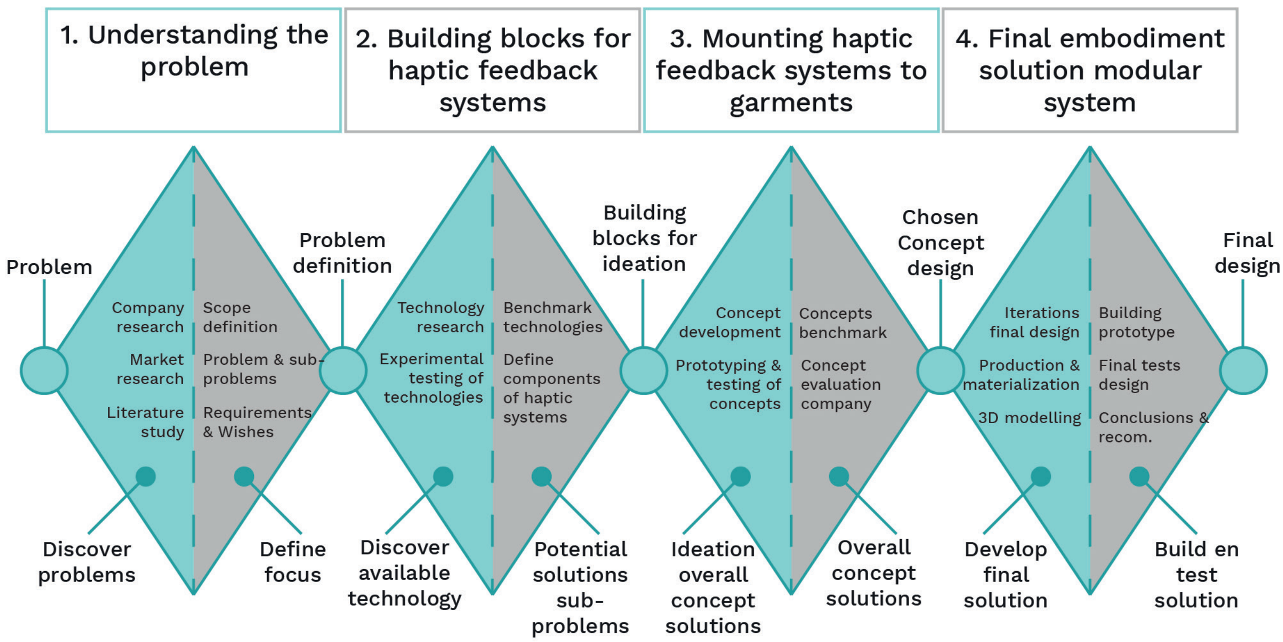


Figure 8. The Four diamond design process of the project.

1.4 The principles of haptic feedback

In this chapter the foundations of haptic feedback and the classification of haptic wearable applications are discussed. Moreover, the standard vibration motors on the market and their working principles are elaborated, together with the different configurations, also known as constellations.

What is haptic feedback

Haptic feedback, also known as tactile feedback or haptics, uses vibration patterns to convey information to its user.
These vibration patterns can be used by products to provide feedback, without the use of more invasive visual or audible alerts. An example is the way-point navigation used by the Mission Navigation Belt (Elitac Wearables, 2021c), that uses vibration patterns to guide soldiers in a particular direction, making additional communication redundant. According to Precision Microdrives (2021), a large motor producer, this form of feedback is in increasing demand to enhance or replace visible and audible forms of feedback.

Classification of haptic wearables

When categorising haptic feedback wearables, Shull & Damian (2015) present a classification according to the degree of sensory impairment of the user, see Figure 9. The first classification is total sensory impairment, resulting in sensory replacement haptic feedback. Next, partial sensory impairment will result in products that provide sensory augmentation. Finally, no impairment, results in products that provide training to its users. When applying the classification to the products of Elitac Wearables, the GaitKeeper project (providing tactile feedback for prosthetic leg users) would fall under sensory impairment, the BalanceBelt under sensory augmentation and the FysioPal, SmartShoulder & Cycling Shirt under Trainer.

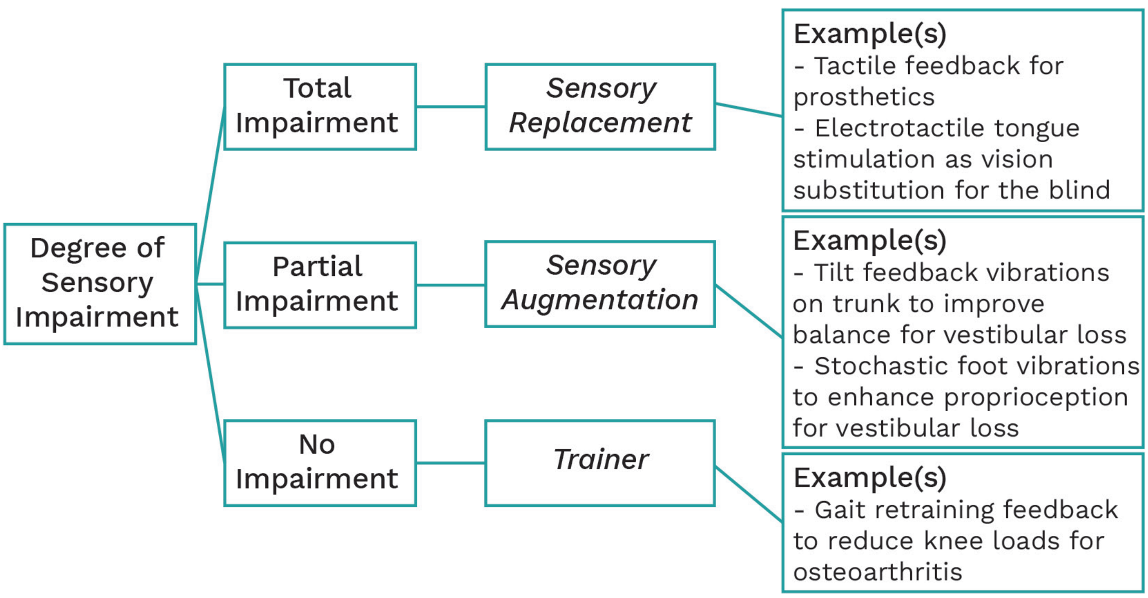


Figure 9. Haptic wearable applications classified by degree of sensory impairment (Shull & Damian, 2015, p. 2)

Vibration motors

In order to generate vibrations, so called vibration motors are used which are driven by an electronic circuit. A micro controller will determine when and how the vibration motors will vibrate, as the brains of the system. There are two types of well-known vibration motors on the market: ***ERM*** and ***LRA motors*.**

Eccentric Rotating Mass (ERM) motors

At present, Elitac Wearables uses Eccentric Rotating Mass (ERM) as haptic feedback motors in their designs. This cheap technology spins an unbalanced mass to create vibrations, which is either done in a shaft (Figure 10) or coin configuration. This technology relies on direct current (DC) voltage to operate. The shaft configuration can provide stronger haptic feedback than the coin configuration, and can be felt through multiple layers of fabric. The coin configuration is more suitable for direct skin contact. Downsides of ERMs are the large amount of power required for actuation, their size & weight (Precision Microdrives, 2021).

Linear Resonant Actuator (LRA)

The second well-known type of vibration motors on the market is the Linear Resonant Actuator (LRA), which uses a magnetic coil and spring to push a mass up and down, and relies on alternating current (AC) voltage. These vibration motors are cheap, are less heavy and have a faster start-up time than ERMs. However, they are still bulky, difficult to integrate in textiles, suffer a lot of energy loss due to the magnetic coil construction and less powerful than ERM vibration tactors (B. Bicknese, personal communication, Apr. 20, 2021). For a more detailed description of the different motors and alternative vibration motors and their pros and cons, See Appendix A2.

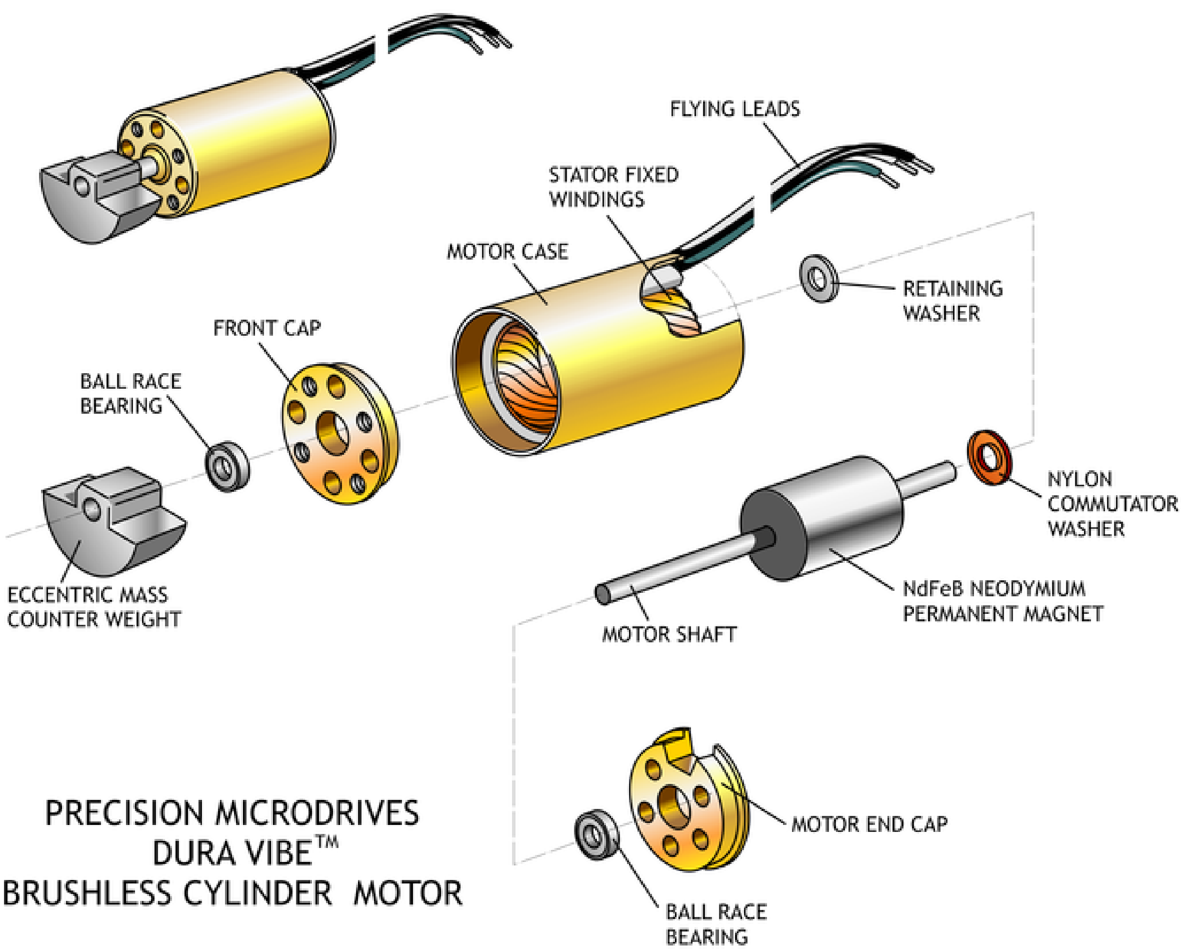


Figure 10. ERM in shaft configuration (Precision Microdrives, 2021a).

Constellations of vibration motors

During the design stage, the number of vibration motors in a product can be varied. Next to this, the configuration of how these motors are placed respectively can also be determined. This physical configuration will be from now on referred to as ***'the constellation'***, after a star constellation. Elitac Wearables uses three particular constellations: point, line and triangle.

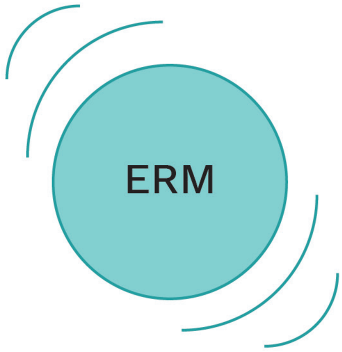


Figure 11. A point constellation, with just one singular vibration motor

Point constellation

The point constellation consists of just one vibration motor as shown in Figure 11. This constellation can only provide haptic feedback at the exact location of the vibration motor.

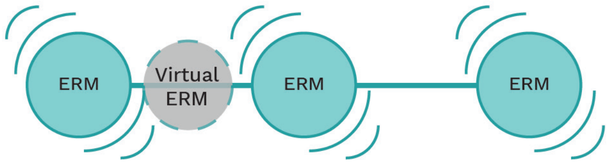


Figure 12. The line constellation with a virtual vibration motor visualised on a singular axis.

Line constellation

The line constellation as shown in Figure 12 & 14, allows for more haptic feedback freedom. Two vibration next to each other can be powered simultaneously, creating the sensation of 'a virtual' vibration motor. If both vibration motors are powered equally, the user will sense the vibration exactly in the middle of the two motors. By playing with vibration intensity of each motor, the virtual vibration can be sensed along the one dimensional line that represents the shortest distance between the two tactors. This phenomenon is also known as ***interpolation.***

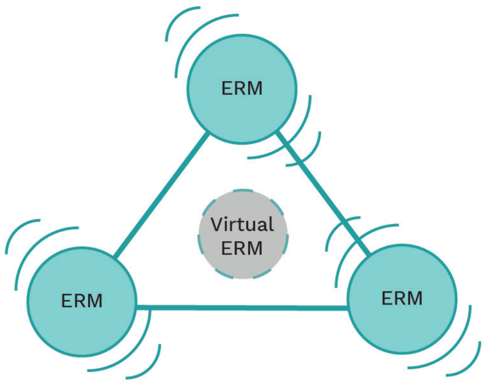


Figure 13. The triangle constellation, showing the virtual tactor over 2 axis.

Triangle constellation

The final constellation is the triangle constellation, which consists of minimally 3 vibration motors, see Figure 13. Again, interpolation can take place if all three motors are powered equally. A large advantage over the line constellation, is the two dimensional freedom of the virtual tactor. Meaning that the virtual tactor can be felt everywhere in the triangle, resulting in high precision haptic feedback. (B. Bicknese, personal communication, April 20, 2021).

Figure 14. Mission Navigation Belt implements a line constellation (Elitac Wearables, 2021)

1.5 Component analysis

In order to design a modular system for the products of Elitac Wearables, all products were analysed in terms of parts and functionality. A component overview is created to understand what parts should be included or compatible with the new solution. An overview of all the products can be found in Appendix A3, together with two products analysed more in detail. The main function of the products of Elitac Wearables is to support their user when doing a certain task. They enable them to perform a task better or to focus more another task at hand.

Textile carrier

The textile carrier has the functionality to make the product wearable on the body and allow for assembly of a larger electronics configuration on a soft body. Textile can either be stretchable and non-stretchable, woven, non-woven or knitted. A pattern is created to ensure a proper fit with the human body, see Figure 15.

Trims

Trims are all the components used to finish off a textile product. Examples are zippers and buttons. Trims have the functionality to enable the user to put on/off the piece of clothing more easily or adjust the size, see Figure 16.

Sensor

A sensor is part of the electronics hardware design and has the functionality to measure a certain property of the environment (e.g. light, temperature). The sensors used in the current products of Elitac Wearables are: light sensor, heart rate sensor, AHRS (compass), inertial measurement unit (IMU) & accelerometer. See Figure 17 for an example. Sensors most probably implemented in future products are heart rate ECG/ EMG electrodes, stretch, gas & pressure sensor according to G. de Hoog (personal communication, March 2, 2021).

Controller

The controller is a device that is the brain of a complete electronics system, and also falls under the electronics hardware category. It interprets the data collected by the sensor and tells the actuators how to respond to this data. The controller is often a Printed Circuit Board (PCB), see Figure 18. Presently, each actuator has it's own small PCB and there is one main PCB that communicates with them via an Inter-Integrated Circuit (I^2C-bus) communication system. Another option could be to use only one central controller and have individual data communication wires for each tactor, however this might cause extra interference and additional electromagnetic compatibility (EMC) radiation. (W. de Vos, personal communication, March 9, 2021). A low level of EMC radiation is necessary to get a product Conformité Européenne (CE) certified (enable trading on the European market).

Actuator

An actuator is a component that can have influence on its environment and is controlled by the controller. Examples of actuators used in recent designs of Elitac Wearables are eccentric rotating mass (ERM) tactors that vibrate (see Figure 19), power LEDs or speakers. An actuator is also considered to be hardware. For complicated actuators an additional hardware driver is necessary to act as intermediary between low-level electronics and the load (Schweber, 2020).

Power supply

Electrical components need a source of power to operate, this can either be done by tapping into an external power source or by implementing an internal battery (see Figure 20). When tapping into an external power source, an additional connection is necessary to facilitate this, for example (micro-)USB.

Figure 15. The Nadi X uses a stretchable textile as carrier for the electronics (Wearablex, 2021)

Figure 16. Examples of different kind of trims (Sewport, 2021)

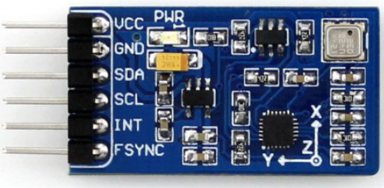


Figure 17. An IMU sensor (Waveshare, n.d.)

Figure 18. Seeeduino Xiao that can function as controller (Disrelec, n.d.)

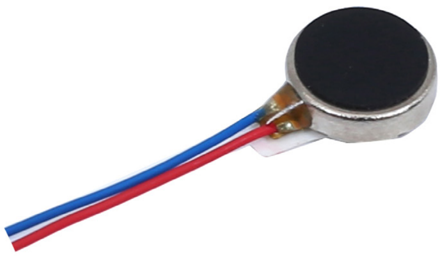


Figure 19. Coin ERM motor that can serve as an actuator (Alibaba, n.d.)

Figure 20. A 3.7V 600mAh Lithium-ion battery that can serve as internal battery (AliExpress, n.d.)

Wiring & interconnections

All electrical components need to be interconnected in order to communicate with each other. Also a power line is needed to allow each component to function. Electrical conductive wires are used to achieve this, and at present, thick inflexible cables are used housing a minimum of 4 separate wires, grouped in one insulating mantle, see Figure 21. A tactor needs at least 4 different wires, 2 power and 2 data lines. Recent research has been done with more flexible flat cables that have potential. Other potential options to create a connection between components is printing conductive material, conductive yarns or even wireless data transfer. At present, soldering and overmolding of conventional electrical wires is used as interconnection solution.

Casing

A casing has the functionality to protect vulnerable electrical components from dust & water. At the moment, casings are produced by applying the overmolding technique (PA) or through 3D printing, see Figure 22 & 23.

Connection textile to hardware components

In order to integrate the electronics with the textile carrier and make it one product, these have to be connected. At the moment, these are often integrated by creating cut-outs in a foam layer to submerge the electronics parts. These are then fixated by overmolding the electronics on a mesh material that is sewn or glued to the foam layer. A second option is creating an inner-outer sleeve construction, where the inner sleeve holds pockets for electronics and the outer sleeve protects it from dirt (Figure 23).

Software

Software is the internal code that tells the controller how to interpret the data collected from the sensors and how to control the actuators. Without software, the system would not know how to behave. Unlike hardware, this part is intangible. For this project, software is out of the of scope.
In Figure 24 & 25 a schematic overview of the components and their configurations used in designs of Elitac Wearables.

Conclusions

When designing a new more integrated technology system, this should consider the implementation of the following components: a ***textile carrier*** and ***trims*** to make the electronics wearable, ***sensors***, ***controllers***, ***actuators*** and ***drivers*** to make it smart, ***wiring*** for ***power supply*** and ***data*** (or wireless), ***interconnections between hardware components***, a ***casing*** to protect electronics from dust and water, ***connections between textile and hardware***, and lastly but considered outside of the scope, software design.

Figure 21. Currently used cables as wiring within products (Elitac Wearables, 2021).

Figure 22. A 3D printed casing for the controller of the ScienseSuit (Elitac Wearables, 2021)

Figure 23. BalanceBelt pockets in inner belt for overmolded tactors (Leeger, 2021)

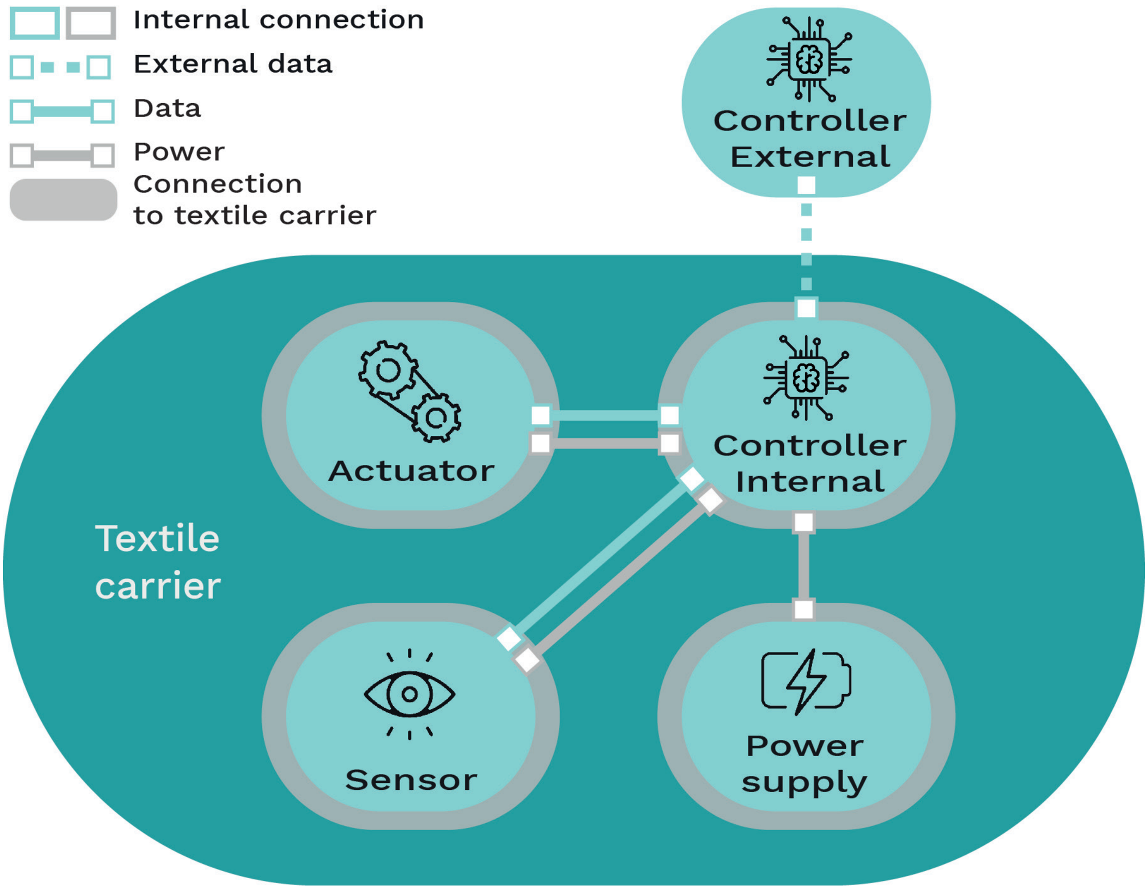


Figure 24. Component configuration products of Elitac Wearables with internal power supply

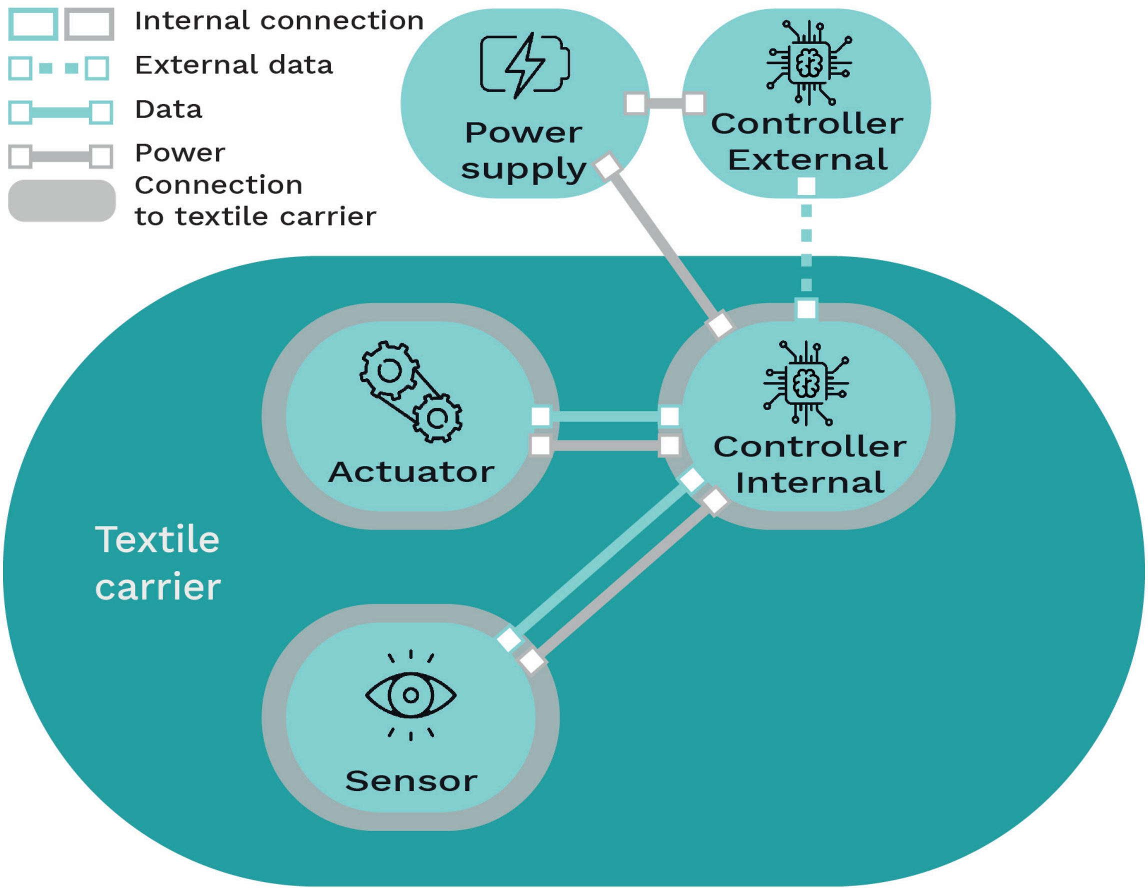


Figure 25. Component configuration products of Elitac Wearables with external power supply

1.6 Challenges of smart textile wearables in literature

In this paragraph the challenges of smart textiles described by literature are collected. This allows us to support our findings from the company interviews, analyse problems that might have been overlooked and possible interesting solution areas.

Usability
Cho et al. (2009) indicate that smart clothing should provide ***easy input*** and ***output interfaces*** to its user. The usability can be rated on five categories: ***learnability, memorability, errors, efficiency and satisfaction,*** see chapter 5 for more information on ergonomics for smart textile wearables. .

Durability
Smart textiles are required to withstand the harsh conditions during ***laundering and every day use***, and should either be removed or well protected before laundry according to Cho et al. (2009). Smart textile fibres may be exposed to large tensile strains and bending radii even smaller than 1mm. Moreover, the ***degree of tensile strain*** depends on the following three factors according to Cherenack & Van Pieterson (2012): the ***textile architecture***, the ***position on the body*** and the ***location of the textile circuit***.

Compatibility textiles and electronics
On the one hand ***electronics*** are often ***rigid*** and ***vulnerable,*** however ***textiles*** tend to be ***flexible, stretchable*** and ***durable***. However, the shape and size of electronics are being made more compatible with textiles and the development of electronic functionality into yarns and fibres is the next level, according to Kirstein (2013). However, the writer also mentions that the challenges will lie in the reliability of the functions and the scalability together with the industrialisation of the fabrication processes involved.

Cleanability
Washable electronics are still missing on the current market. At the moment ***electronics*** are either ***removed before washing***, or a ***waterproof packaging*** is used for protection (Cherenack & Van Pieterson, 2012).

Safety
According to Cho et al. (2009) safety of the ***physical form, electromagnetic waves*** and ***electrical current*** should not be forgotten in smart textiles, especially when worn close to the body.

Comfort
Comfort can be divided into three categories: ***thermophysiological comfort, sensorial comfort*** and ***body-movement comfort*** (Hatch, 1993). The thermophysiological comfort is about the interaction with the smart textile and climate effects on the body (heat, moisture, etc.). The feeling that users experience when the come in direct contact with the smart textile can is referred to as the sensorial comfort. Finally, according to Cho et al. (2009), the freedom of movement the smart textile allows is the body-movement-comfort. Adhering to all forms of comfort is often a challenge for smart textiles when hard, rigid, non-stretchable electrical parts are used.

Development, production & commercialisation
The ***scalability*** of technologies used, and the ***industrialisation of the fabrication processes*** was already mentioned to be a challenge according to Kirstein (2014). Moreover, Cherenack & Van Pieterson (2012) argue that the electronics field still dominates product development. Moreover, clothes are considered to be a fashion item, making it important to find a balance between functionality, ergonomics and aesthetics (Cho et al., 2009).

Furthermore, Cherenack & Van Pieterson (2012) mention that product development in such an innovative field can result in many unsuccessful prototypes. The use of the newest technological developments when it comes to electronics, textile and production processes, increases the pricing of smart textiles making them too expensive for the average consumer (Cherenack & Van Pieterson (2012).

Power supply

Every electrical component will need power to function. For smart textiles transportable power is preferred, to allow free movement of the user. Most smart textiles are therefore powered by rechargeable batteries. Some systems, such as these of Elitac Wearables, require rather large power to operate. Making it difficult to integrate the power sources due to their size, weight and rigidity (Cherenack and Van Pieterson, 2012). Recent research has been focussing on the development of more ***flexible and lightweight power sources***, such as flexible printable batteries (Patringenaru, 2020), ***super capacitors*** and ***energy harvesting devices*** such as tribo-electric nanogenerators (Somkuwar et al., 2020).

Conclusions

The main challenges of smart textile wearables mentioned in literature were analysed in this paragraph. These vary from ***usability*** and ***durability*** to the ***compatibility of textiles and electronics***. Moreover, the ***cleanability*** and ***comfort*** were mentioned as important factors to pay attention to. In addition, ***product development and production*** should keep in mind the ***scalability*** and the ***industrialisation*** of the fabrication processes. This also has a direct effect on the difficult ***commercialisation*** process of the smart textile wearables. Finally, ***wearable power supply*** still poses a real challenge, even though electronics are becoming more sustainable in power consumption. Flexible batteries and energy harvesting devices are currently being developed and researched for future implementation in smart wearables.

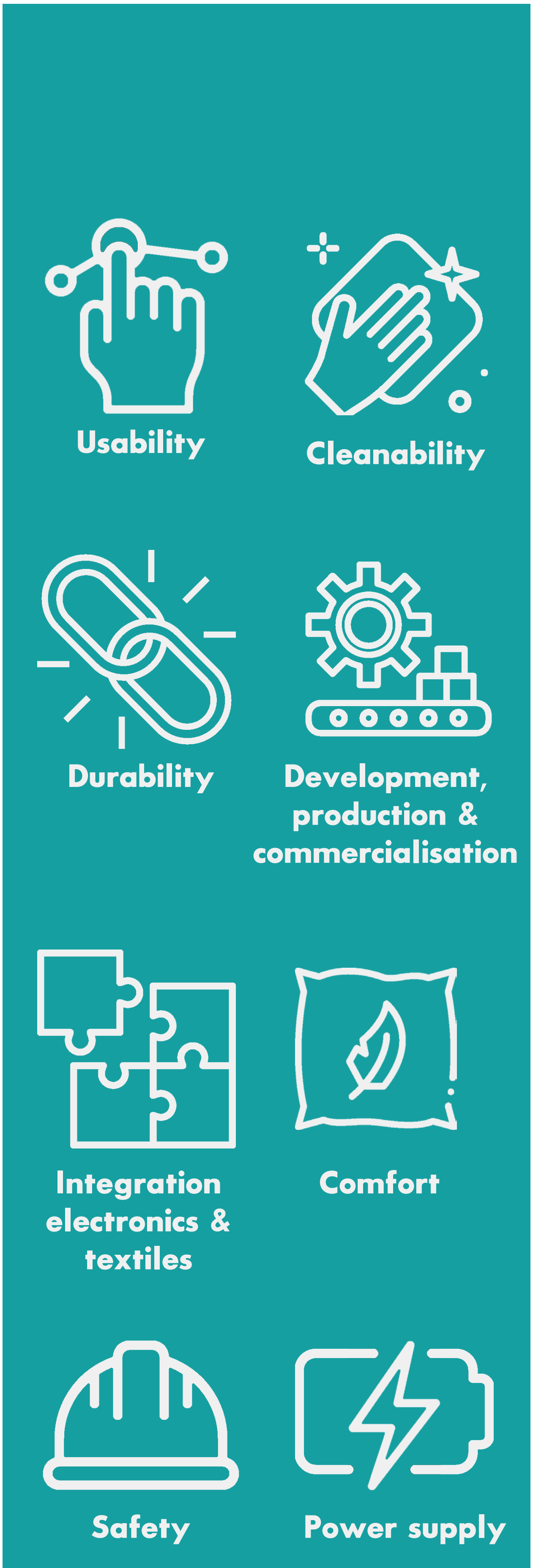


Figure 26. Challenges in literature of smart textile wearables

Phase 1. Understanding the problem

The main goal of Phase 1 is to emphasize with the problem owner Elitac Wearables and getting to understand the field of smart textile wearables.

In chapter 2 the company Elitac Wearables will be assessed by taking a look at use-cases and applications of products in paragraph 2.1. Moreover, in paragraph 2.2 a summary of the results from internal interviews are discussed, explaining the main challenges Elitac is currently facing when designing haptic feedback wearables.

Chapter 3 focusses more on market research, where a brief trend analysis of the smart wearables field is given in paragraph 3.1. In addition, a state-of-the art of smart textile wearables can be found in 3.2, together with an analysis of competing products and the cleanability in paragraphs 3.3 and 3.4 respectively.

Next, in chapter 4, the important ergonomic factors are presented that need to be taken into account during the design phase.

Chapter 5 presents a brief summary of all the insights gathered during the company, market, cleanability and ergonomics research.

Based on these findings, chapter 6 presents a detailed problem definition in the form of a problem tree. This allows us to break down the problem in small parts, to make the overall problem more specific and tangible. Finally, in chapter 7, the design drivers and the program of requirements and wishes are presented in paragraphs 7.1 and 7.2 respectively.

These findings will serve as starting points for research in phase 2.

2. Company research

In this chapter the problem owning company, Elitac Wearables, is analysed. The main goal is to empathize with the company and get to know the problems they are currently facing. The information is used as input for a problem definition including a problem tree, a program of requirements and a program of wishes.

2.1 Use-cases and applications of Elitac Wearables' products

In Appendix A3 the use cases of the products of Elitac Wearables were analysed. From this overview we can divide the type of use-case in 4 categories use during high profile work, physical activity, everyday life and during medical treatments & recovery.

Use during high profile work

The user is under high physical stress or has a physical job at hand that requires focus. The goal of the smart wearable is to take away side tasks, so the user can focus more on the main task with physical risks. Examples of this type of product are the SmartShoulder (Figure 27) and the MNB. The SmartShoulder allows field technicians to keep their hands free during maintenance work by providing them with automated lighting, while the MNB sends soldiers directional haptic feedback so they can navigate without looking at their GPS system. Both products are considered to fall under the category trainers as explained by Shull & Damian (2015) paragraph 1.4.

Use during physical activity

The user is participating in physical activity and wants to train more effectively. The goal of the smart wearable is to provide the user with feedback on their physical state of being. Examples of this type of product is the Cycling Shirt (Figure 28), which provides the user with feedback on their heart-rate. This product is considered to be a trainer.

Use during everyday life

Some of the products are used during everyday life. The main goal is to take over a task that the user is unable to do themselves anymore or support them in an everyday task. Examples of this type is the BalanceBelt (Figure 29) which allows the user to keep their balance again even though they have a balance disorder. It can be placed under the product categories sensory replacement or sensory augmentation.

Use during medical treatments & recovery

Some products are used by an expert while treating a patient and others are used to help recovery the patient faster from medical injuries. The goal is to take pressure off the user and allow them to focus more on the task by providing them with additional feedback. Examples of these type of products are the NeuroShirt, which informs a surgeon about the proximity of critical structures during skull based operation, and the FysioPal (Figure 30) that helps rehabilitate the body from health related problems caused by incorrect posture and upper-body positions. The NeuroShirt could be considered a sensory replacement device, as it takes over the visual translation of information by the user. The FysioPal can be considered a trainer.

A new project that is being setup by Elitac that also falls under the latter category is GaitKeeper, in which a smart haptic feedback wearable helps to teach first-time prosthetic leg users to learn to walk faster, easier and safer. This project will be elaborated on further in chapter 16 and used as a case during the concept creation phase.

Conclusions

The ***context of use is often diverse,*** as products can be used in ***active, high demanding outdoor context, general everyday life*** situations or ***static indoor contexts*** where the user needs to perform a task highly concentration. However, the overall goal of the product is to ***support*** the user and ***make their job to do easier.*** The level of support of a haptic feedback smart wearable can be classified according to the level of sensory impairment of the user: Sensory replacement, sensory augmentation or trainer (Shull & Damian, 2015).

Figure 27. Use during high-profile work: A field technician doing maintenance in a remote area (Elitac Wearables, 2021)

Figure 29. Support of everyday life: a user walking with the BalanceBelt (Elitac Wearables, 2021).

Figure 28. Physical activity support: Heart-rate tracking of a training athlete (ANN ID, 2018)

Figure 30. Medical recovery: Fysiopal being worn for posture correction. (Elitac Wearables, n.d.)

2.2 Interviews with employees of Elitac Wearables

Qualitative interviews with employees from Elitac Wearables were conducted to get a better overview of the stakeholders involved in the project and to analyse occurring problems in their designs. Only the main takeaways will be elaborated in this part of the report. For a more detailed overview and the transcriptions of the interviews, see confidential Appendix C1. A total number of 9/19 employees participated. The departments represented were R&D Marketing & Hardware.

The main goal of the interviews was to answer the following two questions:

1. What are currently the problems the company is facing with the products they are designing and producing?
2. Do employees have a vision for a solution direction?

Key challenges

The first challenge is the ***integration of electronics and textile***, both materials wise and industry wise. Electronics are rigid, fragile and often not washable, where textiles are the direct opposite, being flexible, durable and washable. The two industries involved are thus not familiar with each others materials and production processes. Also, assigning a responsible party for integration is difficult. When and how to involve both sectors in the design process also remains a question unanswered. This challenge is confirmed by literature in paragraph 1.6.

A second confirmed challenge is creating ***robust and durable connections.*** Products most often break at connection points, as high tension areas are created when materials transition from hard to soft. Also, daily use and cleaning put high mechanical stresses on these connections. Furthermore, hard parts pulling on the textile carrier, make products aesthetically and ergonomically unpleasant to wear.
Thirdly, designing for ***mass production,*** (thousands of products a year) is difficult, as production techniques are not yet scalable in terms of time and costs.
Again, this was confirmed during the literature study in paragraph 1.6. Therefore it is extremely important to limit the number of steps for production and choose technologies that are widely implementable.

Cable management turns out to be a fourth challenge, as the presently used cables are large and stiff, preventing proper integration and adding weight.

Next, ***waterproofing and the cleaning*** of designs can be challenging. Often, products worn directly on the body need to be washed regularly, which is not possible for the electronics presently used. However, the recent creating of a new casing seems to be promising. Again, this challenge is supported by literature (paragraph 1.6).

A sixth area of trouble is the lack of ***an overview of all the tools and technology options available*** when it comes to the implementation in new projects. Now, with every new project, the design team starts from scratch. A design tool=kit with available technologies, integration methods and materials to choose from, was mentioned as work-in progress solution direction.

Lastly, finding ***reliable suppliers*** is difficult, since Elitac Wearables is working at the forefront of innovation, trying to bring new technologies to the market faster. This results in the use of parts that are also just brought to the market that could be potentially pulled at any moment in time. Often leaving Elitac Wearables to look for a new supplier and changing their design or production process.

Solution Directions

Solution directions mentioned focussed mainly on ***improving the cables***, waterproofing the electronics by ***overmolding*** them, more flexible electronics and casings. Furthermore, ***potential replacements for the ERM tactors*** were mentioned together with an ***increased starting voltage*** strategy.

Conclusions

The current electronics design is ***labour intensive*** due to the many wires necessary per tactor. Also tactors cannot be located too close to each other, as the mold for the overmold cannot fit in-between. Moreover, it is difficult to optimise production for large scale production. Furthermore, the presently used ***cabling*** is uncooperative as it is very ***stiff and twists in all directions.*** Also, the cabling design should allow for stretch of fabric, which results in ***accumulation of cabling*** at certain points in the design. Moreover, the ***integration of hard electronic parts*** and the overmold pull on the fabric, making it ***ergonomically and aesthetically unpleasant***. Often the ***transition of hard to soft materials and at connection points*** is where the product breaks. Next the waterproofing and cleanability of the products seems to have become less of a problem.
Moreover, problems Elitac Wearables is facing is not only about the design and production of products, but also about the design methodology used. It seems that the ***hardware department needs to work more closely together with the textile designers*** to create better integrated electronics. The question is then how to achieve this. Also, ***a standardised design tool-kit*** in the form of ***available technologies presented*** as building blocks and ***how to apply these in the design process*** is desirable.

When comparing the challenges by doing internal research at Elitac Wearables and the ones found in literature in paragraph 1.6, the following four findings are supported: ***Durability, integration of electronics & textiles, cleanability and the development, production and commercialisation of smart textile wearables.***

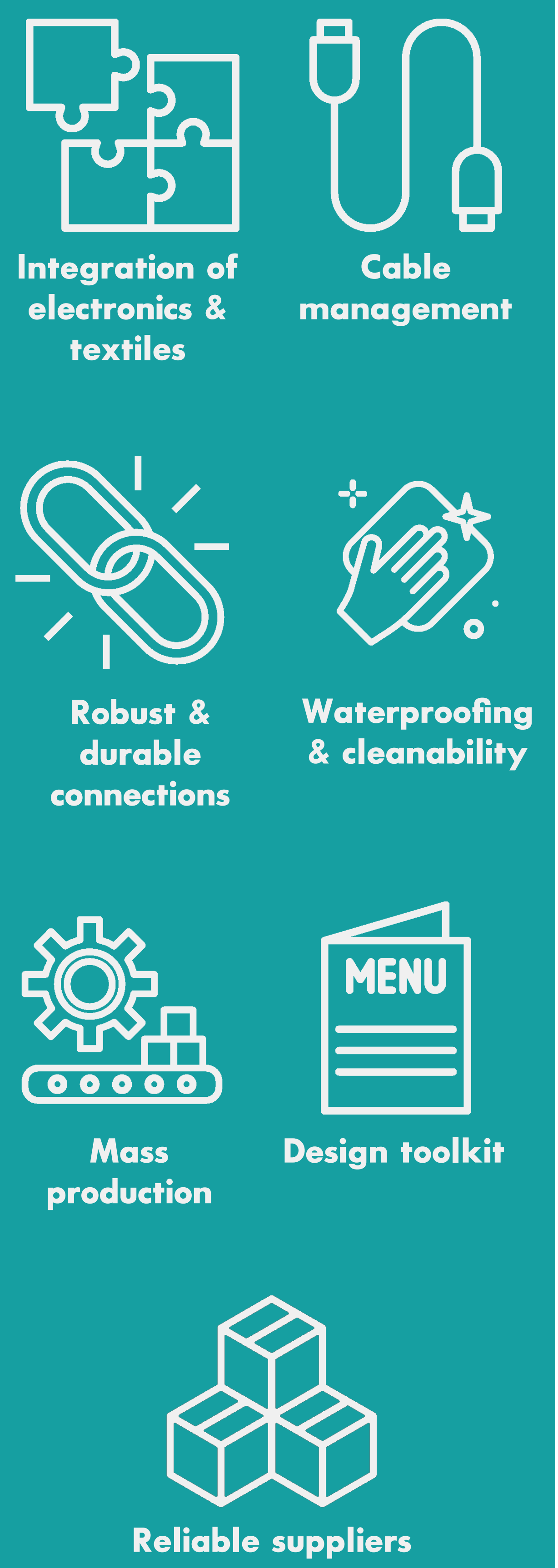


Figure 31. Challenges of smart textile wearables for Elitac Wearables

3. Market research

In this chapter the smart textile wearables market is analysed. First, a trend analysis is done in paragraph 3.1, followed by a state-of-the art analysis in paragraph 3.2. Moreover, in paragraph 3.3 competing products are researched further, together with the cleanability in paragraph 3.4.

3.1 Trend analysis of wearable smart products

According to Buchilly (2018), Research & Innovation Manager at Fischer Connectors (a leading company that designs and manufactures high-performance connectors and cables for electronics) the overall wearables market will grow from 113,2 million shipments from 2017 to 223,3 million shipments in 2021. Moreover, industries in which the use of wearables are increasing are the healthcare & medical, industrial, defence and sports sector.

Healthcare & medical

The market value of medical wearable devices will be $14,41 billion by 2022 (Buchilly, 2018). The main goal of wearables in this sector is to monitor patient's biometrics, help diagnostics and provide support to its users with specific conditions. This is also confirmed by Garrod (2020), who mentions medical wearables to be among the top wearable trends in 2020. A example of medical wearables is the Skiin smart underwear created by Myant (Figure 32) that can monitor a person's sleep, posture, movement, breathing intensity, temperature and heart-rate. Many sensors are integrated directly into the fabric through knitting of conductive yarns. Another example is the Care Taker medical wearable that can monitor many of a patient's vitals by using only a simple finger cuff, see Figure 33.

Figure 32. Skiin smart underwear (Myant, 2017)

Figure 33. The Care Taker (PatientCareSolutions, n.d.)

Industrial

The industrial field smart wearables are upcoming to enhance the working experience and support safe working environments. Smart glasses (Figure 34) head-mounted displays and headsets with augmented reality (Figure 35) are all examples of innovative wearables used in the industry. Moreover,

> *"The Internet of Things (IoT) is being integrated into wearables to improve workers' safety, reduce error rates and thereby raise both productivity and the quality of work." - Buchilly (2018, p. 11)*

Defence

The use of wearable electronics is also increasing in the defence sector, as this can help to improve communication and the speed, quality and decision making process. It also has the potential to reduce risks, errors and can help to eliminate the need to travel (Buchilly 2018). Examples of wearables developed for the defence sector is the Mission Navigation Belt shown in Figure 36 and The BAE Broadsword power and data distribution harness with e-textiles embedded shown in Figure 37.

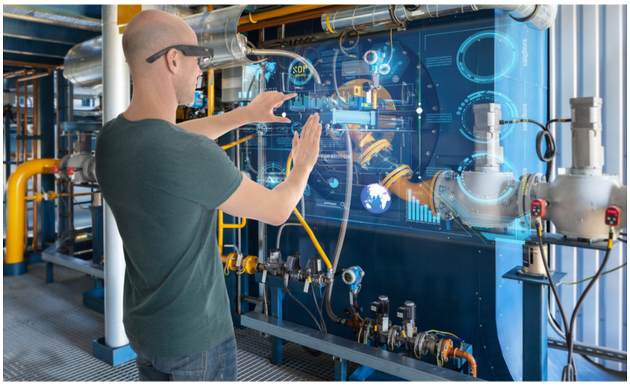


Figure 34. Smart glasses used on the industrial work floor (Davis, 2020)

Figure 35. Smart Helmet supporting maintenance workers (UK construction online, 2017)

Figure 36. Mission Navigation Belt (Leeger, 2021)

Figure 37. BAE Broadsword power and data distribution harnesse (BAE Systems, 2015)

Sports

Fitness fanatics, athletes and people generally interested in a healthy lifestyle can now buy improved fitness trackers. Nowadays they are not only able to monitor the number of steps and calories burned, but other biometrics such as heart-rate and sleep quality as well (Garrod, 2020). Multiple improved fitness trackers can be seen in Figure 38. Moreover smart clothing that can track biometric data is also being developed. The Polar smart shirt shown in Figure 39 can be used to improve trainings and prevent injuries by tracking vitals and storing data of its user. More and more 'on-body' and smart wearables and e-textiles are being developed to support fitness and well-being. These devices are often connected to a control module via Bluetooth or WiFi (Buchilly, 2018).

Figure 38. Multiple smart wearable fitnes trackers (van Ballegoie, 2020)

Figure 39. Polar smart wearable shirt that tracks real-time heartrate & metrics (Polar, 2017)

Conclusion & decisions

The use and development of wearables is increasing for the ***healthcare & medical, industrial, defence*** and ***sports sectors***. Wearables are used to ***monitor people's health, improve everyday life, facilitate*** more ***effective trainings*** and ***safer working conditions***. Moreover, they support ***data monitoring*** and ***sharing*** through the ***Internet of Things***, making it possible to use this data for predictions trainings in the future. Trends show an ***increase in on body smart wearables*** and ***e-textiles*** such as smart glasses and fitness shirts. Often the control modules of these devices are ***wireless connected*** to 3rd party system via ***Bluetooth*** or ***WiFi.*** Finally, smart wearable products nowadays have a more ***fashionable*** and ***professional*** appearance as technology is progressing.

D. The appearance of the to be developed technology system should adhere to the professional and fashionable appearance trend.

3.2 State-of-the-art of smart textile wearables

Currently, many smart textile wearables are available on the market or under development. In this paragraph representative smart textile wearables are analysed and their pros and cons are stated.

Figure 40. Stridalyzed insoles for running shoes (ReTiSense, 2021).

Stridalyzed
Is a smart insoles for your running shoes to help you become a better runner and prevent injuries, see Figure 40. Integrated in the sole are 5 pressure sensors and 1 motion sensor. Bluetooth Low Energy is used to connect the product to an application on your phone and a USB connection is used for charging. (ReTiSense, 2021).

Pros: Wireless (Bluetooth LE), Rechargeable
Cons: Not washable
Costs: $169 (insoles) - $2,299 (dev. kit) USD


Figure 41. Hexoskin with control module (Hexoskin, 2021)

Hexoskin
A fitness tracker that continuously monitors cardiac, pulmonary, activity and sleep data of the user. It includes a built-in textile ECG, respiratory sensors and a precise activity sensor (HexoSkin, 2021a). It has 12-30 hours of battery life. The control module is modular and attachable to the shirt with a cable and is charged via USB, see Figure 41.

Pros: washable, quick dry and breathing material, wireless (Bluetooth LE 4.1)
Cons: Large control module & battery module, not integrated in textile carrier
Costs: $579 USD


Figure 42. Athos shirt for men (Athos, 2021).

Athos
Athos tracks biometrics in real-time of muscle activity, heart rate, activity time and rest time during fitness training, see Figure 42. It uses a modular core as controller to connect to the embedded sensors inside the fabric and an application (Athos, 2021a).

Pros: Wireless & washable
Cons: control module not integrated
Costs: $398 USD (incl. core)

Nadi X

A smart yoga pants that helps you improve your postures, see Figure 43. It uses woven-in technology to measure your pose and generate pulsing feedback at the hips, knees and ankles to show the user on which areas they should focus. By connecting the pants to an application on your phone you will receive real-time feedback on your pose. It uses a clip-on control system with a battery (370mAh) called "the Pulse" that is placed on the upper leg and charged via USB. (Wearablex, 2021a).

Pros: Wireless (Bluetooth), gentle wash & tumble dry, woven-in technology

Cons: control module is not integrated in the fabric

Costs: €250,-

Figure 43. Nadi X smart yoga pants (Wearablex, 2021)

Sensoria Sock 2.0

This smart sock is there to improve your running and helps to prevent injuries by tracking: cadence, foot landing techniques and giving you an impact score. Moreover, it also tracks speed, calories burnt, number of steps, altitude and distance travelled. The design uses pogo-pins to snap the control module into place, see Figure 44. The sensors are directly woven into the sock. The module can be connected to an application on your phone via Bluetooth and will provide you with real-time audio cues when training (Sensoria, 2021).

Pros: Wireless connection (Bluetooth), washable sock & 100% textile sensors, easy clip on method.

Cons: Not integrated control module

Costs: $199 USD (incl. control module)

Figure 44. Smart sock v.2.0 (Sensoria, 2021)

Interesting to note is the production method of the textile-carriers is knitting for all. A paper where smart electro-clothing systems are reviewed, most of the products are also fabricated through knitting (Muhammad Sayem et al., 2020).

Conclusions & Decisions

Currently, ***sensors and wiring*** are more and more ***integrated in the fabric*** of smart textiles, however the integration of the ***control module,*** often combined with the ***battery***, is made ***detachable***. This ensures the cleanability of the textile carrier. The control module is regularly ***wireless connected*** to an application on an external device (phone, smart watch, tablet etc.) to ***monitor and track data***. This connection is mainly established via Bluetooth & Bluetooth LE and in case of much data communication, WiFi is used. Moreover, ***stretchable and breathable materials*** seem to be in favour of the market to ensure ***a close body fit*** for the user. Many times the textile carriers are available in different sizes for different sexes or have a size adjustment functionality to improve the fitting of the wearable. Finally, more and more ***real-time data tracking and feedback*** is available in smart textile wearables. Data is also stored on an external device (phone, tablet, etc.) and from the user's data history ***trend forecast*** are created and ***injuries are prevented***. Lastly, the general production method for the textile carrier is ***knitting*** on the market.
Prices are relatively high for consumer products, ***starting from $169 going up to $597.*** Even professional development kits can be bought for research purposes, costing a couple of thousand Euros. It is expected to see the prices lower over the next coming years, due to the increasing trend in smart wearables which will create a market push and of improved materials and production processes.

D. In order to improve the cleanability of the product, the most important technology, the micro controller also known as the brain of the product, will be made detachable. The vibration motors will be integrated in the design to allow proper cleaning. This is practical, as the user only needs to remove one piece of electronics before cleaning the product instead of all.

D. Breathable and stretchable materials will also be used to improve the comfort of the user.

Figure 45. Smart Shirt (Elitac Wearables, n.d.)

3.3 Competing products

Three interesting competing products are analysed in this chapter The Tesla Suit (resemblance with the ScienceSuit), the NaviBelt (similar to the MNB & BalanceBelt) & the Nadi X (smart yoga pants). The goal was to understand how particular problems were solved, such as stretchability of wires, fixation of vibration motors, data communication, etc.

Tesla Suit

The Tesla Suit can provide the user with a full-body haptic feedback experience while also capturing motion and biometrics, see Figure 46. The design consists of two pieces: a jacket and trouser. The suit is claimed to be stretchable, breathable, durable, and even washable. It uses 80 electro-stimulation channels for tactile feedback, 10 internal motion capture sensors for motion tracking and has a rechargeable battery life of 8-10 hours (TeslaSuit, 2021).

Electro-stimulation & climate control

The Tesla Suit uses electro-stimulation to deliver haptic feedback to its user. Meaning that small electrical pulses cause muscle contraction. The system uses electrode contact points directly located on the skin (see Figure 47), and combined with Peltier elements climate control is an additional feature (Marozau, Khurs & Aleksandrovich, 2016).

Construction & communication

The suit consists of modular plates that are linked with elastic material and some of these plates are removable to enable washing or repairability (Marozau, Khurs & Aleksandrovich, 2016). WiFi is the wireless communication medium for the data.

Pros: Overall body experience, stretchability, breathability, wireless (WiFi) & washable.

Cons: Tight fit is needed to give electrodes a good connection, needs to be cleaned more often

Costs: €1500-2750,-

Figure 46. The TeslaSuit jacket (TeslaSuit, 2021)

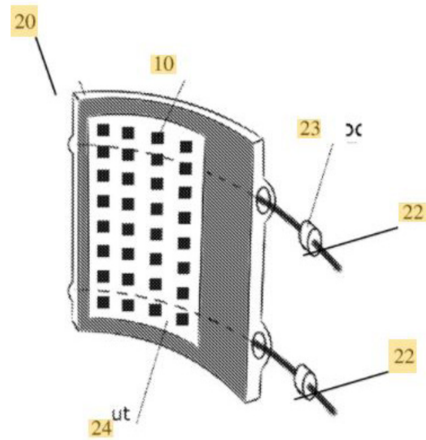


Figure 47. Example of Electrodes and sensors located on the inside of the Tesla Suit (Marozau, Khurs & Aleksandrovich, 2016).

NaviBelt

The NaviBelt from FeelSpace is designed to guide blind people through life by making people feel paths and directions via haptic feedback. It is worn around the waist of the user (Figure 48). and has one central control module in the front. The design uses eccentric rotating mass (ERM) motors as haptic actuators. The control module also contains the battery that powers all tactors. As a physical version of NaviBelt was available, this product was disassembled and photographed in detail from the inside out, to understand more about the technology used, see Appendix A4.

Figure 48. NaviBelt for blind people with central control module in the front (FeelSpace, 2017).

Construction & communication

The NaviBelt uses an inner and outer belt structure just as the Mission Navigation Belt, see Figure 49. This enables washing of the outer belt The inner belt that includes the electronics is fixated in the outer sleeve with the use of Velcro. The motors all share the same power lines, but each one of them has a separate data line wire to actuate each tactor individually.


Figure 49. NaviBelt wit inner and outer belt construction

Production

The material used for the outer belt is made from 55% PES, 35% viscose, 5% PA & 5%. The inner belt is made of 95% cotton and 5% elastane. Both belts are stretchable. The general production method is sewing. To fixate the tactors, stretchable webbing is used, which is sandwiched between a felt piece with a recess for the motor, see Figure 50. To avoid breaking of connection points, additional conductive wire is added in between each tactor, to facilitate the stretching and bending of the NaviBelt.

Pros: Washable outer sleeve,

Cons: Bulky and heave control module in front pocket

Costs: Unknown

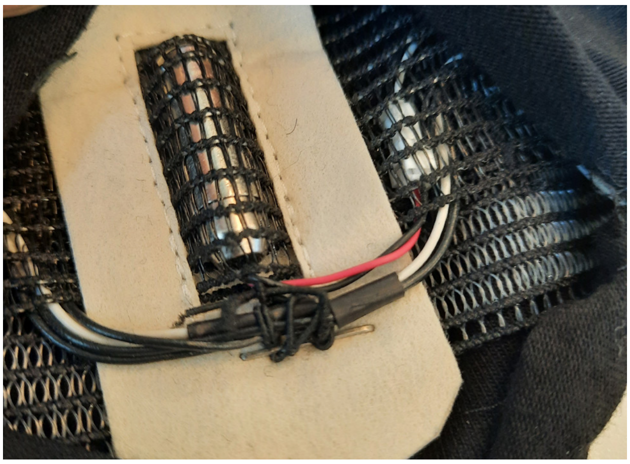


Figure 50. NaviBelt internal electronics connection

The Nadi X

As the Nadi X is an interesting product that we can learn from a lot when it comes to cleanability, one yoga pants is tested and opened up to get a better understanding of the materials used. Both the overall experience and the interconnections were analysed. The product experience is described in Appendix A5 and the connections will be elaborated in this section.

The model tested was the Nadi X Mesh size L, shown in Figure 51. The Pulse as shown in Figure 52 is the brains of the smart yoga pants, which is connected to a phone via Bluetooth. It uses 4 snap buttons as attachment method to the textile carrier, see Figures 52 & 54.

Opening up the Nadi X

To get a better understanding of the technology used and how they made the Nadi X cleanable, the inside is opened up for inspection. The left leg was chosen, as this side also included the connection point of the Pulse, see Figure 54. The textile carrier is lined at the parts where the electronics is present so it is not visible or in direct contact with the skin. This linage was opened up at one seam to make it easily closable afterwards.
The vibration motor modules are connected to the Pulse through the use of stretchable wires as shown in Figures 55 & 56. The tactors are chained in series and work through an I2C Bus structure. There are four wires in total, two for power, 1 for the data and the last one for the clock. These wires are sealed with a type of stretchable PU tape that is seems to be ironed on to the textile carrier. The size is about 1 cm in width.
Then we take a closer look at a vibration motor module. Each vibration motor module has two vibration motors located on opposite sides and PCB in the middle. The area around these electronics is completely sealed with a type of glue that merges the layers, see Figure 57. The PCB includes a driver for two parallel chained motors (double H-bridge) and an XYZ-accelerometer that is used to determine the pose of the user, see Figure 58. Many different layers of materials and glue are used to protect the electronics from liquids. See Figure 59 that shows multiple layers of PU tape used to protect the wires and Figure 60 for a coin tactor encapsulated in a waterproof casing. Figure 61 shows a schemic overview of the different layers and materials used in a vibration motor module. The total number of vibration motor modules used are 5, resulting in 10 vibration motors per pants. A schematic overview of the components inside a tactor module can be found in Figure 62. The connection point of the Pulse was not analysed further, as all layers of the textile carrier were also merged at this point.

Figure 51. Nadi X Mesh model (Wearablex, 2021)

Figure 52. The connection point of the Pulse X

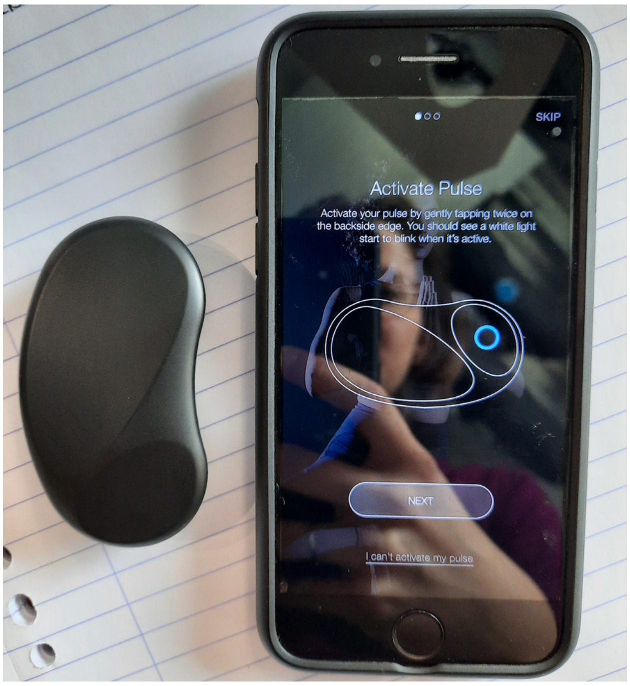


Figure 53. The Pulse and the instructions on how to active it

Figure 55. The Nadi X opened up on one side

Figure 54. The location of the Nadi X on the inside back of by left leg

Figure 56. The power and data wires used

Figure 57. A vibration motor module which is sealed off 360 degrees with a layer of glue. Each module encloses 2 coin vibration motors and a driver PCB module

Figure 58. The driver PCB with the double H-bridge and accelerometer

Figure 59. Multiple layers of TPU sealing off the tactor module

Figure 60. A coin vibration tactor covered in a waterproof packaging

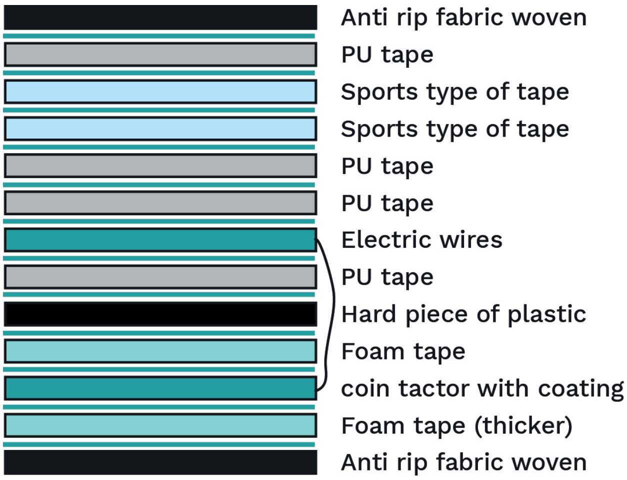


Figure 61. All layers used to waterproof and create a tactor module of the Nadi X

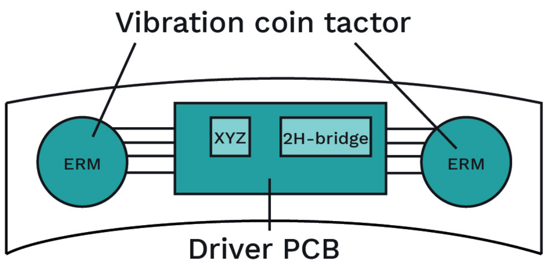


Figure 62. Vibration motor module components inside the Nadi X

Conclusion

The ***TeslaSuit*** is an interesting competing product that can be compared to the ScienceSuit of Elitac Wearables, and provides a ***full-body haptic feedback experience***. Instead of using ERM vibration tactors, it uses ***electro-stimulation*** that excites the nerve endings controlling muscles in the human body. Therefore the product should be ***worn directly and tightly to the skin*** to function properly. It uses ***80 electro-stimulation channels*** for tactile feedback and 1***0 internal motion capture sensors*** for motion tracking. The ***NaviBelt*** on the other hand is a competitor of the Mission Navigation Belt, as it also provides users with navigational feedback and is constructed by the use of an ***inner and outer belt.*** A difference is the data communication structure to actuate the vibration motors: The Mission Navigation Belt uses I^2C communication to actuate in series chained ERM motors, while the NaviBelt uses ***an extra wire*** to ***chain*** the ***ERMs in parallel.***

The Nadi X uses ***many layers of materials*** to ***waterproof*** the system, with in particular ***PU seam tape.*** Each module contains ***2 vibration tactors*** and a ***PCB*** that includes the ***driver*** and an additional ***accelerometer*** for posture determination. The system uses an ***I^2C Bus structure*** for communication and therefore all the motor ***modules are chained in series.*** By ***laminating*** many layers, the Nadi X can be ***washed up to 25 times***. All these things considered, waterproofing a smart textile wearable product for laundry is challenging.

3.4 Cleanability of smart textile wearables

To get a better understanding of the cleanability of smart textile wearables, the materials, fabrication method and the cleaning instructions were analysed for some products currently on the market. This also helps to set realistic targets in the define stage of the design process.

Hexoskin smart shirt

The Hexoskin has a detachable control module that is removed before washing, see Figure 63. Its textile carrier is made of 73% micro polyamide & 27% elastane, and is fabricated through knitting (Muhammad Sayem et al., 2020) . On the website the following 'care' instructions are given:

> *"1. Before washing, remove the Hexoskin device and put the wire connector back into the zipped pocket to protect it.*
> *2. Use the Delicate cycle with cold water.*
> *3. Hang to dry. The Hexoskin shirt does not go in the dryer.*
> *4. Avoid twisting the fabric. This could damage the textile sensors."*
> *- Hexoskin (2021a para. 7).*

Hexoskin also provides its users with two clear videos on how to wear and remove the product. These are to ***prevent the user from over-stretching the elastic sensor bands*** and wrinkling of the fabric. Moreover the electrodes have to be moistened with water, gel or cream to enable proper signal recording (Hexoskin, 2021b).

Athos men's shirt

The men's shirt also has a detachable control module and is made of 75% Nylon & 24 % Spandex Lycra, see Figure 64. The main fabrication method is also knitting (Muhammad Sayem et al., 2020) and according to their website this material allows for a tight fit. Moreover the following care instructions are given:

> *Preferred care instructions*
> *"1. The first step is to remove the Core, which is the central micro-controller.*
> *2. Step two is to hand wash with gentle cleaner (e.g. Woolite)*
> *3. Pat dry with a towel (do not wring)*
> *4. Air dry overnight" - Athos (2021b, para. 2)*

They also mention that ***air drying is ideal***, but that the garments can also be placed in the dryer in a ***fine-mesh garment bag*** on a ***low heat setting for 45 minutes***. High heat is ill-advised as it may damage the sensors and the inlay. (Athos, 2021b). Moreover, they mention alternative care instructions:

> *Alternative care instructions*
> *"1. Remove Core.*
> *2. Place garments in individual fine-mesh laundry bags.*
> *3. Machine wash in cool water with a gentle cleanser.*
> *4. Hang to dry or place in dryer (in a fine-mesh laundry bag) on low-heat for 45 min.." - Athos (2021b, para. 3)*

Furthermore, the product should be worn as a base layer (no underwear) and should be tight to the skin. Also, lotions, oils or hot/cold creams should be avoided under the garment, just as using athletic tapes at the locations where the sensors touch the skin of the user (Athos , 2021b).

Nadi X

The Nadi X also has a detachable control module named "The Pulse", see Figure 65. The type of material used for the textile wearables is unknown, however we do know that the fabrication method is knitting/weaving. (Muhammad Sayem et al., 2020). On the Wearablex website they mention that the Nadi X pant's life span is ***25 washes.*** Furthermore, the warranty for The Pulse controller is 1 year and has a has a 370 mAh Lithium-Polymer battery integrated that should be able to last up to 3 yoga practices. (Wearables, 2021b). The given care instructions are:

"1. Remove pulse before washing
2. Once the pulse is removed, hand wash with gentle soap and cool water
3. Water temperature should not be over 30 degrees Celsius (86 degrees Fahrenheit)
4. Keep tumble dry at lowest heat or do not surpass 30 degrees Celsius (86 degrees Fahrenheit)
5. Do not iron.
6. Do not dry clean.
7. Do not bleach."
- (Wearablex, 2021c, p.16-17).

They continue to give advice on the maintenance and storage of the product, as no vibes are allowed to be killed and it should be ***avoided to keep the pants soaked in any liquid for prolonged periods of time*** including sweat. Also, the pants should be stored in a cool or dry environment and should not be kept on a metallic surface (Wearablex, 2021c).

All cleaning findings are summarized in Table 1 to create an overview.

Figure 63. Hexoskin with module (Wearables4rent, n.d.).


Figure 64. Athos men's shirt with module (Pai, 2015)


Figure 65. Nadi X with visible "Pulse" and integrated sensors/actuators (Caddy, 2018).

Product	*Cleaning*	*Cleaning product*	*Drying*	*Not allowed*
Hexoskin smart shirt	Delicate machine cycle with cold water	N.d.	Hang to air dry	Twisting, wringing or overstretching of the sensors
men’s shirt	Preferred: Hand wash Alternative: Machine wash cold water in laundry bag	Gentle cleaner (e.g. Woolite)	Preferred: Pat dry with a towel & air dry Alternative: Low heat max 45 min. in laundry bag	Wringing, and lotions, oils or hot/cold creams in direct contact with the product
Nadi X	Preferred: Hand wash with cool water < 30 degrees Celsius Alternative: delicate machine wash water < 30 degrees Celsius in laundry bag.	Gentle soap	Tumble dry on low heat < 30 degrees Celsius	Ironing, bleaching or dryclean. Prolonged soaked product in any liquid

Table 1. Quick overview of the materials, production and cleanability processes of smart textile wearables on the market

Conclusion & Decisions

On the current market we generally see the use of ***flexible, stretchable*** and ***breathable materials*** for smart textile products. Another interesting finding is that the term wearables ***“care instructions”*** is preferred over washing or cleaning instructions when talking about smart textile wearables. The three products analysed ***remove the most important electronics before washing***. A ***delicate hand wash has the preference*** to clean the products in general, though ***delicate machine washing cycles with cold water*** settings and not too aggressive cleaners is sometimes also possible. For drying ***air drying is the preferred option***, however some designs can also handle ***low temperature tumble dry*** settings. Many products advice ***against twisting and wringing.***

D. The goal will be to design a technology that can be hand washed with cold water and a delicate cleaner. In the most ideal case, the technology can be laundered on a delicate cold water washing program in a laundry bag.

D. Air drying will be the requirement for drying.

4. Ergonomics of wearables

In this part of the report ergonomics of smart textile wearables is researched. The goal is to understand the factors that play an important role when it comes to comfortable products that can be worn closely to the body.

Smart textile wearables are products that combine textiles, electronics and software, that need to be considerate of their users and environments according to Cho et al., (2009) and Chae & Buso (2021). The human aspects that play a role in the ergonomics of smart textile wearables are: usability, functionality, durability, safety, comfort and fashion (Cho et. al, 2009), see Figure 66.

Usability

Usability is associated with five attributes according to Nielsen (2004):

- **Learnability:** The system should be easy to learn so the user can work with the product quickly
- **Efficiency:** The system should have a high productivity level once the user knows how to use it.
- **Memorability:** It should be easy to remember how to use the product, even over a longer period of time of no use.
- **Errors:** The number of errors the user can make should be limited and if an error occurs, the user must be able to recover from it quickly and catastrophic errors are not allowed.
- **Satisfaction:** The product should be pleasant to use and leave the user satisfied after use.

Functionality

If the electronics function according to what they were designed to do must be tested. Do buttons, sensors and actuators perform the way that they are supposed to? This can be done signal testing of the electronics.

Durability

Durability is also important, as smart textile products will have to withstand harsh conditions from everyday use to laundering according to Cho et al. (2009). It is important to set a wear life and laundry life goal when it comes to the design of the product.

Safety

> *"Safety is the state of being safe, the condition of being protected against physical, social, psychological or other types of harm" Cho et al. (2009, p. 599).*

When it comes to smart textile wearables, it is important to keep in mind the physical form, electromagnetic waves and electrical current among others.

Fashion

Keeping in mind that clothing and wearables are a considered to be a fashion item, aesthetics should be balanced with functionality in order for people considering to use the product (Cho et al., 2009).

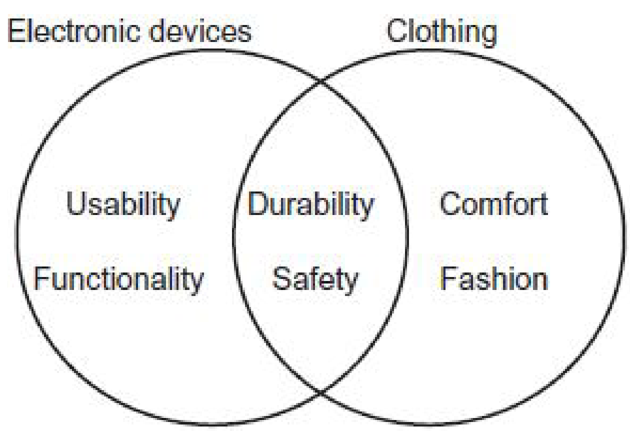


Figure 66. Human aspects that need to be considered when developing smart textile wearables (Cho et al, 2009, p. 594)

Comfort

As explained in paragraph 3.5 there are three levels of comfort that need to be considered when developing smart textile wearables: Thermophysiological comfort, sensorial comfort and body-movement comfort (Hatch, 1993). Chae and Buso (2021) also mention Emotional comfort and provide us with tools to measure some of the levels of comfort.

Thermophphysiological comfort

Thermophysiological comfort focusses on the climate effect of the textile on the user. The Wearer Trial Test & Sweating Thermal Manikin Test are performed in an environment that is suitable for the measurement of heat and moisture transfer in smart textile products (Chae & Buso, 2021). The wearer trial test uses a real person compared to the sweating thermal manikin test and can therefore also collect subjective measurements.

Sensorial comfort

How consumers actually feel when their skin comes into contact with the smart textile can be considered sensorial comfort according to Cho et al. (2009). This type of comfort can either be measured subjectively or objectively. Subjective measurements use the hand of a real person to give subjective ratings about the touch, squeezing, rubbing and handling of the smart textile. Examples of these test are AATCC and Fabric Hand tests (Chae & Buso, 2021). Objective measurements are obtained by mechanical testing with instrumental data and sensory reactions (Chae & Buso, 2021). The KES-F or objective Fabric Hand testing can be used for this.

Body movement comfort

Body movement comfort focusses on the freedom of movement, reduced burden and body shaping as mentioned by Cho et al. (2009). These characters are dominated by the fit of the design, pattern construction and the elasticity and or stretchability of the design according to Teyeme et al. (2020).

Emotional comfort

Emotional comfort is the subjective response of the user to a product. A common method to rate the emotional comfort of a smart textile wearable is the Comfort Rating Scales (CRS) that rates across 6 dimension: emotion, attachment, harm, perceived change, movement and anxiety, according to Chae & Buso (2021). This test also partially takes into consideration the body movement comfort.

Finally, both Chae & Buso (2021) and Teyeme et al. (2020) mention that different levels of comfort can be measured by combining methods.

Conclusion

In order to design and develop ***ergonomically smart textile wearables,*** the following factors should be taken into consideration: ***usability***, ***functionality***, ***durability***, ***safety***, ***fashion*** and ***comfort***. For the evaluation of different levels of comfort multiple tests can be performed, examples are the ***Wearer Trial Test***, ***Fabric Hand*** test and ***CSR***. It is possible to evaluate multiple levels of comfort in one test by ***combining methodologies*** in literature.

5. General conclusions phase 1

During the discover phase the market, the company Elitac Wearables and technology involved when developing haptic feedback products were analysed.

Company research

Elitac Wearables design products for a large field of application, as their products are used in ***active, high demanding outdoor contexts***, more ***general everyday life situations*** or a more ***static indoor contexts*** with ***high concentration tasks*** at hand. The main functionality of these products is to support its user in the task at hand.
The main challenges they are struggling with when developing products are: ***integration of electronics and textile***, ***robust and durable connections***, designing for ***mass production, cable management***, ***waterproofing and the cleaning*** and finding ***reliable suppliers***.

Market research

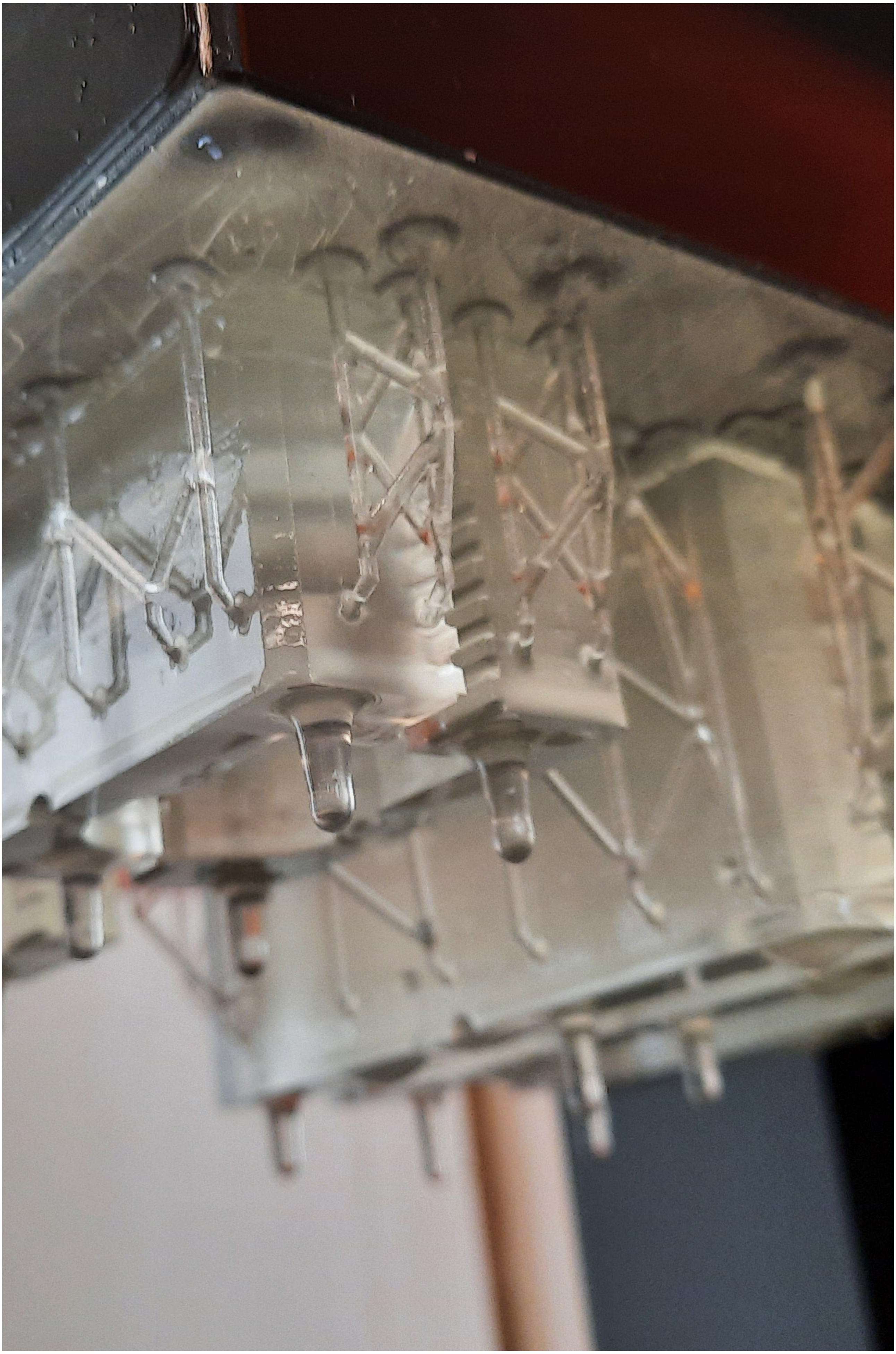
The development of wearables is increasing for the ***healthcare & medical, industrial, defence*** and ***sports sector.*** These products are taking over a tasks, making tasks easier, more efficient or safer. An increase in development of ***on body smart wearables*** and ***e-textiles*** can be seen. These products often ***collect real-time data*** and can provide the user with feedback. The electronics used in these products are becoming ***more and more integrated in the textile carrier.*** To make these products cleanable, the ***most important electronics is removed before washing*** and a ***delicate hand wash*** with delicate soap is often the standard. ***Air drying*** is suggested for most designs as many advice ***against twisting and wringing*** to avoid breaking electronics.

Cleanability

The term ***care instructions*** is used to describe the cleanability process of smart textile wearables on the market. Most smart wearable products ***remove the most important electronics before washing*** and ***a delicate hand wash with delicate soap is often the standard.*** Sometimes ***a delicate machine wash cycle with cold water*** is also an option, however this does ***reduce the lifetime*** of the product. The maximum washing cycles for the Nadi X smart yoga pants is mentioned to be 25 times. ***Air drying*** is suggested for most designs, however some products can also handle ***low temperature tumble dry*** settings. Many products advice ***against twisting and wringing*** to avoid breaking electronics.

Ergonomics

It is important to design a smart textile wearable that is ergonomically to wear and use. To realise this, the following factors should be taken into account during the design process: ***usability***, ***functionality***, ***durability***, ***safety***, ***fashion*** and ***comfort***.
By performing user tests, these factors can be rated and the design can be adjusted where necessary.



6. Problem definition

From all the aforementioned research, a problem definition was created based on the methodology described in Roozenburg & Eekels (1998). From the main problem, a problem tree was created to get a good overview of all the sub-problems that need to be resolved in the next design phase, idea generation.

Who has the problem?

The company Elitac Wearables is the problem owner, however, based on literature research, it can be stated that the problems stated in this paragraph are generally known for the whole innovative smart textile industry.

What are the problems?

Elitac has the overall problem that they want more durable and integrated smart textile wearables that are ergonomically and aesthetically pleasing. This main problem can be divided into 6 distinctive problems A through F and their sub-problems.

Problem A: Lack of proper integration of electronics and the textile carrier

The first sub-problem contributing to this problem is the combination of hard and rigid electronic components, that have to be integrated in flexible and stretchable textiles when it comes to smart textile wearables. Secondly, the connections often result in anaesthetic products. And thirdly, creating an ergonomic fit often poses a challenge as well due to the hard and soft combination of materials.

Problem B: Lack of robust and durable (inter-)connections

Current smart textile wearables designs on the market leave the textile and electronics industry separated. Efforts in the past to bring the two disciplines together have resulted in difficulties with robust and durable connections. The first sub-problem contributing to this is the difficulty of merging flexible and non-flexible materials. The weakest points of designs is often at the locations where there is a transition from stiff material to less stiff material, as at these points the stresses are highest. Stretchable materials connected to non-stretchable materials pose the same challenge.
A third sub-problem contributing is the effect of every day life that challenges these connections with mechanical stresses.

Problem C: Poor cable management

In order to power and transport data original cables from the electronics industry is often used. However, these are difficult to integrate as they are large in size compared to the rest of the design. A second sub-problem is often the stiffness and inflexibility of the design, resulting in twisting, pulling and deformation of the textile carrier. A third sub-problem is the need of additional cable length to facilitate stretching and movement of the user, creating bulks of wires at certain spots in the product. This in turn reduces the aesthetics and ergonomics of the product.

Problem D: Waterproofing and cleanability

Waterproofing and cleanability is one of the biggest challenges faced by smart textile products. The first sub-problem contributing to this is that electronics are not washable yet. Therefore, in current designs the most vulnerable electronics and textile carrier are completely separated to make the product cleanable. However, this results extra effort for the user and more chance of breaking the product when forgetting to take out the electronics. Moreover, as second sub-problem: cleaning electronics puts materials and connections under a lot of stress, decreasing the life expectancy of product significantly.

The problems A through D from Elitac Wearables are also confirmed by the literature research performed in paragraph 1.6.

Problem E: Products are not fit for mass production

Due to the lack of scalability of production processes, the availability of parts for a longer period of time and high prices, products are often not scalable for mass production. Finding production partners that can work with both electronics and textiles is also difficult. Furthermore, components are often new to the market as they are innovative solutions themselves and a market interests needs to be developed and maintained. This is often not the case, and components that were implemented in the designs of Elitac need to be replaced by a new solution or developed by themselves.

Problem F: Lack of a standardised design tool-kit to aid decision making process

The company has a multi-disciplinary team that designs new products. Having a centralized discussion when deciding on what technologies to use during product design is crucial. Research has shown that their is a lack of an overview of all available solutions and their pros and cons, to help in the design process and decision making.

For an overview of all the problems and their sub-problems, see Figure 67 for the problem tree.

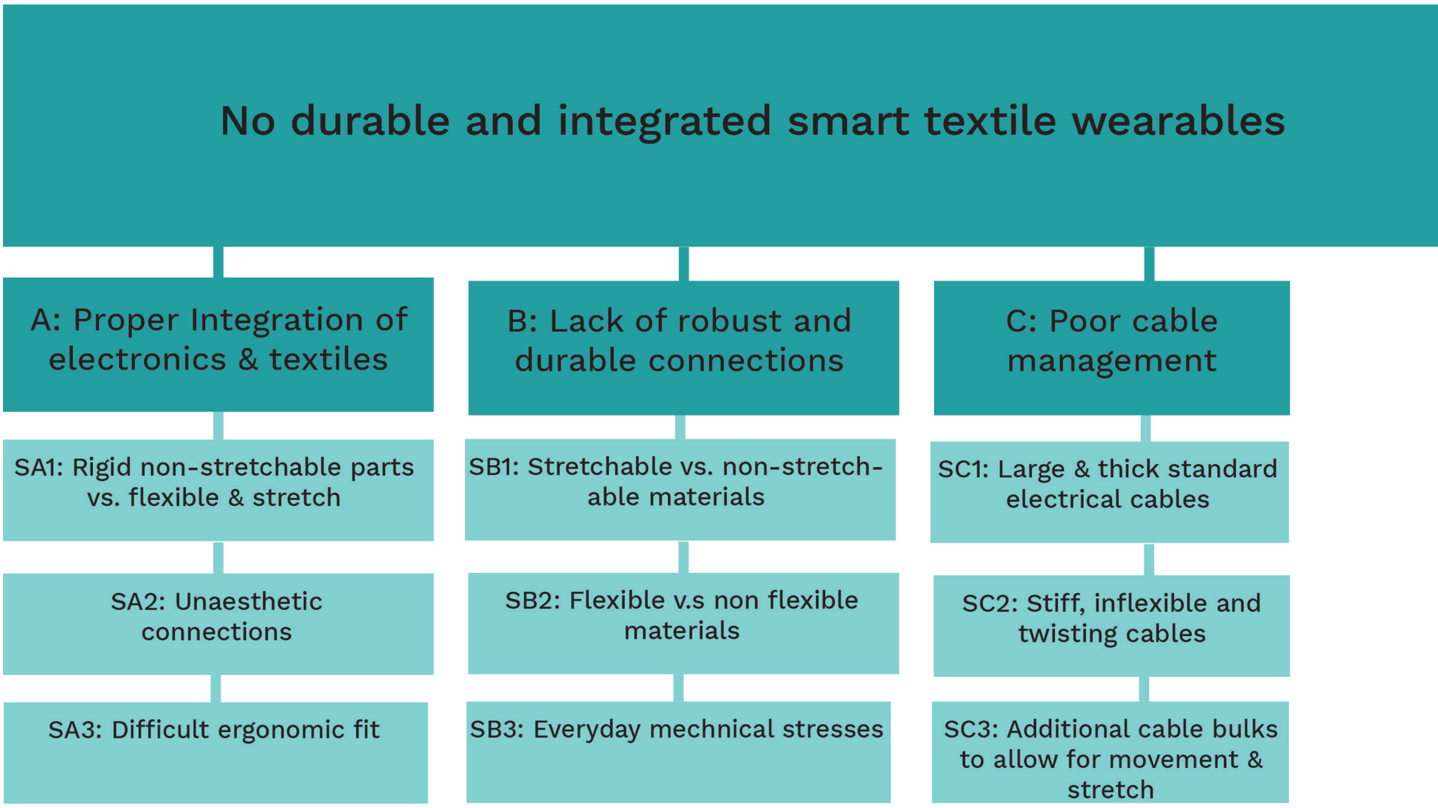


Figure 67. Problem tree with the 6 problems and their sub-problems in one overview

Scope definition

Problem A to E are considered to be inside the scope of this project as this is directly related to the initial assignment given. Problem F will be considered outside of the scope, as creating a decision design methodology for the company would be a graduation assignment on its own. Therefore, for the next parts of the problem definition, the goals, to be avoided side effects and admissible actions for problems A to E will be discussed.

Goals to be achieved

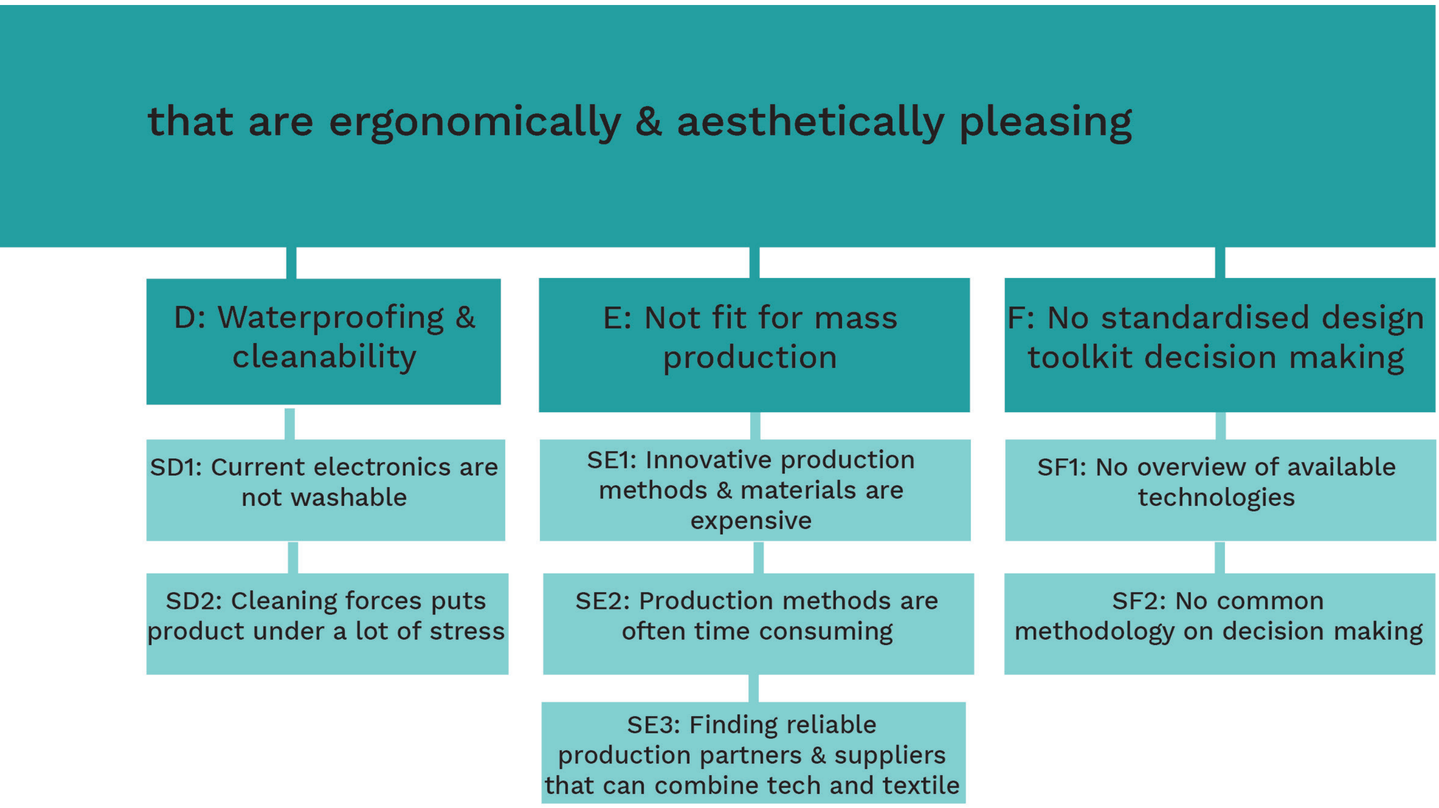
Goal 1: A new robust and durable technology design that is scalable and widely implementable in current and future products of Elitac Wearables.
Goal 2: More integrated in the textile carrier and thus more ergonomically and aesthetically pleasing.
Goal 3: A solution that can be mass produced in the near future.
Goal 4: A cleanable solution.

Side effects to be avoided

The new technology design should not become extremly costly compared to the current design. Furthermore, it should not be potentially harmful to wear on the body. Examples are to ensure that heat produced by electronic circuits will not burn the human skin and remains below the allowed temperature. Finally, the use of technology that makes Elitac solely dependent on one single company should be avoided, as this creates large risks for production if the supplying company cannot deliver these components any longer.

Admissible actions

If Elitac Wearables does not have the machinery or equipment to work with new interesting technologies or materials, new suppliers and manufacturers are allows to be contacted to test hypotheses. Also on-boarding for real production of new partners is not out of the question. Investment in new equipment is also possible if this adds real additional value to the design process.


that are ergonomically & aesthetically pleasing
D: Waterproofing & cleanability
E: Not fit for mass production
F: No standardised design toolkit decision making
SD1: Current electronics are not washable
SD2: Cleaning forces puts product under a lot of stress
SE1: Innovative production methods & materials are expensive
SE2: Production methods are often time consuming
SE3: Finding reliable production partners & suppliers that can combine tech and textile
SF1: No overview of available technologies
SF2: No common methodology on decision making

7. Design criteria

In this chapter the design drivers are presented in paragraph 7.1. Moreover, the program of requirements and wishes are discussed in paragraph 7.2.

7.1 Design drivers of the project

The design drivers presented are based on findings in the analysis phase. The order in which the design drivers are discussed represent the level of importance. They represent a summary of the more detailed program of requirements and wishes presented in paragraph 7.2. They are later used to help evaluate final design.

1. Robust & durable
The design should be able to withstand everyday life, cleaning processes and possible outdoor environments.

2.Widely implementable
The technology design should be easily applicable in a multiple product designs of Elitac Wearables.

3. Scalable
The materials, technology and production processes used should be scalable to a level of at least 25 pieces produced per batch. In the best case, mass production can be facilitated by potential industry partners.

4. Cost effective
The new technology design should be cost effective compared to the old design, and not cost more than 2x the current production costs of the electronics design (G. de Hoog personal communication, 8th of April, 2021).

5. Cleanable
Should be at least hand washable, but prefereably also machine washable at minimally 30 degrees Celsius.

6. Ergonomically
The design should be ergonomically to wear on the human body & to interact with.

.

7.2 Program of Requirements & Wishes

In this paragraph the most important requirements and wishes are discussed that the modular interconnection system must fulfil. All of them are based on research and personal communication with the company. The requirements and wishes can later be used to evaluate concepts generated.

1. Performance & implementation

R1.1 ***The design should be able to power and control at least 7 vibration motors worn closely to the body, of which 3 motors will maximally work at the same time*** (Product portfolio & B. Bicknese personal communication, April 20th, 2021)

R1.2 ***The vibration of the motors should be strong enough that they can be noticed by the user during dynamic conditions on the designed locations.*** (Product portfolio)

R1.3 ***The design should be able to facilitate implementation of other sensor and actuators in the future*** (G. de Hoog, personal communication, April 6th, 2021)

R1.4 ***The design should be able to withstand every day mechanical stresses when used, being stretched and folded.*** (Product portfolio & Problem definition).

R1.5 ***The design should be able to withstand stretching of the textile carrier of 10%*** (Cai, 2020)

R1.6 ***The design should be able to withstand human sweat.*** (W. de Vos, personal communication, April 7th, 2021).

R1.7 ***The maximum circuit resistance of the system should be 6.85 Ohms for cylinder motors and 9.09 Ohms for coin motors in triangular constellations.*** (9.2 Resistance test & calculations).

R1.8 ***The system is allowed to have a maximum operating voltage of 20V DC.*** (W. de Vos, personal communication, April 7th, 2021)

W1.1 ***The system should be able to power 40 tactors in total in the most ideal case.*** (G. de Hoog, personal communication, April 6th, 2021)

W1.2 ***The design should be preferably applicable to as many products of Elitac as possible*** (G. de Hoog, personal communication, April 6th, 2021)

W1.3 ***The design should preferably withstand stretching of the textile carrier of 20%*** (Mattmann, 2008)

W1.4 ***The circuit resistance should preferably be as low as possible*** (9.2 Resistance test & calculations).

W1.5 ***The system should preferably have an operating voltage of 5V DC.*** (W. de Vos, personal communication, April 7th, 2021)

2. Production and Processing

R2.1 ***The design should be suitable for small batch production of minimally 25 pieces*** (Personal observations)

R2.2 ***The technologies used should be more widely available on the market and not make Elitac dependant on one critical part.*** (Problem definition)

W2.1 ***The design should preferably be suitable for small batch production of 100 pieces*** (B. Bicknese, personal communication, Apr. 20th 2021)
W.2.2 ***The production steps needed should be as low as possible and the least time consuming.*** (Problem definition).

W.2.3 ***The product should be fit for mass***

production with production partners. (Problem definition)

3. Costs

R3.1 ***The design should not be more than 2x expensive than production costs of most current designs.*** (G. de Hoog, personal communication, April 6th, 2021)

W3.1 ***The design should preferably be as expensive or even less costly than current designs.*** (G. de Hoog, personal ommunication, April 6th, 2021)

4. Cleanability

R4.1 ***The design should have IP54 enclosure: protection against objects less or equal to 1.0 mm in diameter, access to hazardous parts with a wire and splashing proof (IEC, 2001).*** (G. de Hoog, personal communication, April 6th, 2021)

R4.2. ***The design should be able to withstand 25 delicate cold water hand washes.*** (smart textile wearables and cleanability)

W4.1 ***The design should preferably have IP67 enclosure: Dust-tight, protection against hazardous parts with a wire and protection against temporary immersion. (IEC, 2001).*** *(G. de Hoog, personal communication, April 6th, 2021)*

5. Ergonomics & Aesthetics

R5.1 ***The design should not restrict movement of the users body in any way.*** (Ergonomics of smart textile wearables)

R5.2 ***The technology used should be easily integrated in the textile carrier. (***Problem definition & Market research)

R5.3 ***The design should be aesthetically pleasing to see for humans, following the professional and futuristic trend.*** (Market research)

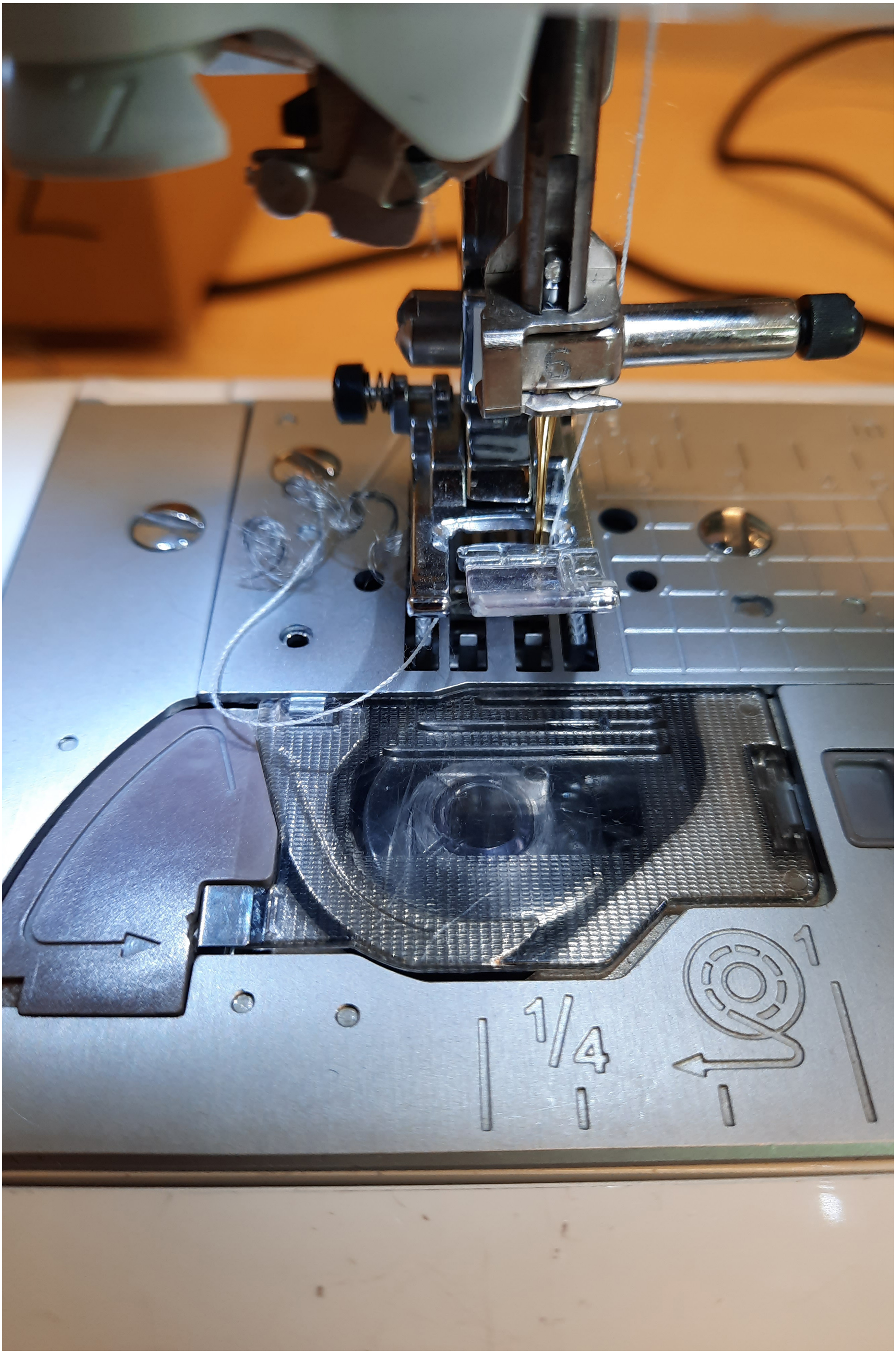
R5.4 ***The design should be comfortable to wear, keeping in mind sensorial comfort thermophysiological comfort.*** (Problem definition & Ergonomics of smart textile wearables)

R5.5 ***The design should be comfortable to wear, keeping in mind the thermophysiological comfort.*** (Problem definition & Ergonomics of smart textile wearables)

R5.6 ***The design should ease to use for the final user, by limiting the possibility of wrong use through design.*** (Ergonomics of smart textile wearables)

R5.7 ***The design is not allowed to become warmer than 43 degrees Celsius*** (NEN, 2015)

W5.1 ***The product should preferable be as ergonomic as a normal textile product*** (Ergonomics of smart textile wearables).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Phase 2. Finding building blocks for haptic feedback systems

The goal of this phase is to dive deeper into interconnection technologies necessary to solve the problems defined in phase 1. Chapter 8 therefore presents the technology research about wire connections for power and data transport (8.1), electrical connections (8.2,), integration techniques of electronics and textiles (8.3) and removable connections (8.4). In addition, modular electronics are explored in paragraph 8.5 for inspiration.

Chapter 9 describes initial test of ERM motors used by Elitac Wearables in paragraph 9.1. Resistance tests and corresponding calculations are presented in paragraph 9.2. Moreover, a conductive yarn demonstrator is presented in 9.3, followed by a conductive velcro and ink test in paragraphs 9.4 and 9.5.

Chapter 10 presents a categorisation of the modules to be designed in the solution.

Chapter 11 summarises the general conclusions of phase 2.

8. Technology Research

In this chapter available technologies are analysed and screened for potential application in smart textile wearables. Different wire connections are described in paragraph 8.1, electrical connections are mentioned in 8.2 and integration of electronics and textile can be found in paragraph 8.3. Moreover, removable connections are presented in paragraph 8.4. Modular electronics examples are discussed in 8.5 for inspiration.

8.1 Wire connections for power & data transport

In this paragraph different wire options for power and data transport are discussed and benchmarked. At the end a recommendation of most promising options is given.

Standard electrical cabling

The most well-known wiring to transport power and data are the standard electrical wiring made of copper strings, as shown in Figure 68. These wires can come in any size and shape, and are highly conductive. A downside however is that they are often stiff and difficult to integrate in textile carriers. This is the standard technology currently used by Elitac Wearables for power and data supply of their electronics.

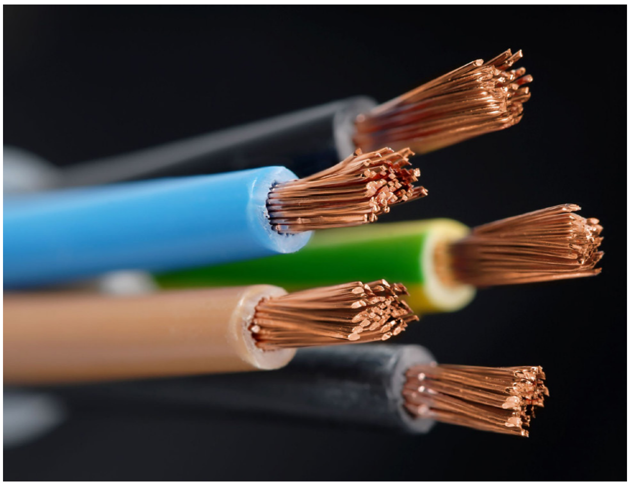


Figure 68. Standard electrical wiring made of twisted copper wires (Science Learning Hub, 2010)

Flat Cables

Another interesting development in the electronics and textile field are flat cables that can transport power and data over multiple wires. The company Ohmatex for example has created conductive flat cables that consist of 4-8 wires, as shown in Figure 69. Amohr and LiTex have even designed elastic flat cables in meandering form, see Figure 69.

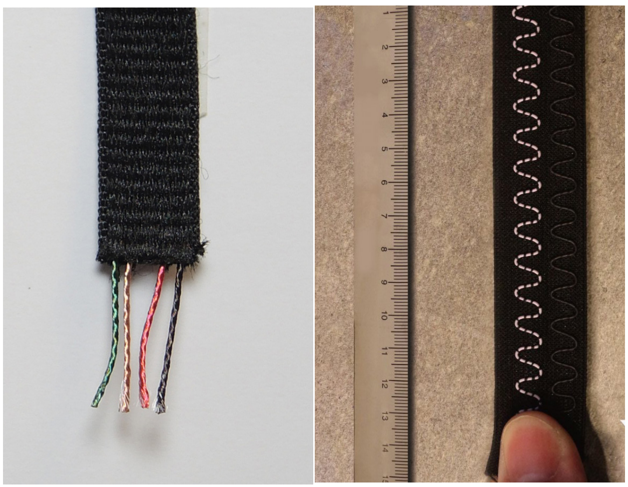


Figure 69. 4-wired flat cable Ohmatex (n.d.) (left) & Meandering flat cables by LiTex (n.d.) (right)

Conductive paints & prints

Another electrical connection option is conductive paint that can also be applied to any type of fibre, however, it is weak and brittle compared to conductive epoxy and does not give a mechanical connection. Machine-printed electrical lines of PEDOT or silver is another option. Again this only is an electrical connection and has a medium strength. The same goes for screen-printing of electrical lines, though this results in a weak connection according to Castano & Flatau (2014). See Figure 70 for an example of screen printed electronics.

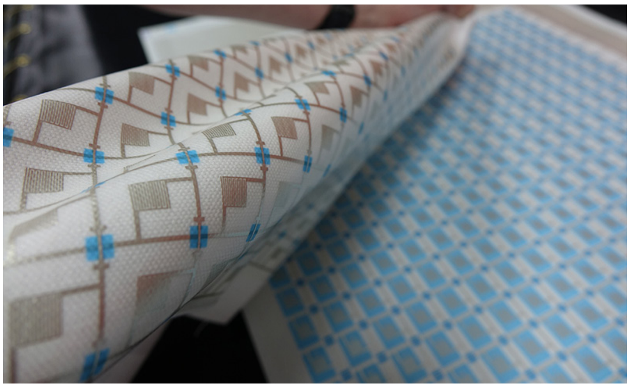


Figure 70. Screen printed electronics (Metafas, n.d.)

Conductive polymers

Conductive polymers (see Figure 71) are interesting, as they can be connected to any type of fibre and although they are medium to weak in their strength, they are very flexible (Castano & Flatau, 2014).

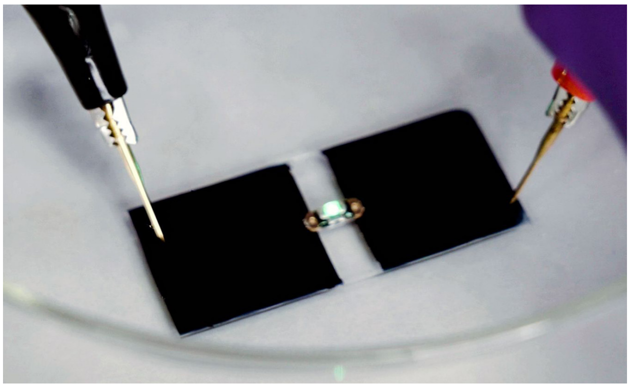


Figure 71. Conductive polymers (MIT News, 2020)

Conductive yarns

One can create conductive yarns by coating yarns with conductive polymers and fibres according to Ismar et al. (2020). However, conductive polymers do offer low processability due to being insoluble, having non-melting characteristics. Moreover, they often have poor mechanical properties, though by combining them with more commonly used textiles this can be overcome (Ismar et al., 2020). Conductive yarns can also have a metal base, resulting in superior electrical conductivity over conductive polymer yarns, though the sensation on the skin is less comfortable according to Ismar et al. (2020).
Examples of conductive yarns can be seen in Figure 72 & 73. Currently, graphene is known to bring about high performance conductive textiles due to its thermal and electrical conductivity, flexibility and chemical stability (Ismar et al., 2020).


Figure 72. Metal conductive yarns by Shielday (n.d.)

Well-known producers of conductive yarns are Statex, Elektrisola, Bekaert Fiber Technologies, Bekintex, Taierxinfiber and Aracon. In Figure 74 an overview of the different types of yarns and their electrical conductivity is given in S/cm. The higher this numberer the higher the electrical conductivity. This graph shows us that conductive yarns made from metal fibres have the highest conductivity (up to 6.25 E+05 S/cm for silver fibres) and metal coated carbon fibres the lowest (5.90 E-06 S/cm).


Figure 73. Carbon conductive yarn by Taierxin (n.d.)

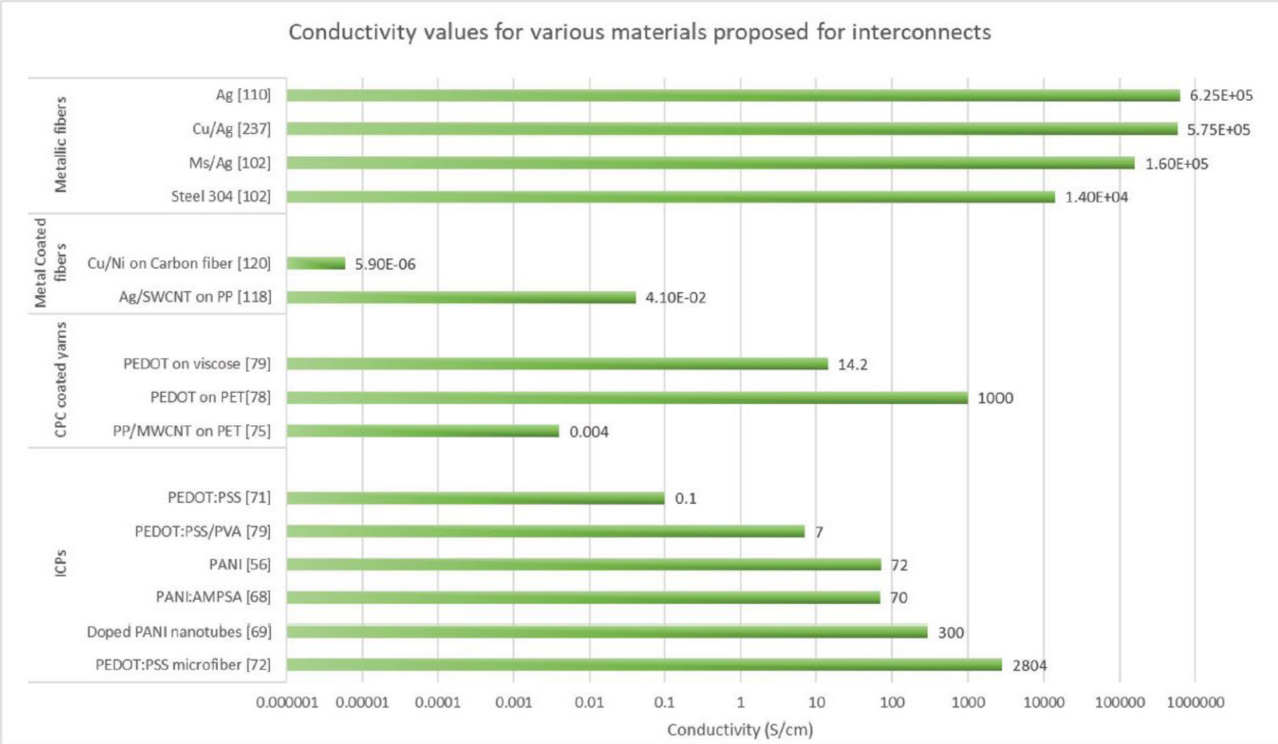


Figure 74. Overview of the electrical conductivity of conductive yarns (Agcayazi et al., 2018, p. 12)

Applications of conductive yarns were already found in chapter 3 during the market analysis. A company specialised in producing woven-in or knitted sensors and actuators is Myant. Sensors and actuators they create are ECG, motion/angle, EMG, pressure and stretch among others (Myant, 2021) This company might be an interesting company to partner with from Elitac's view if they plan on implementing more sensors and actuators in their products in the future as was claimed by Creative Director G. de Hoog (personal communication, March 2, 2021).

A plus side of conductive textiles and yarns are the ability to form directly integrated (woven-in) sensors and actuators only consisting out of conductive yarns, making them highly integrable in the textile carrier. Downsides are the relatively high resistance, the launderability when it comes to retaining conductivity on the long run, and possible short circuits. However, more and more research and new conductive yarns are being developed to overcome these downsides in the future. Most often, good design can also help to overcome most of these problems. Conductive textiles can be often be processed through sewing. Conductive yarns on the other hand are processable through weaving and knitting, and sometimes sewing and embroidery as well, depending on the stiffness and thickness of the yarns. Silver metallic fibres are the most conductive yarns, whereas Cu/ANi coated carbon fibres have the highest electrical resistance.

Conductive fabric

Conductive fabrics can come in many different structures: woven, knitted, non-woven, nets, braided and tufted (Figure 75). Moreover, a combination of fabric structures can be created though layering of fabrics, creating composites (Castano & Flatau, 2014).

In order to create conductive fabrics, one can implementing metal or conductive polymers in fabrics. Conductive polymers are also known as "synthetic metals" and have combined properties of plastics and metals. Conductive textiles and films can be obtained by covering them with conductive polymers such as polyanaline (Ismar et al., 2020). An example of conductive fabric that is metal based is metallic silk organza, shown in Figure 76. This type of fabric is woven is such a way that each fibre can be individually addressed and when shearing the fabric, no short circuit will be created. Meaning that only folding contact with themselves should be avoided by adding a coating or insulating layer (Post et al.,

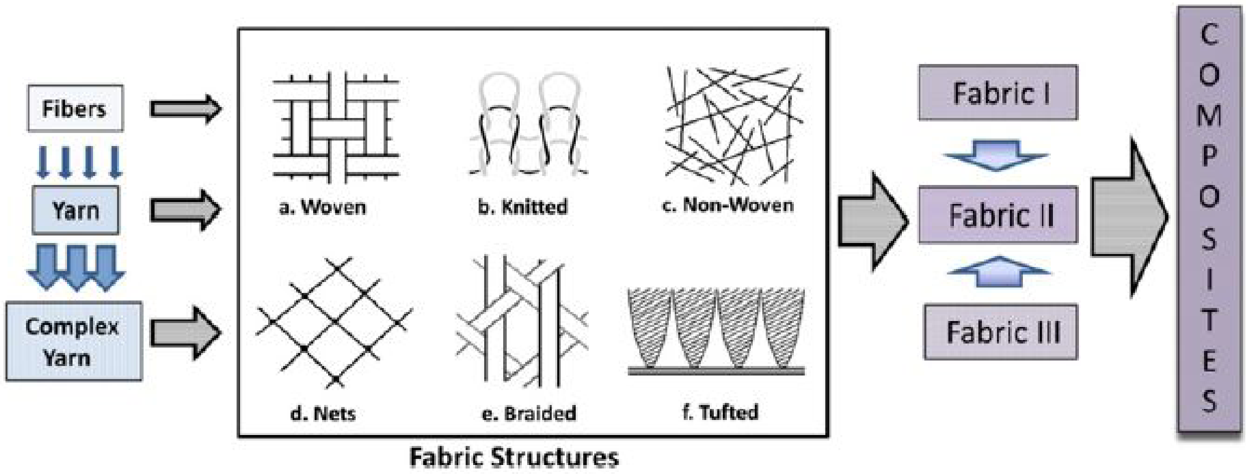


Figure 75. Different fabric structures explained (Castano & Flatau, 2014, p. 2)

2000). Though, the coating may disturb the level of conductivity. Another example of a conductive fabrics are the knitted fabrics from Statex, shown in Figure 77. Ali et al. (2019) looked into conductive silver plated fabrics and their ageing properties, and can conclude that they have strong resistance to change in functional properties due to mechanical stresses, are very durable and even washable.

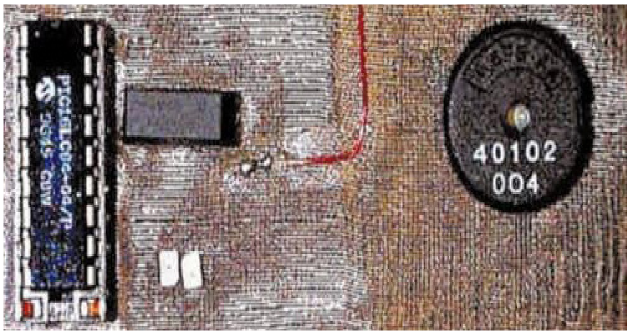


Figure 76. An electronic circuit embedded on metallic silk organza (Post et al., 2000, p. 849).

Rapid iron-on tool for conductive wires

A new rapid iron-on user interfaces tool to connect flexible conductive wires and fabrics was developed by Klamka et al. (2020), see Figure 78. The small tool uses spools of flexible conductive wires combined with textile adhesives (e.g. Vliesofix). When pressed down, the heating element will melt the adhesives and iron the wires on to the textile carrier. This new design might be interesting to use during rapid prototyping or to implement in future production methods when more scalable.

Figure 77. Silverplated conductive yarn Shieldex® Medtex P70 (Statex, 2021)

Benchmark wire connections

Next, the wire connections for power and data transport were benchmarked on the following aspects: conductivity, flexibility, stretchability, ease of processing, processing possibilities, costs, integration in textile, launderability and validation (has it been done before).

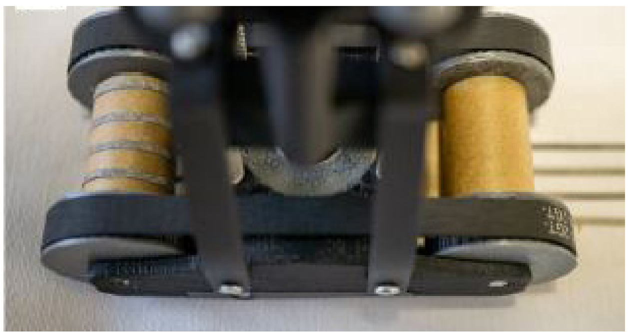


Figure 78. Rapid iron-on user interface designed by Klamka et al. (2020, p. 1).

From this benchmark the following four candidates remain interesting for the

concept generation phase: Flat cables, conductive yarns, conductive textiles and conductive inks (see Table 2).
Flat cables have a low resistance per meter, are both flexible and stretchable, and are durable. However, processing them offers a challenge as most of the conductive copper wirings are isolated, making it necessary to remove the coating before these can be connected to the rest of the electrical system. Conductive yarn score well on all fronts, but do have challenges when it comes to durability and launderability. Not all yarns on the market will maintain their high conductivity after multiple washing cycles and some conductive yarns are extremely fragile. Finally, conductive inks are also interesting, as they are highly integrable in textile carriers and were previously validated by Pauline van Dongen (personal communication, G. de Hoog, April 6th, 2021) doing a project for Elitac Wearables. The stretchability can affect the resistance and the processing techniques available are time consuming. For a more extensive rating per individual technology see Appendix A6.

Connection	***Product example***	***Conductivity (<6.85 Ω)***	***Flexibity***	***Stretchability (min. 10%)***	***Ease of Processing (1 = really bad - 5 = really good)***
Standard Electrical wiring	Copper cable currently used by Elitac	Highly conductive ~ 16.78 nΩ/m	Medium	No, add more free wirelength	4
Flat cables	Amotapes, Ohmatex flat cables & LiTex conductive woven tapes	0.5 Ohm/m 0.4 Ohm/m from 89.4 Ohm/km	Good	Yes, some even up to 90%	3
Conductive yarn	Statex, Eletrisola & AMANN Group	From 2.2 Ohm/m	Good	Yes, through design	4
Conductive textile	Statex woven, non-woven	From 0.02 Ohms/sq	Good	Yes	4
Conductive ink	DuPont PE873	75 mOhm *sq/25 micrometer	Good	Yes, can affect conductivity	3
Conductive tape	Copper tape	0.001 Ohm	Good	No	3
Copper wires printed on TPU	Tested by Elitac	Highly conductive	Good	A little	3
Conductive polymers	n.a.	Adjustable	Medium	Through design	2

Table 2. Benchmark table wire connection possibilities for power and data transport.

Conclusions & decisions

Currently available wire connections for power data transport were analysed and benchmarked. These connections vary from standard electrical wiring used by Elitac at present, to conductive polymers and inks. The following four connections have the highest potential and will be ***implemented during concept generation: Flat cables, conductive yarns, conductive textiles & conductive inks.*** All four options scored relatively well on ***conductivity, flexibility, stretchability, ease of processing, processing techniques, launderability & durability.***

D. The 4 technologies considered for wire connections in the concept generation stage are the flat cables, conductive yarn, conductive textiles and conductive inks.

D. Conductive yarn was not implemented before to power vibration motors and will therefore need to be validated with a proof of principle test.

Processing techniques	*Integration in textile*	*Launderability (<30 degrees Celsius)*	*Durability in active environment*	*Validation*	*Costs*
Soldering, glueing, taping, crimping, lamination	1	No	Good	Elitac Wearables	€
Soldering, glueing, taping, crimping, lamination	3	Good	Good	Elitac Wearables	€€
Sewing, knitting, weaving, taping, shrinking, glueing, lamination, braiding, crimping, gripping	5	Medium - Good, some can be washed until 95 C	Medium - Good	Not yet	€€
Sewing, glueing, lamination, taping, gripping	5	Medium - Good	Medium - Good	Zhi Cai (2020)	€€
Inkjet printing, screenprinting, glueing	5	Medium, needs protective layer	Medium	Pauline van Dongen & Elitac Wearables	€€€
Taping, glueing	2	Bad	Bad	Not yet	€
Lamination, soldering	3	No, tends to break	Bad	Elitac Wearables	€€
Gripping Glueing,	2	No	Medium	Not yet	€€€

8.2 Electrical connections

In this paragraph different interconnection methods between electrical components are analysed and benchmarked, as electrical components will need to be connected via a conductive connection in order to transport data and power.

There are two interconnections to be distinguished: The wire-to-wire connection in which multiple wires (data or power) are connected, and the wire-to-board connector, in which a wire that transports data or power is connected to a Printed Circuit Board (PCB). Most connections are fixed, however, some are removable.

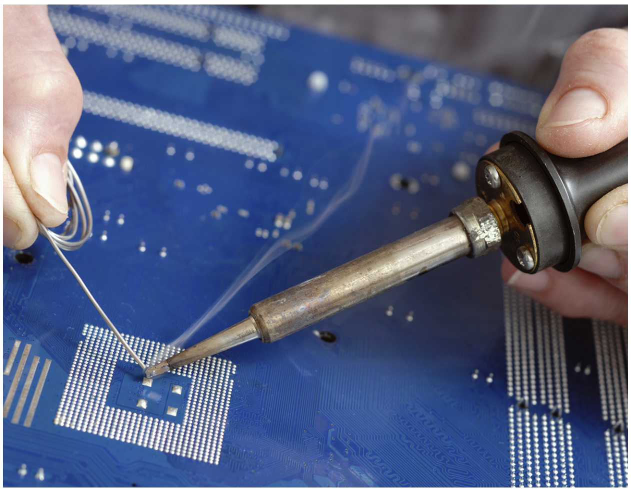


Figure 79. Soldering close-up (Sentry Air Systems, 2010)

Soldering

A widely used connection method to connect electronics is soldering, in which metal parts are joined by melting a metal alloy (solder) that acts as a bonding agent upon re-solidification, see Figure 79. This method requires precision and requires heat ranging from 90 degrees Celsius to even above 450 degrees Celsius (TWI, 2021a). If not done properly, electronics can become damaged. Solder metals used range from lead based, to brass, antimony, bismuth, copper, indium, tin or silver (TWI, 2021a). Soldering is used for both wire-to-wire connections and wire-to-board connections. However, these connections are fragile and will have to be protected from mechanical stresses among others.

Figure 80. Microspot welding (Sunstone, n.d.)

For wire-to-board connects two distinct soldering techniques can be used: ***Through-hole technology*** or ***surface mount technology***. The first technique uses a hole and pin soldering connection and the second one solders parts directly onto a surface.

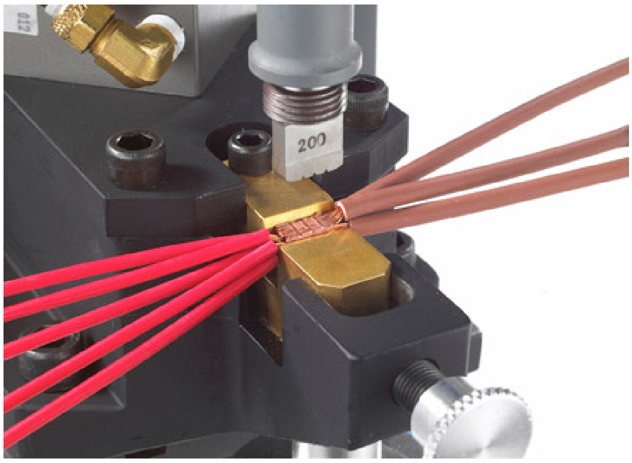


Figure 81. Ultrasonic welding (Sonobond, n.d.)

Welding

Another commonly know connection method is welding. Welding differs from soldering as it does not use a solder, but melts the two metals itself by applying high temperatures to them. There are many welding techniques, but two examples commonly used for electronics are micros-pot and ultrasonic welding, see Figure 80. Micro-spot welding uses a high temperature to melt the two metals and join them, only on a small surface Ultrasonic welding rubs the two materials together on a high frequency, heating them up due to the friction forces and melting them together (Figure 81). This last mentioned method is also the most expensive one, as it is requires expensive precision machinery. Other high potential welding techniques are hot air, hot wedge, laser and radio frequency welding.

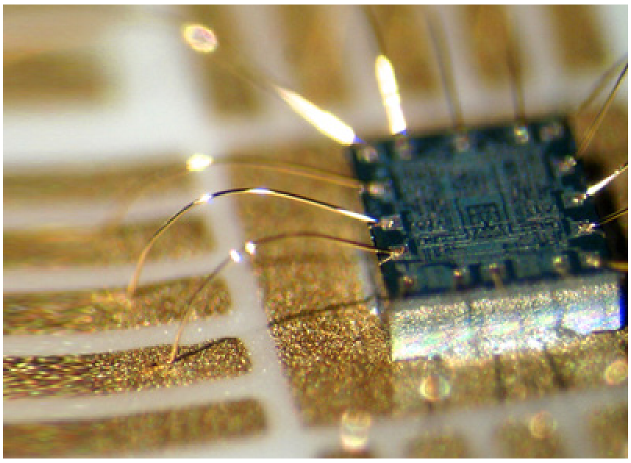


Figure 82. Wirebonding close-up (Accelonix, n.d.)

Wire bonding

Another common method to connect microchips electrically is wire bonding. In this technique gold or aluminium is heated first on the chip and bonded through thermosonic bonding, then the hot metal is pulled like a wire and finally, the end of the wire is again bonded on the preferred spot. This creates small "arches" of wires as shown in Figure 82. Advantages of this process is that it is highly flexible and a high reliability for the interconnections structure. However, according to Chalmers (n.d.) the technique is known to have robustness and reliability problems brought about by environmental conditions, requires relatively large quantities of expensive metals and can have a relatively poor electrical performance if the length of the "arches" are too long.

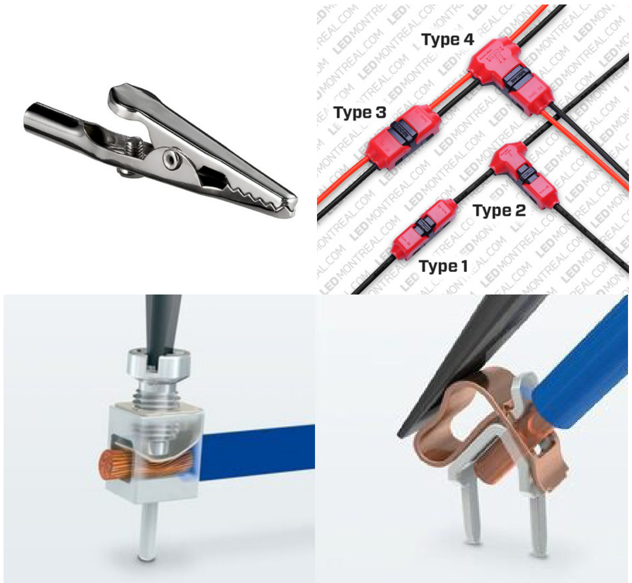


Figure 83. Aligator grip (Allekabels.nl, n.d.) (top left), Grip & Clip (Led montreal, n.d.). top right), screw connection (bottom left) & spring-cage connection (bottom right) (Phoenix Contact, 2021).

Grip connectors

These type of connectors do not ask mechanical joining of metals to create a connection, but instead use clamping forces to keep connections in place. Examples are the Aligator grip and Grip & clip connectors shown in Figure 83, but also the screwing connections and crimp connections. These connections can be used for wire-to-board connections. Another form of grip connectors are the twist on wire connector and terminal blocks shown in Figure 84.

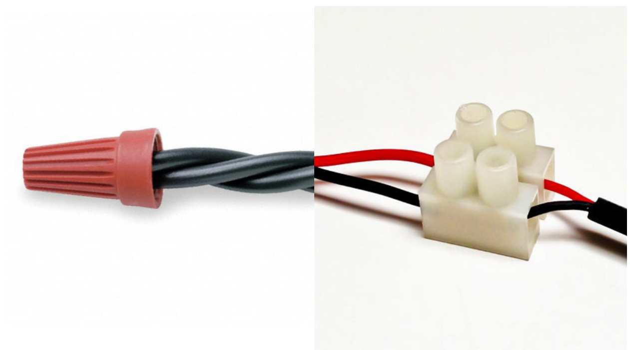


Figure 84. Twist on wire connector (Grainger, n.d.) (left) & Terminal block (Flexfireleds, n.d.) (right)

Conductive Adhesives

Electrically Conductive Adhesives (ECAs) are designed to replace thin lead solder in electronic circuits and are made of a polymeric part (epoxy or silicon) and a conductive metal/fillers (silver, gold, nickel, copper, carbon etc.). (Ismar et al., 2020). They are known to have a high durability, high conductivity, and are mentioned a good mechanical impedance match between more rigid electrical components and the softer textile carrier due to its relative flexibility (Post et al., 2000). Conductive epoxy is often used for wire connections, is relatively strong and can be applied to any type of fibre (Castano & Flatau, 2014). This technique can both be used for wire-to-wire connections and wire-to-board connections. A downside of these connections is the drying time during production. See Figure 85 for an example image of a conductive glue.

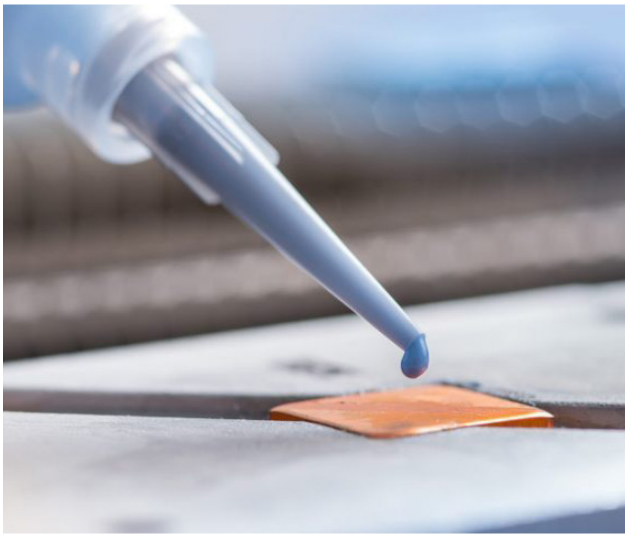


Figure 85. Conductive glue (Appli-Tec, 2018)

Insulation tape

Insulation tape is another type of adhesive connection that can be used to make wire-to-wire connections, however this is not durable or waterproof, see Figure 86.

Figure 86. PVC electrical insulation tape (Wikipedia, 2021)

Conductive tape

Also conductive tape exists, that can replace soldering joints, is flexible and can be formed through heat application, see Figure 87. However, according to TWI (2021b) it has a higher electrical and thermal resistance compared with solders and the electrical performance during life in particularly joint resistance might not be as good as a solder. The company Amohr claims to be able to design the resistance and size of a conductive tape to your wishes.

Figure 87. Conductive copper tape (Amazon, n.d.)

Castano and Flatau (2014) have researched and benchmarked different connection methods for smart textile fabrics, see Table 3. Together with the input from table 2 and the gathered information a benchmark was created for all research connections in this paragraph. They were benchmarked on: Conductivity, Flexibility, Stretchability, Durability, Ease of application, Duration of processing, Costs, Aesthetics, Ergonomics

Sewing

Conductive yarn can be used to make an electrical connection to PCBs as shown in Figure 88. This is an easy way to integrate electronics into textiles, while also remaining rather flexible. However, the connections can be fragile when overstretched or bended directly at the contact points, needing additional protection against these mechanical stresses. Moreover, these contacts need to be protected against oxidation.

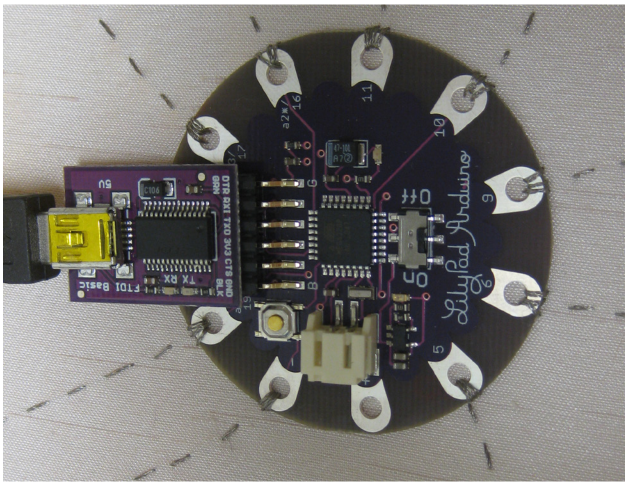


Figure 88. LiliPad connected through conductive yarns sewn through holes (Sparkfun, 2011)

Threadframe joining

Another connection method is mentioned by Post et al. (2000) that directly joins a components threadframe to a stitched circuit. The result is however quite vulnerable and needs to be strengthened. An example of this connection method used can be seen in Figure 89 where a Plastic Threaded Chip Carrier (PTCC) is bonded. The number of connections can be customized per design.

Figure 89. Threadframe joining a PTCC (Post et al., 2000, p. 853)

Technique	Types of fibers	Connection to	Type of bond	Strength	Typical connector
Miniaturized electronic connectors[a]	Wires, threads require a pre-connection	Other wires, acquisition system	Mechanical	Strong	Pin socket
Mechanical gripping, crimping[b]	Wires, conductive fibers	Fabrics, electronic components	Mechanical	Medium/flexible	Gripper snaps, sewable ring magnets
Soldering and wire bonding[c]	Solderable metals	Electronic components, wires	Physical/chemical	Strong/brittle	Soft alloys of Pb, Sn, Ag
Microspot-welding[d]	Stainless steel	Leadframes, (with threaded connections)	Physical	Strong/brittle	Cu, Sn, Pb
Conductive epoxy[e]	Any type	Wires	Electrical/mechanical	Strong	Doped epoxy
Conductive paint[f]	Any type	Sensors, fibers and fabrics	Electrical	Weak/brittle	Silver paint
Machine-printed line[g]	PEDOT, silver	Electronic components	Electrical	Medium	Printed PEDOT line
Screen-printed line[h]	Silver conductive paste	Electronic components	Electrical	Weak	Screen-printed line
Conductive polymer[i]	Any type	Sensors, fibers and fabrics	Mechanical/electrical	Medium–weak/very flexible	Conductive adhesive
Interposer pad with conductive adhesive[j]	Copper wires	Fabric	Electrical/mechanical	Strong	Interposer pad
Lamination[b]	Textile surface	Fabric, fibers, electronics	Mechanical/electrical	Strong	Non-conductive thermoplastic elastomer

Table 3. Connection methods for Smart Textile Fabrics (Castano & Flatau, 2014, p. 7)

Benchmark electrical connections

In Table 4 a summary and benchmark of previously discussed electrical connections is presented. Based on this benchmark, lamination, conductive glue and conductive yarns are considered to be valuable options that can be implemented during concept generation.

Lamination scores rather well on integration in textiles and has a medium to good lifespan. However, the production can be time consuming due to the application of multiple layers after another. Next, conductive glue is durable and is also easily integrated in textiles as it can act as a semi-flexible connection between soft textiles and more rigid electronics (Ismar et al., 2020). Though, drying times should be taken into account during production. Finally, conductive yarns are highly integrable in textiles and flexible. The durability of the yarn can be increased through proper product design. Stitches can for example be made stretchable and an additional protective layer can be added so it is less prone to mechanical forces inflicted on it.

Connection	*Durability in active environment (1= really bad & 5=really good)*	*Flexibility (1= really bad & 5=really good)*	*Stretchability (min. 10%)*	*Ease of Processing (1 = really bad - 5 = really good)*	*Integration in textile (1 = really bad - 5 = really good)*
Soldering	2	1	No	4	2
Welding	3	1	No	3	2
Wire bonding	1	1	No	2	2
Lamination	3	3	No	3	4
Grip connectors	3	2-3	No	2	2
Conductive tape	2	3	A little	3	3
Conductive glue	4	3	A little	3	4
Sewing conductive yarn	3	4	No	3	4
Threadframe joining	2	3	A little	3	4

Table 4. Benchmark electrical connections

Conclusions & decisions

Currently available interconnections from and to electronics were analysed and benchmarked. These connections varied from permanent connections such as soldering and glueing, to less permanent connections such as grip connectors. All analysed interconnection methods are not washable solely on their own and will need a protective layer, such as a casing to waterproof and fixate the connection.
The three interconnections found to have the most potential are: ***the lamination process described by Krshiwoblozki et al. (2012), conductive glue*** and ***conductive yarn***.

These three methods score rather good on ***durability, flexibility, integration in textile*** and ***lifespan.*** These three ideas will be implemented during the concept generation phase.

D. The following electrical connections: lamination process, conductive glue and conductive yarns will be considered for implementation in the concept generation stage.

Launderability (<30 degrees Celsius)	***Lifespan***	***Validation***	***Costs***
No, needs protective layer	Good	Electronics market	€
No, needs protective layer	Good	Electronics market	€€
No, needs protective layer	Medium	Electronics market	€€
No, needs protective layer	Medium - Good	Krshiwoblozki et al. (2012)	€€
Medium, needs protective layer	Medium	lectronics market	€
No	Bad	lectronics market	€€
No, needs protective layer	Good	lectronics market	€€€
No, needs protective layer	Medium	Arduino Lily Pad	€€
No, needs protective layer	Medium - Bad	Post et al. (2000)	€

8.3 Intregration techniques of electronics and textile

In this paragraph different methods to connect rigid electronic parts to textiles are presented and compared.

Non-conductive Adhesives

Non-conductive adhesives (NCAs) such as epoxy or textile glue are good mechanical connection options according to von Krshiwoblozki et al. (2012), see Figure 90. These connections are often more flexible than other commonly used connection methods, however they often do not leave an aesthetic appearance.

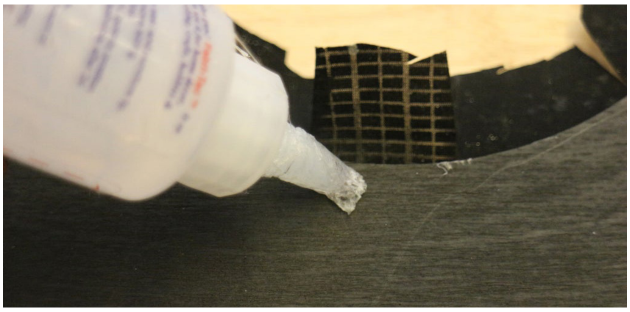


Figure 90. Non-conductive adhesives used on textile (Audreyobscura, n.d.)

Interpose pad with conductive adhesive

Interpose pads offer both an electrical and mechanical connection if desired. They are often made of copper fibres, ideal for a strong bond with fabrics (Castano & Flatau, 2014). See an example designed by Locher (2006) in Figure 91. These pads act as soft buffer between more rigid electrical components and can be more ergonomic for smart textile wearables.

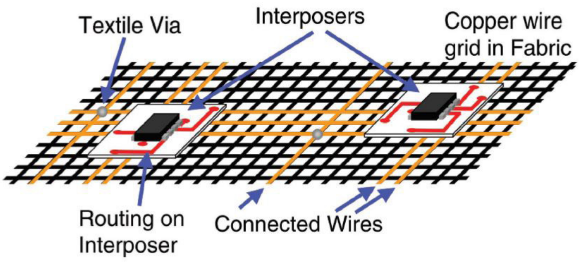


Figure 91. Conductive interposers as mechanical & electrical connection (Locher, 2006, p. 58)

Textile tapes

Another option to connect electronics to textiles is by the use of textile tapes such as TPU seam tape and Framis® Italia tape, see Figure 92. A good property of TPU seam tape is the waterproofing of the material it covers, however this is not permanent and will wear over time. This was used by the Nadi X to waterproof thin conductive wiring and can easily be ironed on the textile carrier.

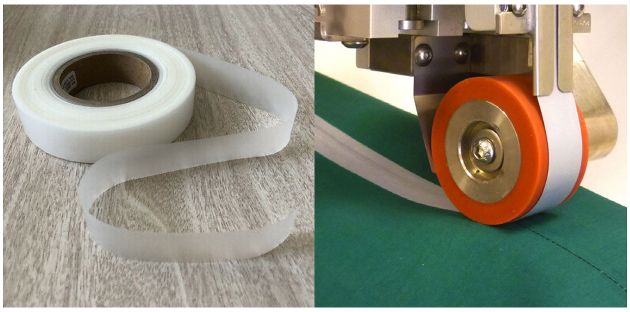


Figure 92. Textile TPU seam tape (left) (Ebay, 2021) & Framis® Italia material (right) (Framis®, 2021)

Piping and tunnels

Piping and tunnels as shown in Figure 93 can be used to cover electronics and guide electrical wiring. This method can also be used to isolate electrical wiring from external objects.

Figure 93. Piping used in the textile world that can guide wiring (Punkin Patterns, 2011).

Embroidery

Embroidery can be used to attach external wiring to the textile carrier or for isolating wires. However, with this technique a maximum stitch width of around 10 mm can be achieved. See Figure 94 for an example of embroidery around a cable.

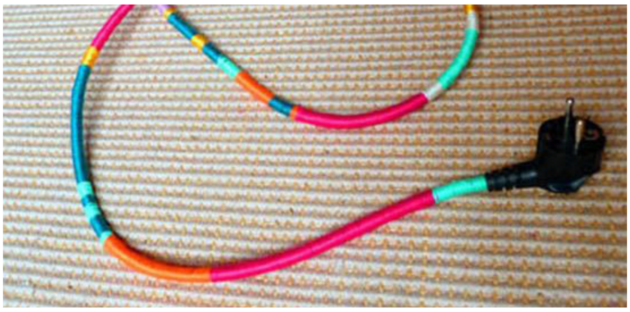


Figure 94. Embroidery of cabling (Babble, n.d.)

Lamination

Another interesting option mentioned by Castano & Flatau (2014) is lamination. This method connections multiple layers of fabrics and materials on top of each other. Adhesives or Vliesofix can be used to obtain this result. Also Heat pressing can be used to melt adhesives or layers together. Non adhesive layers can help to sandwich electronics in between multiple layers of fabric. The use of additional stitches can help to keep the electronics in a certain place. An example of lamination used in a product is the vibration modules from the Nadi X shown in Figure 95. Another good example of TPU lamination is demonstrated by Wicaksono et al. (2020) in Figure 96.

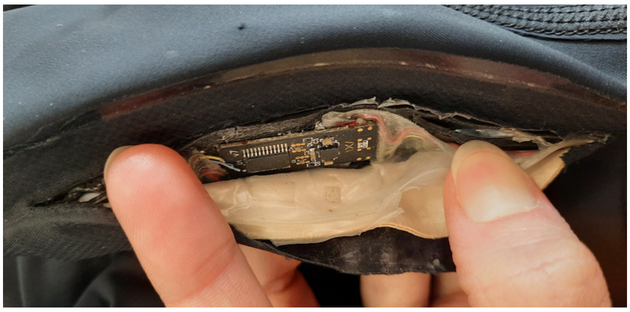


Figure 95. Lamination used in the Nadi X to protect harware components & vibration motors

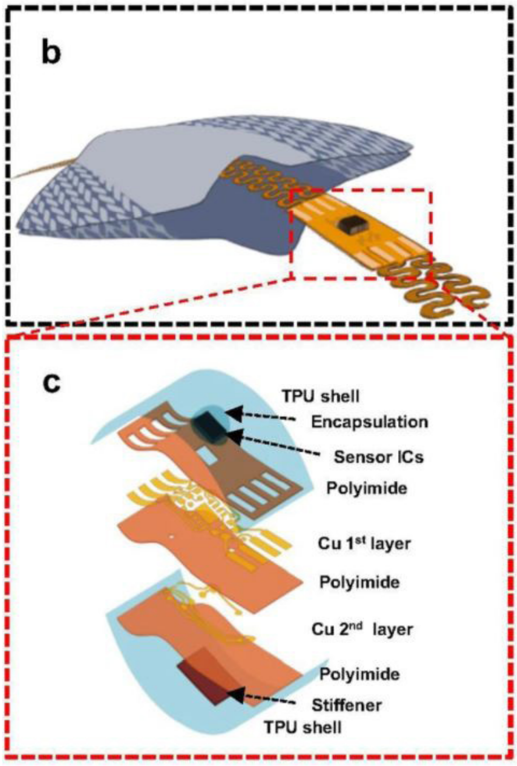


Figure 96. TPU lamination Wicaksono et al. (2020, p. 3)

Overmolding

Directly overmolding electronics on top of fabric is another good option. It is a strong mechanical connection that does require design for strain relief. Looking at flexible overmold materials might help to soften the rigid parts and improve comfortability. An example of an overmold directly on fabric is shown in Figure 97.

Sewing pads

Adding a special pad that can be stitched to the textile carrier as provided by the LP360™ Fischer connector shown in Figure 98 (left) or the LilyPad made by Arduino (right), is another interesting option to integrate electronics and textiles.

Stapling

This method was used by the NaviBelt designed by the company FeelSpace, see Figure 99. It is a cheap and quick connection method, though it is damaging to the textile carrier, might not be as durable and needs additional protection layers to avoid damage to the wearers skin.

Knitting pockets

Another option to integrate electronics into textile is the knitting of pockets and placing electronics in these pockets, see Figure 100. This immediately covers-up the electronics and gives the outside the same textile appearance just as the rest of the textile carrier. Creating electrical connections with this technique might however be challenging and the tightness of the pockets might decrease over time, giving the electronics space to move around.

Figure 97. Overmolded PP ring on a strap (Jtti, n.d.)

Figure 98. Sewing pad added to LP360™ Fischer connector (Fischer, n.d.) (left) & Sewn LilyPad Arduino (DigiKey, n.d.) (right)

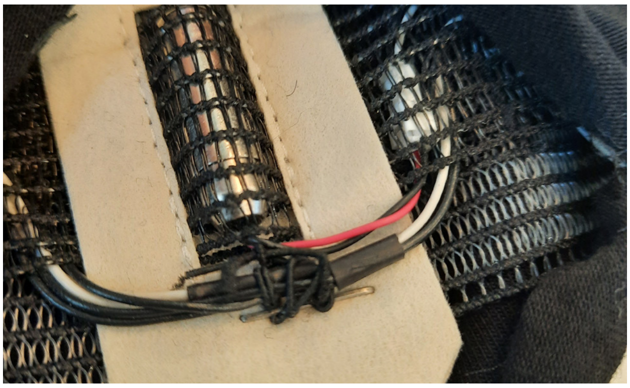


Figure 99. Use of a staple as connection method for the NaviBelt

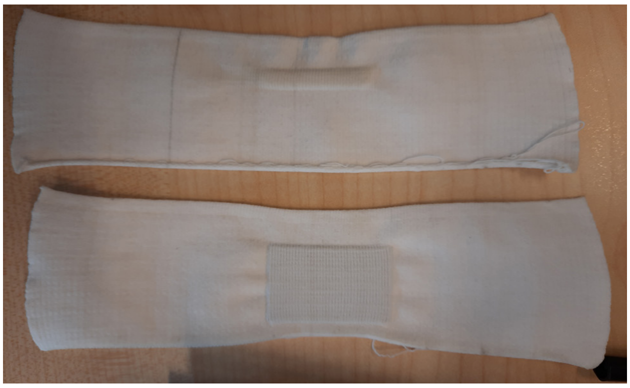


Figure 100. Foam and carboard tightly knitted into pockets (van der Valk, 2020)

Printing of electronics & ink

Multi-layer additive manufacturing is a good technique to create more flexible electronics for smart textile applications. This enables embedding of electronics on flexible substrates, see Figure 101. Moreover, multi-layered flexible printed circuits are a good addition to the possibilities. Next, 3D printing of electronics or screen printing of conductive ink or pastes is an interesting direction, as demonstrated in Figure 102. However, these options are challenging when it comes to the durability and recyclability, according to (Baxter, 2020). Making them less suitable for implementation in the current solution to be designed now, but an interesting option to keep in mind for the future when technology advances.

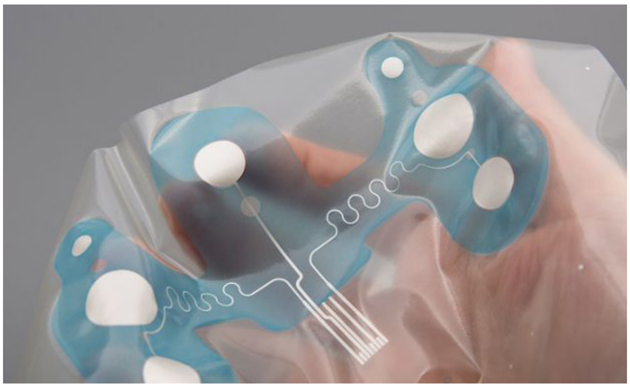


Figure 101. Printed electronics on textile (Baxter, 2020)

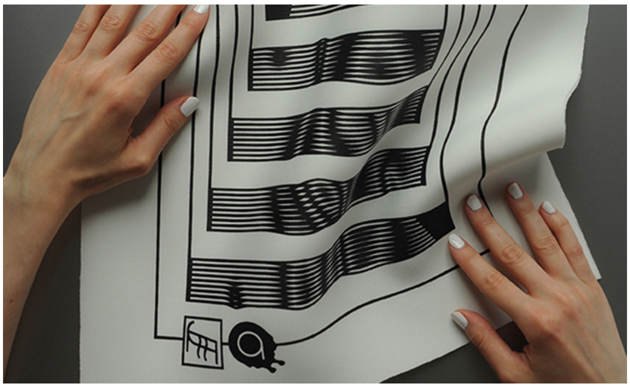


Figure 102. Screen printed electronic ink (Itersnew, 2015)

Benchmark integration techniques of electronics and textiles

These previously discussed connections to textiles were then rated on the following aspects: Integration into textile carrier, ease of application, duration of processing, costs, aesthetics, ergonomics, flexibility, stretchability, durability, launderability & waterproofing. See Table 5 for an overview.

Connection	*Durability in active environment (1= really bad & 5=really good)*	*Flexibility (1= really bad & 5=really good)*	*Stretchability (min. 10%)*	*Ease of Processing (1 = really bad - 5 = really good)*	*Integration in textile (1 = really bad - 5 = really good)*
Non conductive adhesives	4	3	A little	3	3
Interpose pad	4	3	No	4	3
Textile tapes	4	5	Yes	4	5
Lamination	5	4	A little	3	3
Piping & tunnels	4	5	Yes	4	5
Embroidery	4	4	A little	3	4
Overmolding	5	3	No	4	4
Sewing pads	5	3	A little	5	4
Stapling	2	2	No	5	2
Knitting pockets	4	5	Yes	3	5
Printing of electronics	2	3	A little	3	4

Table 5. Benchmark integration techniques of electronics and textiles.

Conclusions & Decisions

Based on the results presented in Table 5, we can conclude that ***most of the interconnection possibilities have real potential.*** Only stapling of electronics to the textile carrier does not seem like a proper option, as this actually breaks the textile carrier. The six options that are considered the best, since they scored at least a 5 and no less then a 3 on other categories, are: ***textile tapes, lamination, piping & tunnels, overmolding, sewing pads and knitting pockets***. All these options will be taken into consideration when developing concepts.

D. All solutions that have a minimal score of 3 at all categories are allowed to be implemented during the concept generation stage.

Launderability (<30 degrees Celsius)	***Lifespan***	***Validation***	***Waterproofing of electronics***	***Costs***
No, needs protective layer	Good	Electronics market	No	€
No, needs protective layer	Medium-Good	Locher (2006) & Krshiwoblozki et al. (2012)	No	€
Yes, however limited	Medium-Good	Widely used on textile market	Yes	€
Yes, however limited	Good	Wicaksono et al. (2020) & Nadi X	Yes	€€
Yes	Good	Widely used on textile market	Yes, if waterproof material is used	€
Yes	Good	Widely used on textile market	No	€
Yes	Good	Elitac Wearables	Yes, IP67	€€€
Yes	Good	Fischer 360™ connector	No	€
No	Bad	NaviBelt	No	€
Yes	Good	van der Valk (2020)	No	€
No, needs protective layer	Medium	Holst Center & van Dongen (Baxter 2020)	No	€€€

8.4 Removable connections

In this paragraph different removable connections are analysed for electrical components, to get an idea of what solutions are already available on the market. Afterwards these connections are benchmarked and the most valuable solutions will be considered for the concept generation phase.

Figure 103. Pogo pin magnetic connection (Cletk, n.d).

When looking at the current market, often the main control module was detachable from the product. Therefore it is interesting to look at easy removable connections of electronics. There are many forms to be found on the market such as, pogo pins, snap buttons, etc. Also washable connections can be found made by both Fischer & Ohmatex.

Pogo pins

Pogo pins are also called probe connectors, and are widely used in all kinds of industries (e.g. aerospace, automobile & medical). Pros of these connectors are the small size, the long service life, its fashionable appearance, suitable for high-end electronic products, fast production speed and low investment costs (Twinlink Technology, 2019). They can come in any form with as many connection points as you want. Downsides are that they require high precision manufacturing and the contact points should not be dirty in order to function properly (Twinlink Technology, 2019). The connection is often fixated by using small magnets, see Figure 103. These magnets might not be strong enough to withstand forces applied during physical activity. In order to solve this problem additional mechanical fixation techniques might be necessary.

Figure 104. Snap button connection (Ternimed, n.d.)

Snap fits

Snap fits are another removable option for electronics. They have been known and used for a long time in the textile industry, which makes them widely available and also

Figure 105. 3D printed conductive snaps printed from Black Magic 3D coductive graphene PLa (Freire, 2017)

low in costs. However, they do need to be modified to a cable connection, as shown in Figure 104. Moreover, they require quite some surface area to be integrated per connection point, making a detachable module quite large in size. Also, the mounting material on which the snap button is fixated should be strong and rigid in order to avoid damaging to the product and electrical connections. Some 3D printing and conductivity tests of snap buttons and conductive yarns has been done by Freire (2017), see Figure 105. Gripper snaps are also known to make a good metal-on-metal bond due to the teeth that pierce both the a conductive substrates and textile carrier. The downside of this strong connection is that it only allows low connection density (Post et al., 2000).

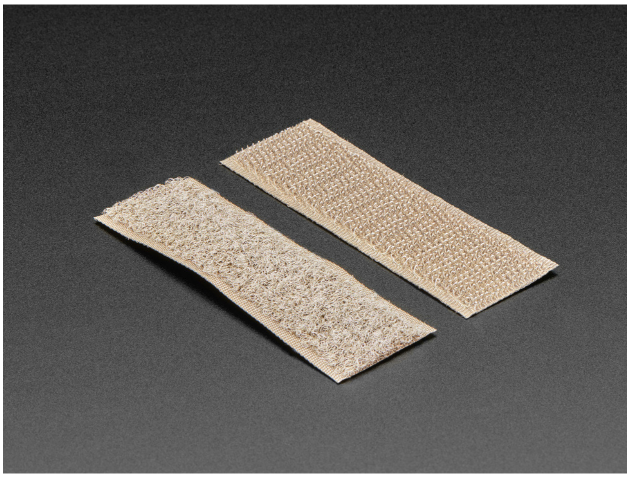


Figure 106. Conductive Hook and Loop (Adafruit, n.d.)

Conductive Velcro

Adafruit has launched Conductive Hook and Loop which can be used to make electrical contacts that are easy (de-)attachable. It is normal Velcro coated with silver, making it easy to cut an sew, see Figure 106. The expected cycle life is 5000 openings/closings (Adafruit, n.d.).

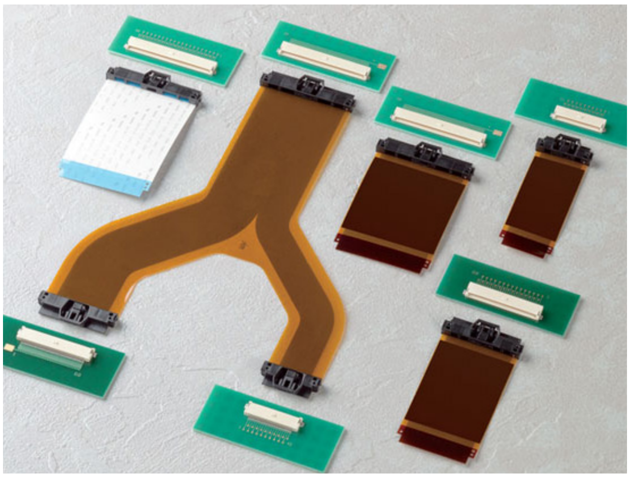


Figure 107. FFC & FFP connectors (Yazaki, n.d.)

FFC & FPC connectors

Flat Flexible Cable (FFC) and Flat Printed Circuit (FPC) connectors (see Figure 107) are often used when connecting electronics. They are mainly used for board in device connections and are easy to mate. The connection also provides a wiping structure as the connectors slide in that can remove dirt and foreign objects before mating (Yazaki, n.d.). They are not that durable when it is attached and reattached often in a lifetime. However, it does make assembly faster and easier during the production process.

JAE's RK01 connector

Another interesting connector is the RK01 developed by JAE's, shown in Figure 108. It is a washable connector that is specially designed for smart textiles and wearable clothing devices. The number of pins can be varied and the insulator material used is PC. It has passed the JIS 1930 (C4G) test, a domestic washing test specified by the Japanese Industrial Standards (JIS) according to JAE (2020). The costs of this connector are however unknown.

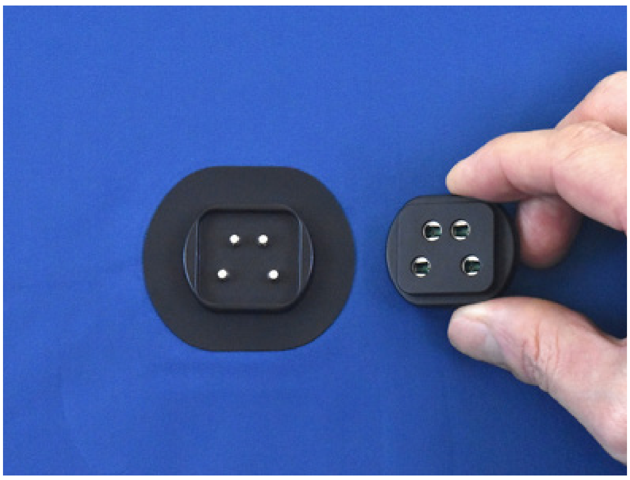


Figure 108. RK01 washable connector by JAE (2020).

Ohmatex washable connector

The Ohmatex connector also works with the male-female principle which are both fully washable, see Figure 109. This connector provides a strong electrical connection, has a built in strain relief and is suitable for application on flexible substrates (Innovation in Textiles, 2014). The processing and production method are however costly and time intensive. Furthermore, the connector is designed to work well with the Ohmatex flat cable the connector is also quite expensive.

Fischer's LP360TM connector

In Figure 110 The LP360™ connector can be seen. This special connector uses a male and female part and is robust, durable and cleanable. Furthermore, it has a 360 degree mating freedom and has the option to come with 7 signal or 4 signal and power contacts. The plastic used is a high-end composite based on PEEK and the square around it can be stitched to the textile carrier (Fischer, n.d.). A downside is the price of this connector and the size of the connection module.

Holst Centre grip connection

In Figure 111 an innovative connection method designed by Holst Center is shown. This connection uses a combination of friction and a snap fit to keep the module in place. It is easily (de-)attachable and stays in place in a dynamic environment.

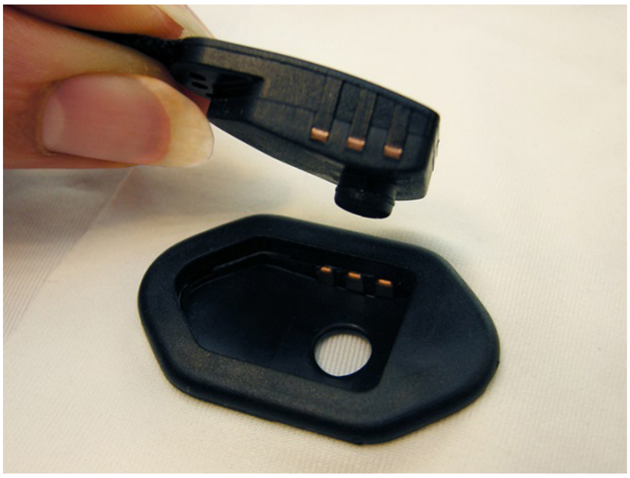


Figure 109. Ohmatex washable connector (Innovative in Textiles, 2014)

Figure 110. 360 degree mating freedom LP360™ connector (Fischer, n.d.)

Figure 111. Holst Centre connection (Sports & Technology, n.d.)

Magnetic Mollii Suit connection

The Mollii Suit uses a magnet to press electrical contacts together, see Figure 112. This is a robust and durable connection method that stays in place while the user is moving around. When asking about the effect of magnets on data transition, it became clear that static magnetic fields do not cause disrupting interference according to B. Bicknese (personal communication, Apr 20th, 2021).

Figure 112. MolliSuit magnetic connection (Palmcrantz et al., 2020).

Ball point pocket connector for wearables

The ball-grid array-like electronics-to-textile pocket connector designed by Mehmann et al. (2015), uses grid structured connection points and silver coated copper conductive threads connected to insulated copper cables through silver epoxy. The prototype shown in Figure 113 is slid into a pocket where conductive stripes shown in Figure 114 make contact. This is an interesting method that also allows for a customized umber of connection. Moreover, it can be used to designing detachable modules for smart textile wearables. The question remains how durable and solid the data connection remains during physical activity of a user. The authors of Mehmann et al. (2015) suggest to fix this problem by designing a tighter pocket, which in turn could affect the ergonomics.

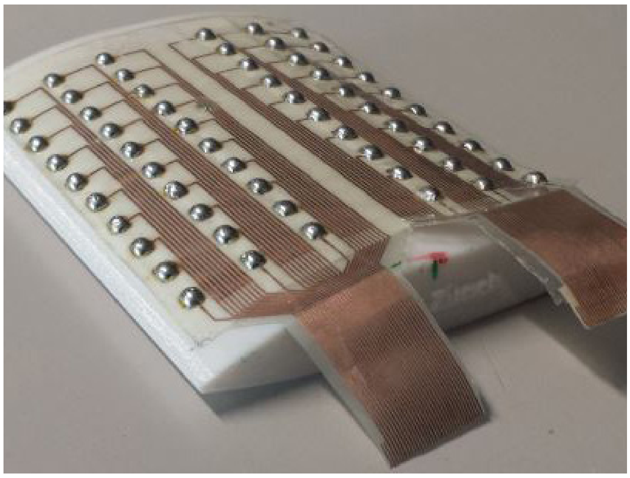


Figure 113. Ball-grid-array-like-electronics connector prototype (Mehmann et al., 2015, p. 3)

Figure 114. Stripes of silver coated copper threads (Mehmann et al., 2015, p. 3)

Benchmark removable connections

The removable connections are rated on the following aspects in Table 6: the durability in an active environment, the number of connection points, dimensions, launderability, ease of processing, estimated lifespan, costs and availability of parts. From this benchmark Pogo pins, snap buttons, conductive Velcro and the ball point pocket connector were found to have the most potential for implementation.

Connection	*Durability in active environment (1= really bad & 5=really good)*	*Flexibility (1= really bad & 5=really good)*	*Stretchability (min. 10%)*	*Ease of Processing (1 = really bad - 5 = really good)*	*Integration in textile (1 = really bad - 5 = really good)*
Pogo pins	4	3	No	3	3
Snap button	4	3	No	3	3
Conductive Velcro	4	4	No	4	5
FFC & FFP connectors	3	3	No	3	3
JAE's RK01	4	5	No	4	5
Ohmatex washable connector	4	4	No	3	4
Fischer LP360™	5	3	No	3	3
Holst Center grip connection	4	3	No	3	3
Magnetic Mollii Suit	4	5	No	3	4
Ball point pocket connector	4	3	A little	3	4

Table 6. Benchmark Removable connections

Conclusions & Decisions

In this paragraph removable connection options were analysed and benchmarked. The most interesting connections were found to be: Pogo pins, snap buttons, conductive Velcro and the ball point pocket connector.

The connectors made by JAE, Fischer, Holst Center and the Mollii Suit are also good candidates, however were specifically made for a certain purpose and not commercially available, or would make Elitac Wearables too dependant on one specific company. Therefore these connection methods are used for inspiration in the concept generation phase when designing removable connections of the main control module.

D. Conductive Velcro, pogo pins, snap buttons, and the ball point pocket connector will be implemented during the concept generation phase.

D. The connections designed by JAE, Ohmatex, Fischer, Holst Centre and Mollii Suit are used as inspiration during the concept generation stage.

Launderability (<30 degrees Celsius)	*Lifespan*	*Dimensions*	*# of connection points*	*Costs*
Yes, up to IP67	Good	4 connections : 14mm (l) X18 mm (w) x 5mm ((h) plugged in	1 to X, customizable	€
Yes, RVS versions	Medium	8.5 mm diameter start	1 per button	€
Yes, however limited	Medium-Good	maximum of 30mm x 6 inch long, thin and light weight	1 per piece	€
Yes, however limited	Good	leight weight and small	customizable	€€
Yes	Good	large and bulky	4	€€
Yes	Good	quite large, light	Up to 6	€€
Yes	Good	quite large and heavy	4 or 7	€€€
Remove module before washing	Good	Not specified, however looks rather large	Customizable	n.d.
Remove module before washing	Good	Not specified, however looks large	Customizable	n.d.
Remove module before washing	Good	Customizable	Curstomizable	€€

8.5 Modular electronics

Elitac Wearables mentioned in the project definition to be looking for a more modular and scalable design of the electronics so it can be widely implemented in different products in the future. Therefore we look at modular and scalable design of electronics and try to draw lessons from them for this specific project.

Wearic Smart textile modular kit
Wearic has designed a special smart textile kit so people can have a go with designing their own smart textile wearables, see Figure 115. The sensor and actuator modules that can be implemented range buttons and pressure sensors to heating elements and wetness sensors, and are all made of textile (excluding the LED's and micro controller). The interconnection methods used are silver coated conductive yarn (235/36dtex), non-woven isolation with adhesive coating and snap fits (Wearic, 2020). This kit is suitable for prototyping, however, for industrial implementation in real products the durability is insufficient.

Vibration motor break-out modules
Another interesting modular design is the vibration motor break-out modules created by Pulsea (2013), see Figure 116. Here two snap fits are connected to a plus and minus of the circuit to power the vibration motor. As a housing the creator experimented quite a lot, ranging form Sugru silicon to thermoplastics and casting resin on top.

Boson: A modular Electronics Kit Building System for Lego and STEM
This kit breaks down complicated circuits into simple and functional modules, see Figure 117. To connect them, no coding or soldering is necessary. The modules use magnets, screws and Velcro to attach to surfaces, and even are compatible with LEGO. The plug-and-play system can be further upgraded with a special module that

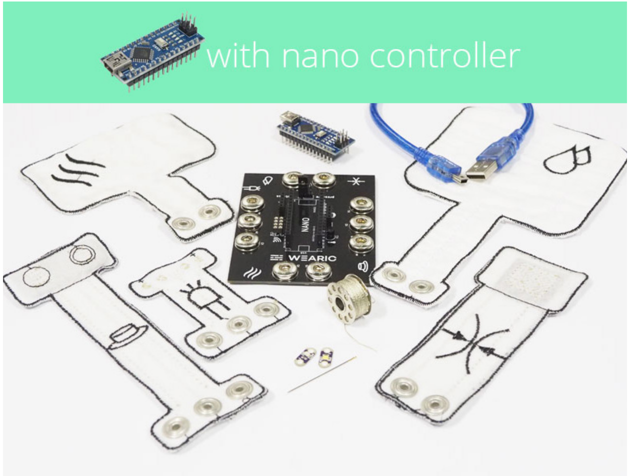


Figure 115. Smart textiles kit with nano controller (Wearic, 2020)

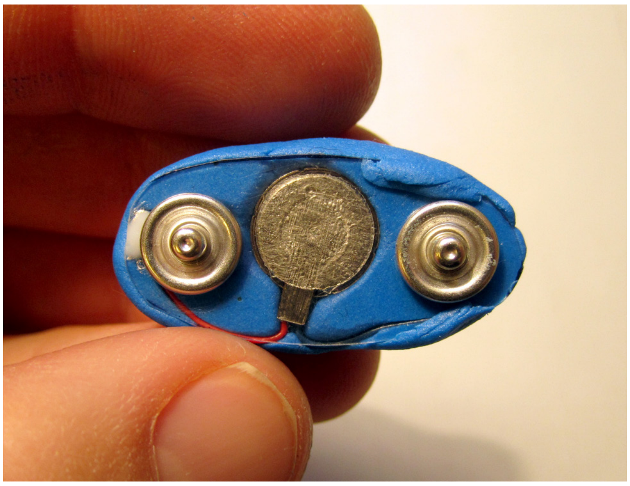


Figure 116. Vibration motor break-out module with snapfits (Pulsea, 2013)

Figure 117. Modular electronics (DFRobot, n.d.)

allows for machine learning and pattern matching capabilities (DFRobot, n.d.)

Modular construction toolkit for interactive textile applications

The Make Your Own Wearables (MYOW) toolkit by Woop et al. (2020) is designed to enable individual projects to implement electronics in textiles without the need of special machines. It comes with a tool to mark the trail for conductive traces and PCB designs that allow for quick design and implementation, see Figure 118 and 119. This toolkit might be a good inspiration to improve the product development and production process by making it faster and more scalable. After all, it includes some handy tools that help design where the wiring should come and can help with the calculation of how much wiring is needed per product. This is also something that takes up quite some time and requires help from multiple people, especially with the current stiff cabling (M. Peters, personal communication, June 2nd, 2021).

Conclusion

The modular electronic examples presented in this paragraph can be used as inspiration during the concept generation phase. It is possible to create a completely modular system where the user has to attach every single piece of electronics. The current vibration motors of Elitac wearables require an additional driver PCB and two extra data connection lines to enable I2C communication, which will increase the size of the module somewhat. Moreover, ***having to (de-)attach every single module is simply not practicle and user friendly for large constellations (>5 tactors).***
The use of a more ***flexible casing*** is interesting to keep in mind for ergonomics. Also, the ***toolkit designed for prototyping*** is inspiring when it comes to widely implementable technology systems.

D. For constellations of more than 5 tactors, the modules will have to be fixated in the textile carrier, or made detachable all at once.

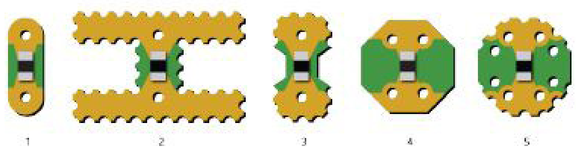


Figure 118. PCB designs by Woop et al., (2020, p 3.)

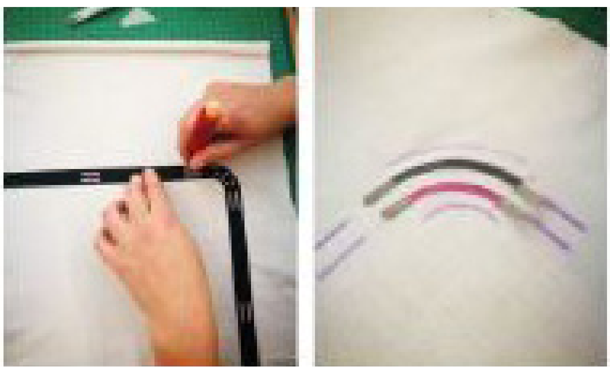


Figure 119. Conductive traces trail market (Woop et al., 2020, p.3)

9. Initial tests

To get to know the restrictions of the system to be designed some basic calculations and initial tests were performed. The ERM motors were tested to get a feeling for the amount of current they draw and the voltage required to start (9.1). Moreover, the maximum circuit resistance for different configurations was calculated in paragraph 9.2. Moreover, potential technologies were tested for implementation A conductive yarn demonstrator (9.3), conductive Velcro (9.4) and screen-printing with conductive ink (9.5).

9.1 ERM motor tests

According to the specifications of the motors, the current necessary to start the motor 192 mA for the cilindrical ERM and 120 mA for the coin ERM. Furthermore, the operating current for both motors lies at a maximum of 80 mA at 3.0V DC.
To see how the motors behave in practice, test were performed. Two cylindrical ERMs and 2 coin ERMs were powered with 3,0 V DC and the current was used as the variable parameter. The motors were connected to the DC power analyser as shown in Figure 120. The current was turned up until the point the vibration motor started to vibrate. This measurement was repeated for 5x per motor. A DC voltage analyser was used to perform the test with. The resistance of soldered wires to the ERM motors were measured beforehand. These added 0.2 Ohm additional resistance to the circuit. For all data collected in detail see, Appendix A7.

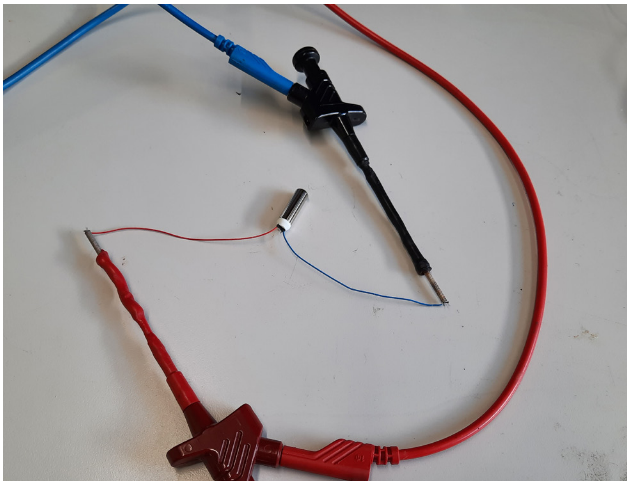


Figure 120. Starting parameters for the current test of the motors

Figure 121 shows the boxplot graphs of the currents at which the motors started to vibrate. For the cylinder motors 1 and 2 the average current is 15.1 mA and 18.2 mA. The coin cylinders have the average values of 20.3 and 10.3 mA. The range of the boxplots vary quite a lot, which can be explained by starting location of the uneven mass. If the mass is in a favourable upward position, in which it can take advantage of gravitational forces, it will require less power to start moving then when gravitational forces work against the mass.
This however does not explain why the measured currents do not come close to the expected starting currents of 192 mA and 120 mA. It is expected that the operating current is measured and not the starting current. Therefore a more specific measurement is done that analyses the current at the exact moment in time when the motor starts, see Figure 122. From this we can conclude that the starting current of the cylindrical ERM comes close to the 192 mA described in de specifications. However, it takes even less than 100 ms to let the starting current return to a normal operating current.

A second small test showed that when setting the voltage to 2.5V and the current to 50 mA, both motors still managed to start properly.

The duration of the peak current is so short (less than 100ms) that even the conductive yarns did not seem to heat up significantly with a quick-and-dirty IFR camera. However, this should be tested more extensively in the future with an IFR camera to see if legislation is met. The maximum allowed temperature of the electronics worn directly on the skin is 43 degrees Celsius for contact lasting longer than 10 minutes (SL Power Electronics, 2019).

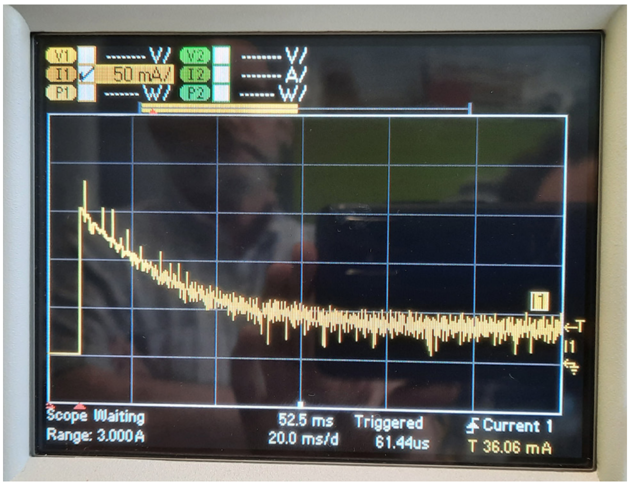


Figure 122. Starting current around 180 mA for the cilindrical ERM motor & 36 mA operating current.

Conclusions & Decisions

The peak current for the motors lie around the specified 190 mA and 120 mA, but after less than 100 mS the required current to keep the motor running lowers to an operating current. The tests showed that these operating currents were a lot lower than the specified 80mA.

To ensure that the motors will start and operate properly, the following values will be used: ***3V DC*** is the preferred voltage, a ***starting current of 192 mA and 120 mA*** for cylinder and coin motor will be taken, and an ***operating current of 50 mA*** for both motors. This last value is higher then the measured values, but includes a safety factor to ensure proper functionality.

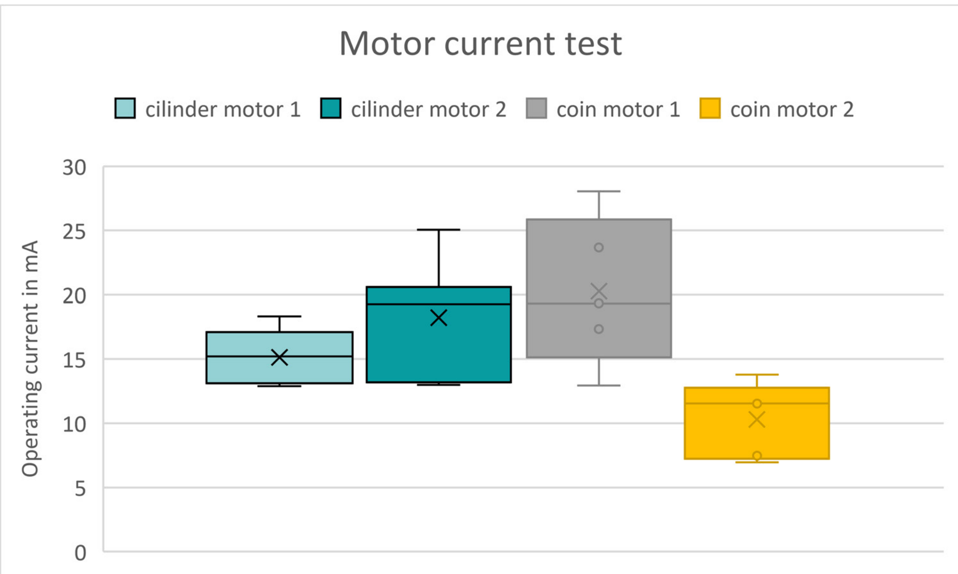


Figure 121. Operating currents measured for the cilinder (top) and coin (bottom) ERM motors respectively

9.2 Resistance tests & calculations

Resistance in practice

Conductive yarn resistance test

To get a better idea of the maximum resistance a power carrier can have before the ERM motors do not receive enough power any more to function, small test were performed with conductive yarns, as these are easy to process and not large in volume.

The resistance was measured over a total length of one meter, and measured with an interval of 0.2 meters. The resistances measured over different lengths and different yarns can be found in Figure 123 & 124. The resistance of the Amberstrand 166 was difficult to measure accurately as the yarn consisted of loose fibres that were not tightly packed together. These yarns were later on braided to demonstrate the processability and the lowering of the resistance due to the parallel resistance law, see Appendix A8.

To get a general idea with which resistance the motors still started, the motors were powered through the different conductive yarns. The set voltage at a distance of 0m on the conductive yarns was 3 VDC and the current 50mA. The motors were then connected at 1m distance and it was noted if the motor started or not. If the motor did not start, the distance was shortened with intervals of 0.2m until the motor did start. The maximum resistance at which the coin and cylinder motor still started to vibrate, okay/soft, lies somewhere around 60-70 Ohms according to Table 7. It should not be forgotten that the position in which the mass is located, results in a varying internal resistance the motor needs to overcome to start. The Y-axis cut off represents the resistance of the measuring circuit, which varied from 0.22 to 3.54 Ohms.

Yarn	*Resistance in Ohms / meter*	*Cylinder motor vibration + distance*	*Coin motor vibration + distance*	*Y-axis cut off*
Bekaert Bekinox VN 12.2.2.175S Steel	12.7	Good at 1 meter	Good at 1 meter	1.53
Bekaert Bekinox VN 14.2.9 175S Steel	67.6	Okay at 1 meter	Soft at 1 meter	0.37
AMANN Group Silver-tech 50 Tex 62	142.2	Soft at 1 meter	Very soft at 1 meter	3.54
AMANN Group Silver-tech 30 Tex 96	65.5	Okay at 1 meter	Soft at 1 meter	1.18
Elektrisola 31900286 copper, silverplated	2.9	Good at 1 meter	Good at 1 meter	0.41
Elektrisola 30004021L copper, silverplated	2.1	Good at 1 meter	Good at 1 meter	0.52
X-steel	2.2	Good at 1 meter	Good at 1 meter	0.37
Amberstrand 166	4.1	Good at 1 meter	Good at 1 meter	0.22
Liberator 40	3.0	Good at 1 meter	Good at 1 meter	0.4

Table 7. Resistance versus the vibration strength of the two vibration motors.

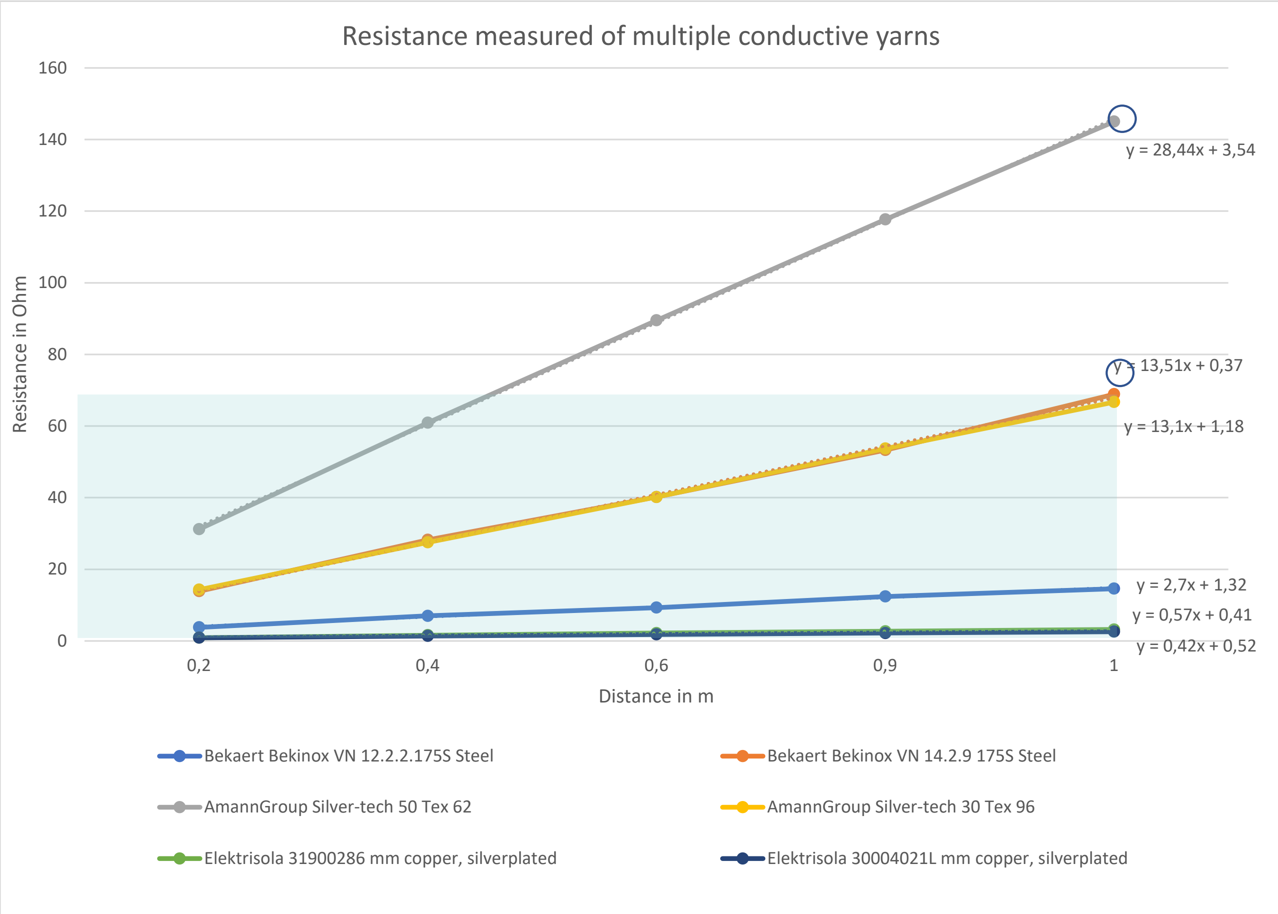


Figure 123. Resistances of multiple conductive yarns, where the slopes of the functions represent the resistance per meter and the blue square represents the resistance level at which the motors still function.

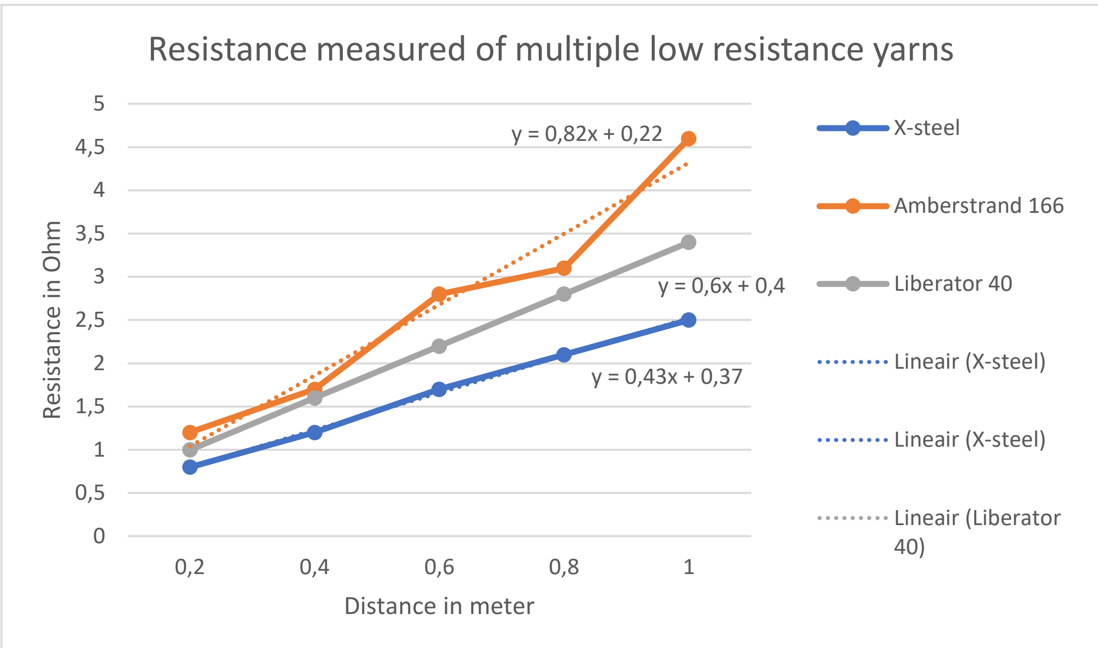


Figure 124. Low resistance conductive yarns measured, where the slopes of the functions represent the resistance per meter. The outliers of the Amberstrand 166 are probably measurement errors.

Overcoming high resistances

The high peak current necessary to start the motors and the required voltage seem to be the limiting design factors. The 3.0 volts are necessary to start and operate one motor properly. The voltage supplied by Elitac Wearables is generally 5V, allowing a maximum drop of 5.0 - 3.0 = 2.0 volts. The resistance of the power supply system is therefore not allowed to be too high, as confirmed by the conductive yarns tested. However, there are a few tricks to overcome these problems:

1. Chain multiple power lines in parallel to make use of the parallel resistance law, to decrease the total resistance:

$$1/R_{total} = (1/R1) + (1/R2) + (1/Rn)$$

This will decrease the overall voltage loss over power lines.

2. Chain motors in series and not in parallel (as Elitac Wearables is used to now) to increase the current provided. However, this does require a higher starting voltage as the voltage law in series is equal to:

$$V_{total} = V1 + V2 + Vn$$

This system could result in uncontrolled powering of the motors as the voltage might not be equally divided. (A. Kooijman, personal communication, April 13th, 2021).

3. Provide each individual motor with its own circuit so no voltage or current has to be shared with other motors.

4. Place a capacitor as booster to help start the motors with a higher current, as shown in Figure 125. This solution will only last a very short moment in time and will not help to overcome a voltage shortage. This however does add an additional component and you will have to take the charging and discharging time into account in the design.

5. Integrate a BUK converter that converts the voltage to a higher voltage when the motors need to start and convert back to a lower voltage after starting. This solution also increases the number of components, increasing the costs, and energy loss during the conversions will occur. This was already once implemented by Elitac and has proven to work in the past.

Capacitor test

To test how big a capacitor is necessary to discharge when starting the motors, a small test was performed. First a cylinder motor was chained in series with a 47 Ohm resistance, powered by 3V and 50 mA. The motor still started properly. The same was done with a 100 Ohm resistance and the motor did not start any longer. This means that the maximum allowed resistance lies somewhere between 47 and 100 Ohms Next, a capacitor of 47 microfarad was chained in series in between the 100 Ohms resistance and motor. 9/10 times the motor would start properly. 1/10 times it would start at the second try. The same test was performed with 47 Ohm resistance. The motor would almost always start at 2.0V applied to the system.

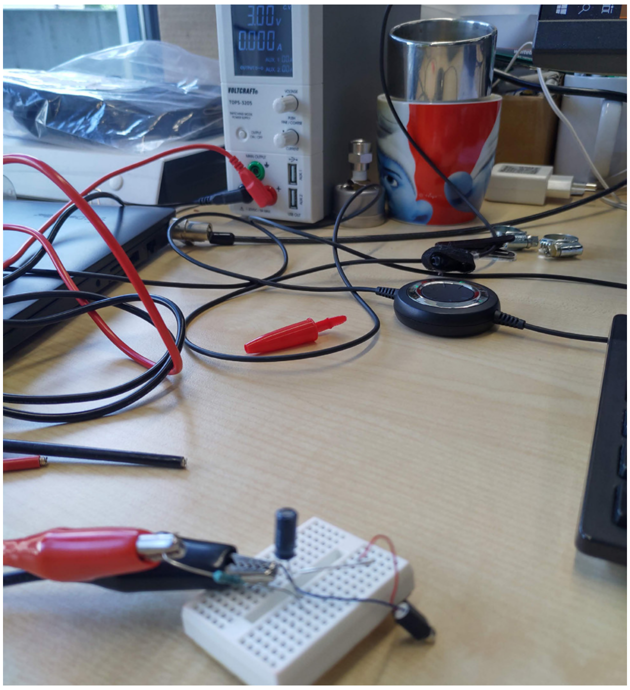


Figure 125. Motor test with capacitor and resistance chained in series (Kooijman, 2021)

Resistance in Theory

To calculate the maximum resistance and current that will be required from a system the maximum number of vibration motors that need to be powered are analysed. According to the requirements mentioned in paragraph 7.2, 3 vibration motors should powered simultaneously. This allows the design of triangular constellations as shown in Figure 126. By changing the vibration intensity of the three different tactors the location of a 'virtual vibration motor' will be felt by the user. By designing for this maximal triangle constellation, a line and point constellation will also be enabled to be implemented in the system.

The 3 motors will not be started all at the same time, but in series, resulting in a peak current (Ipeak) of 2 vibration motors running and the third one starting. This results in the following numbers for cylinder and coin motors respectively:

$I_{peak3cylinders} = I_{operating} + I_{operating} + I_{startcyl}$

$I_{peak3cylinders} = 50mA + 50mA + 192mA = 292\ mA$

$I_{peak3coins} = I_{operating} + I_{operating} + I_{startcoin}$

$I_{peak3coins} = 50mA + 50mA + 120mA = 220\ mA$

So for a triangular constellation of cylinder motors the peak current is 292 mA and for coin motors this is 220 mA.

With the peak currents calculated and the known starting voltage of 5V and necessary operating voltage of 3V at the motors, the maximum allowed voltage drop and resistance of a power transport medium can be calculated:

$\Delta U = I * R$

In which:
ΔU= allowed voltage drop in Volts (V)
I = current in Ampere (A)
R = Resistance in Ohm (Ω)

$\Delta U = 5.0V - 3.0V = 2.0V$

$Rmax3cylinders = \Delta U/I = 2.0V / 0.292A = 6.85\ \Omega$
$Rmax3coins = \Delta U/I = 2.0V / 0.220A = 9.09\ \Omega$

If only one or two motors are to be powered. As for the different constellations, the starting current would be as follows:

$I_{peak2cylinders} = I_{operating} + I_{startcyl}$
$I_{peak2cylinders} = 50mA + 192mA = 242\ mA$
$I_{peak2coins} = I_{operating} + I_{startcoin}$
$I_{peak2coins} = 50mA + 120mA = 170mA$

$I_{peakcylinder} = I_{startcyl}$
$I_{peakcylinder} = 192mA$
$I_{peakcoin} = I_{startcoin}$
$I_{peakcoin} = 120mA$

$Rmax2cylinders = 2.0V / 0.242A = 8.26\ \Omega$
$Rmax2coins = 2.0V / 0.170A = 11.67\ \Omega$
$Rmaxcylinder = 2.0V / 0.192A = 10.42\ \Omega$
$Rmaxcoin = 2.0V / 0.120A = 16.67\ \Omega$

The maximum allowed resistance of the power transport medium for a ***cylinder*** triangle constellation is 6.85 Ohm and 9.09 Ohm for a coin triangle constellation.
For a line constellation with two cylinder or coin motor the maximum allowed resistance is 8.26 Ohm and 11.67. For singular point constellations of cylinder or coin motors the maximum resistance allowed will be 10.42 and 16.67 Ohm respectively.

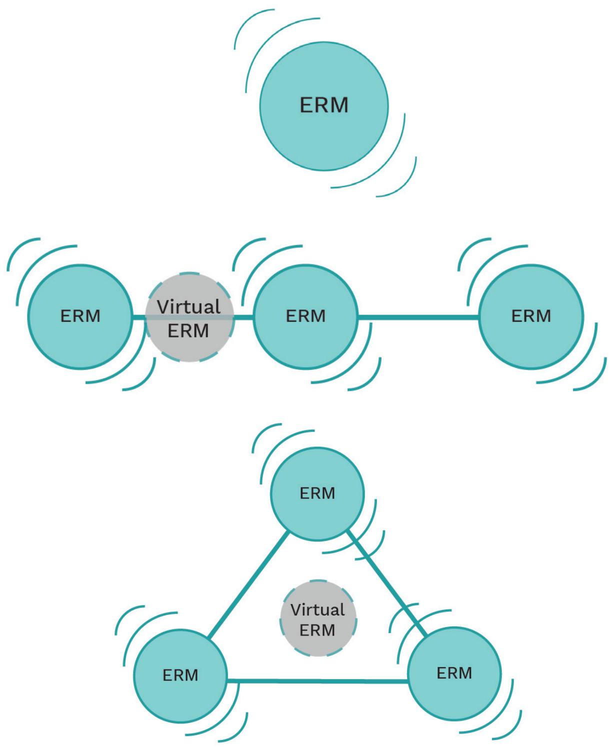


Figure 126. Point (top), line (middle) and triangle (bottom) constellation

Conclusions & Decisions

It is interesting to compare the maximum resistance allowed in theory to the ones found in the experiment. The maximum allowed resistance of the power transport medium for a ***triangular constellation with cylinder motors is 6.85 Ohm and for coin motors 9.09 Ohm***. ***For a line constellation these values are 8.26 and 11.67 Ohm, and for a points constellation these are 10.42 and 16.67 Ohm for cylinder and coin motors respectively.***

Interesting to see is the ***maximum resistance*** to power one motor softly ***in practice lies between 60-70 Ohm.*** This number is higher than in theory, which can be explained by specifications of the motors. The 3V operating voltage is the ideal operating voltage, however the cylinder motor can still function from as low as 1V and the coin motor from 2.3V according to the specifications of the motors. Even though the motors do vibrate, a low voltage will result in a softer vibration that might not be noticeable by the user. Therefore, designing according to the theoretical resistances calculated, will ensure proper functionality and hard enough vibrations in practice. However, there are different design decisions that can help overcome higher resistances such as multiple parallel power lines to reduce the total resistance or start with a higher voltage to allow more loss over the transportation medium.

D. For the design of the system we will work with the values from the triangular cylinder constellation, as this gives the highest design freedom when applying the technology in different product ranges.

D. The next thing to keep in mind is the current limitation because of safety reasons. Direct surface contact temperatures go above 43 degrees Celsius, it is not allowed to wear the device directly on the skin for longer than 10 minutes (NEN, 2015).

9.3 Conductive yarn Demonstrator

The goal of this demonstrator was to show that it is possible to power a single vibration motor through conductive yarn over a large distance.

In Figure 127 a conductive yarn demonstrator is shown that powers a single vibration motor over more than 2 meters yarn.

The conductive yarn used for this demonstrator is Elektrisola 3004021L Litzwire of 0.04 mm thickness and Cu/Ag50 material. This yarn has no coating, is very well suited for soldering according to the specifications and has a measured resistance of 2.1 Ohm/m. The top yarn used was grey non-conductive 100% polyester yarn and the bobbin was filled with the Elektrisola conductive yarn. A zigzag stitch with a length of 2.5mm and a width of 3mm was used to cover more distance in a shorter piece of textile, see Figure 128.

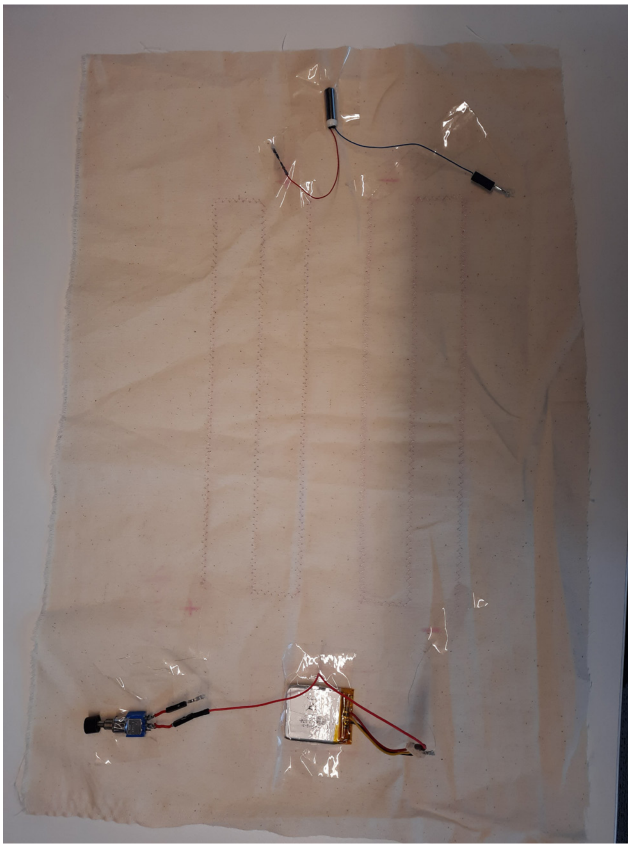


Figure 127. Conductive yarn demonstrator with more than 2m of conductive yarn used in total.

In Figure 129 a schematic overview of the setup can be seen. The total length of the yarn used can be partly measured and calculated by the law of Pythagoras:

$A^2 + B^2 = C^2$
(With A=2.5 mm and B=3mm)
$C=\sqrt{(2.5^2+3^2)} = 3.90$ mm

Per 2.5mm travelled in a straight line 3.905mm of conductive yarn was used.
For 1 meter wire for the plus we will need to travel 807.8 mm in a straight line:

$1000 / 3.905 * 2.5 = 807.8$ mm

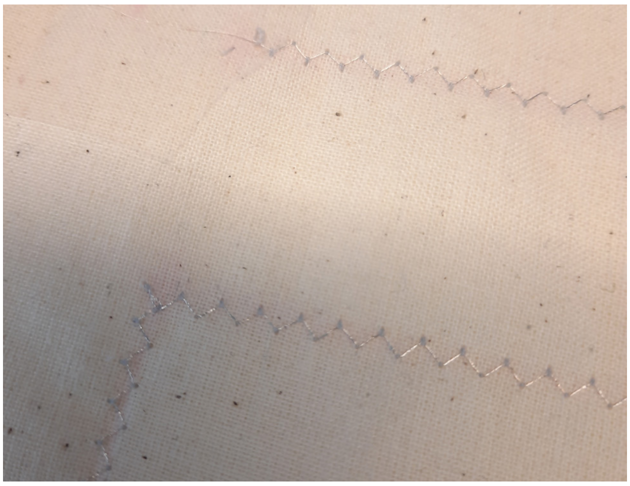


Figure 128. A close-up of sewn conductive yarn in zigzag stitch

To ensure proper electrical contact, the conductive yarns were soldered to electrical pins, see Figure 130. The additional length of the not sewn conductive yarn parts were also measured and the total resistance of the conductive yarns and pins was measured:

$Total_{yarnlength} = sewndistance_{+circuit} + sewndistance_{-circuit} + additional_{wire+circuit} additionalwire_{-circuit=}$

$Total_{yarnlength} = 1\ m + 1\ m + 0.325\ m + 0.216\ m$

$Total_{yarnlength} = 2.541\ meter$

$Total_{resistance} = Resistance_{+circuit} + Resistance_{-circuit} - Zero_{resistance}$

$Total_{resistance} = 3.3\ \Omega + 4.4\ \Omega = 0.4\ \Omega$

$Total_{resistance} = 7.4\ \Omega$

The total length of the conductive yarn used is around 2.5 meters and the resistance is 7.4 Ω.

The demonstrator worked perfect with one motor and we can calculate the voltage drop if the current is 50 mA and the battery used is 3.7 Volts:

$U = I * R$

$U = 0.05 * 7.4 = 0.37\ V$

Resulting in ***3.7-0.37 = 3.33 Volts*** to power the motor.

When starting the motor the maximum voltage drop will be:

$0.192 * 7.4 = 1.42\ V$

Resulting in a starting voltage of ***3.7 - 1.42 = 2.28 Volts.***

When chaining 3 motors in series through the same circuit, all three motors started to vibrate softly. This is understandable as now they have to share the voltage of 3.33V to power all three motors. The motors can vibrate harder by giving them a higher starting voltage than 3.7 Volts.

The conductive wires become warm when a certain current runs through them. During a quick-and-dirty test with an infrared camera the yarn reaches the 43 degrees Celsius maximum around the 300 mA.

With a triangle constellation, 2 motors turning 1 starting ***= 50+50 + 198 mA = 298 mA.*** A maximum of 298mA leaves little room for margin though. However, the total surface of the conductive yarn and the environment play an important role in how hot the yarns will become when implemented in a product.

Conclusions

Conductive yarn is sewable and is suited to power vibration motors. However, ***connecting the conductive yarns to the an electric circuit is a challenge*** that needs additional attention in the design phase. Moreover, a ***zigzag or stretch stitch*** is required to not break the yarn when applied on stretchable textiles, resulting in additional usage of yarn and a higher resistance. This higher resistance will result in a larger voltage drop, that can be overcome by starting with a larger starting voltage. Moreover, the ***maximum temperature that the conductive yarns are allowed to become is 43 degrees Celsius.*** During a quick-and-dirty test the connected maximum current lies around 300m mA. This should be just enough to allow for a triangle configuration, however leaves little margin. When selecting a conductive yarn, the maximum current should be taken into account.

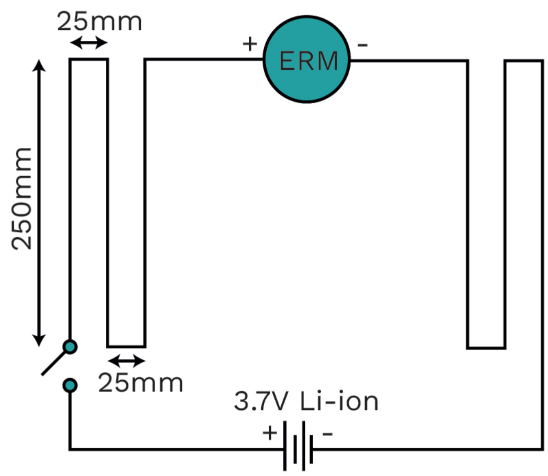


Figure 129. Schematic overview of the circuit for the conductive yarn demonstrator

Figure 130. Close-up of the conductive yarn gripped and soldered to a pin

9.4 Conductive velcro test Adafruit Hook & Loop

The goal of these demonstrators was to see if it is possible to power a single vibration motor with the Hook & Loop connection from Adafruit.

According to the specifications the resistance is supposed to be 0.8 Ohm/sq in closed position and the open-close cycle time is 5000 times (Adafruit, 2021). However, when measuring the resistance of a 20 x 20 mm square with a multimeter, the resistance lied around 0.2 to 0.3 Ohm/sq. Moreover, the contact surface only needed to be very small (a few mm) to already be highly conductive.

Experiment 1

In Figure 131 the first demonstrator is shown, which was made by glueing two pieces of 20x20mm Hook & loop on top of cardboard One side was connected to a 3 VDC power source and the ground. The second piece of cardboard had the motor plus and minus connected to it. The electrical connections were established by using conductive glue. When closing the connection the motors worked properly. Downsides of this model were the long drying times of the glue, making it not that scalable.

Experiment 2

A second demonstrator was created, by using conductive yarn as power transport medium and as fixation of the hook & loop on the textile carrier, see Figure 132. From this demonstrator we learned that only a little contact is necessary to power the motors, and that conductive yarn is a good fixation to connect the hook an loop to both the textile carrier and the electrical circuit. However, the bobbin of the sewing machine was only winded with conductive yarn, resulting in chaotic sewing as blind sewing was used to connect the hook & loop to the textile carrier,
Downsides are the large amount of debris left after each open-close cycle.

Conclusions

The Hook & loop of Adafruit is ***a good conductor*** of electricity and can be used to transport power to vibration motors. By ***using conductive yarn as both mechanical fixation and electrical interconnection***, integration with the textile carrier is easily done. However, the ***durability of the hook & loop is questionable,*** as a lot of debris is left after each open-close cycle.

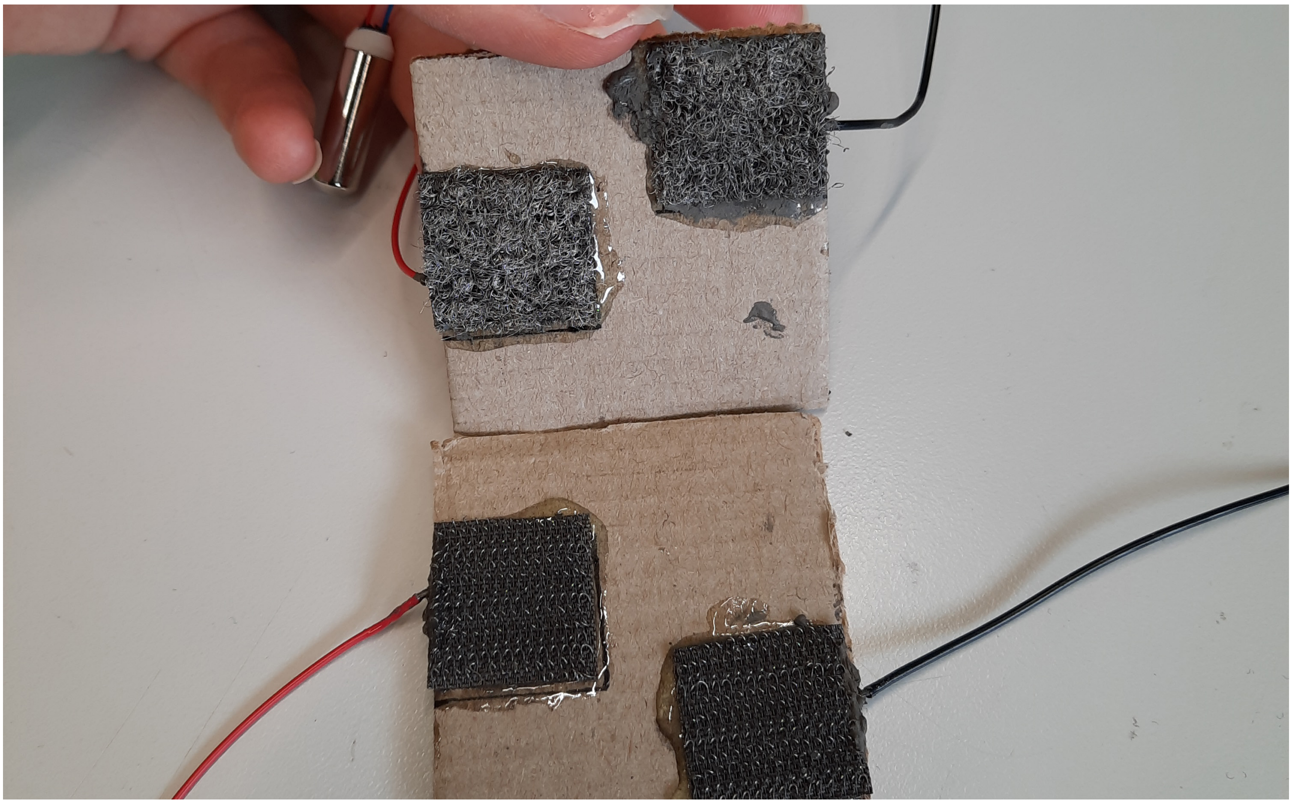


Figure 131. Conductive Velcro demonstrator 1

Figure 132. Conductive Velcro demonstrator 2

9.5 Conductive Ink test DuPont PE873

The goal of this demonstrator was to show that it is possible to power a single vibration motor through conductive ink and get to know the screen printing process.

In Figure 134 the basics of screen printing is presented, as a blade/squeegee drags ink over a stencil through a mesh screen on top of a substrate. The conductive ink used was the DuPont PE873 silver paste, with a resistivity of <75 mOhm/sq with a thickness of 25 micrometer. The mesh used had a T number of 43, meaning 43 strings per inch, making it a very open grid structure for the paste to go through.

Experiment

In Figure 133 the vinyl sticker stencil can be seen placed on top of the mesh screen, with the conductive ink placed ready to be transported by the squeegee. The material used to print on was 100% non-bleached cotton and a stretchy Power Evo made of 75% PA and 26% EA. In Figure 135 the resulting conductive traces of 2 to 5 mm wide can be seen on both substrates. Unfortunately the ink did not go well through the mesh screen, resulting in uneven conductive traces.
However, the ink traces that did come through were cured in the oven on 120 degrees Celsius for 10 minutes for the cotton and 5 minutes for the Power Evo. This resulted in flexible traces that could be folded and bended. However, it did seem that the cotton material soaked up most of the ink.

When trying to power a vibration motor over the conductive ink lines by putting a 3.7V battery on one hand and a vibration motor on the other hand, this did not work. Either the resistance of the traces was too high, or their was no closed circuit. Most probably the latter was the case, due to the uneven created conductive traces.

Conclusions & Decisions

The experiment did not work out well due to the mesh screen holding on to the conductive ink, resulting in uneven conductive traces. The traces either had a too high resistance, which is rather unlikely when looking at the <75 mOhm/sq resistance described in the specifications, or the ink did not go through the mesh enough to create a closed circuit.

Screen printing is suitable for small distances, and patterns to be covered. However, for longer distances putting the ink on equally becomes more and more difficult, as the squeegee should move in one swift motion. This production method does not seem that suitable for printing longer conductive lines on pattern pieces that might not even be flat.

D. Do not use screen printing of conductive ink as method to create the data and power transport system.

Inkjet printing of conductive ink can however still be interesting for concepts, as this can be done very precise, resulting in equal thickness and a closed circuit. However, this does require to buy pre-made conductive ink traces or to find a partner for Elitac Wearables to pursue this direction.

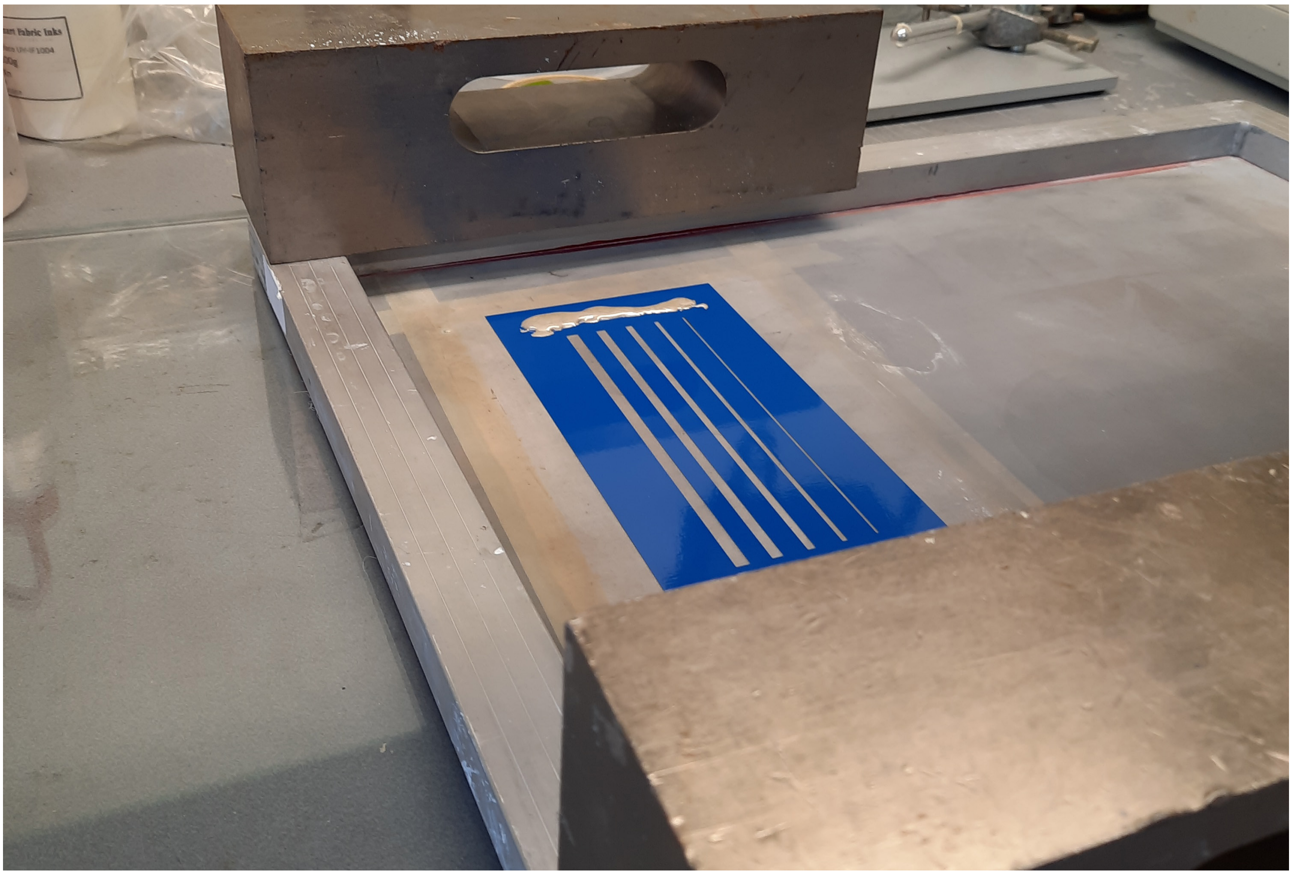


Figure 133. Screenprinting setup with a T43 mesh and DuPont PE873 silver ink

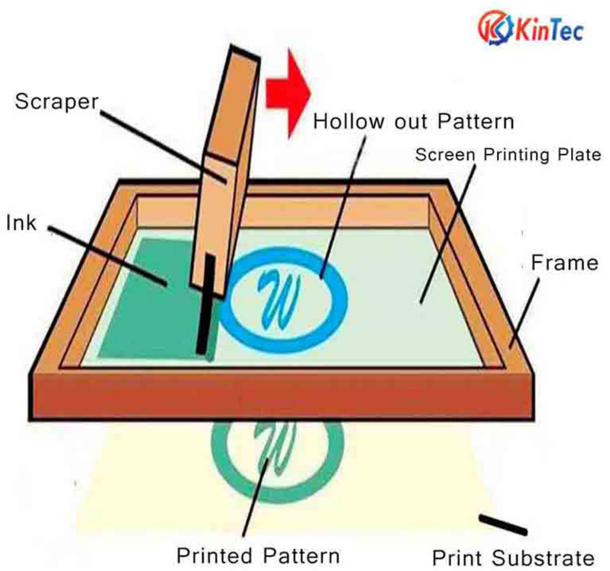


Figure 134. How screen printing works (KinTec, n.d.)

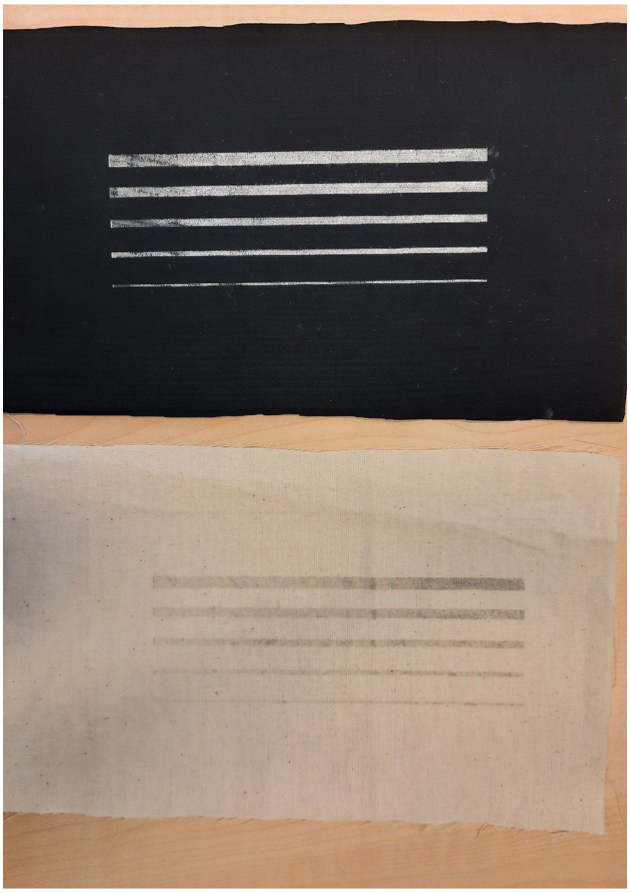


Figure 135. Conductive traces of 2-5 mm wide and 150 mm long on cotton and Power Evo

10. System design modules

In chapter 1.5 Components analysis it became clear what different components need to be included in the design a textile carrier, sensors, controllers, actuators, drivers, wiring, power supply, casing & data transport. Now we divide up the system into modules and connections that need to be taken into account during idea generation, see Figure 136. By splitting the system in modules, a more widely implementable and scalable technology is facilitated. Some initial design choices are discussed as well, and are highlighted in blue.

Module A. Tactor

This tactor module consists of a ***vibration motor,*** a ***driver PCB*** to enable the ***I2C communication method*** and a protective ***casing.*** This module could be substituted by or also include a ***sensor.*** A casing design that complies with the specified IP is required, as ***Module A can be fixated in the textile carrier.*** With this design choice the user will have to remove less components before cleaning and a better integration with the textile carrier can be facilitated, improving ergonomics and aesthetics. This also complies with the trends we see on the current market. However, if desired, the tactors can be removed before washing individually for small constellations (<5 tactors) and all together for larger constellations (>5 tactors). The following connections need to be designed as well:

A1. Connection to power and data transport system (Module B) To ensure power and data communication with the rest of the system. Connections are often fragile and strain reliefs need to be taken into account.
A2 Connection to protective casing. To ensure the proper IP level is achieved and electronics a protected from everyday and cleaning stresses.
A3. Connection module A to textile carrier. A rigid connection that facilitates the integration with the textile carrier.

Module B. Power and data transport system

This module consists of wiring or alternatives for wiring to ensure all electronics are interconnected and provided with power & information from the main controller. Connections to be designed in this module are:

B1. Connections to data and power ports of modules A (A1) and C (C1). Connection B1 is therefore equal to connections A1 and C1.
B2. Connection to protective casing
Module B might need additional protection from the environment and mechanical stresses applied to it during washing and cleaning.
B3. Module B to textile carrier
To enable integration with the textile carrier.

Module C. The main controller

The main controller is the brains of the system and includes the ***micro controller*** that will control all Modules A, and use Modules B to communicate. The main controller will include a ***battery*** to enable wireless power provision to the product, and a ***sensor*** to make the product interactive. ***Module C will be made detachable***, to protect the most important electronics from water and stresses applied during the cleaning process. Again this design choice will follow the trends on the current smart textile wearables market. Connections to be taken into account are:

C1. Connection to the power and data transport system (Module B).
To enable power transportation and data communication from the main controller to all other modules.
C2. Connection to the protective casing
For protection of the brains of the design.

C3. Detachable connection of module C to textile carrier. This connection can be combined with connection C1. It should be robust enough to overcome stressed applied during physical activity.

Module D. The textile carrier

The textile carrier has the function to bring the complete product together and needs to be ergonomic for the user to wear. Moreover it should facilitate attachment of electronics and strain reliefs. ***The connections involved are A3, B3 C3.***
Module D will be made of a stretchable and breathable material.

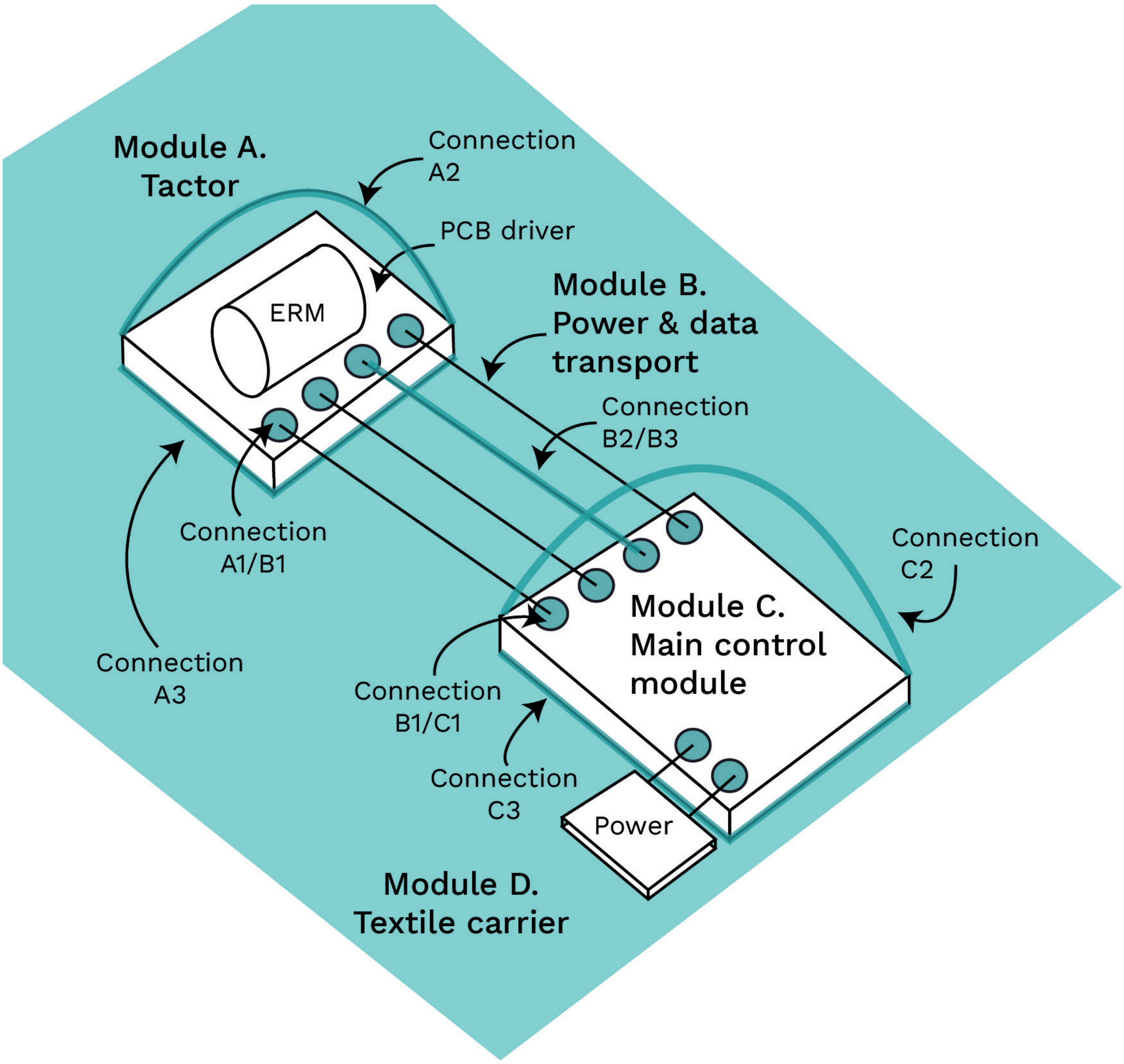


Figure 136. Overview of the modules and their connections highlighted in blue

11. General conclusions phase 2

Technology research

In the end, when selecting solutions technology solutions, the following characteristics play an important role: ***mechanical properties***, ***conductive properties*** (if applicable), ***processability, stretchability, flexibility, durability,*** and the ***costs.***

High potential wire connections for power & data transport found were: ***flat cables, conductive yarns, conductive textiles & conductive inks.*** Electrical connections that should be taken into consideration during concept generation are: ***the lamination process described by Krshiwoblozki et al. (2012), conductive glue*** and ***conductive yarn***. The same goes for the following integration techniques of electronics and textiles: ***tapes, lamination, piping & tunnels, overmolding, sewing pads and knitting pockets***. Moreover, ***pogo pins, snap buttons, conductive Velcro*** and the ***ball point pocket connector*** were considered to be good candidates for removable connectors.

When looking at modular electronics, ***flexible casings*** for ergonomics and a ***toolkit designed for prototyping*** are inspiring when it comes to widely implementable technology systems. Also, it was decided that ***for constellations of more than 5 tactors, the modules will have to be fixated in the textile carrier, or made detachable all at once***, for usability reasons.

In the future, ***combining techniques*** that are on the market and currently being developed could result in a ***perfect hybrid connection*** for Elitac Wearables. Exploring for example the combination of adhesive bonding and embroidery or knitting might be interesting. Just as more flexible electronics combined with flexible overmolds or conductive yarns might help to make combinations less rigid on the human body.

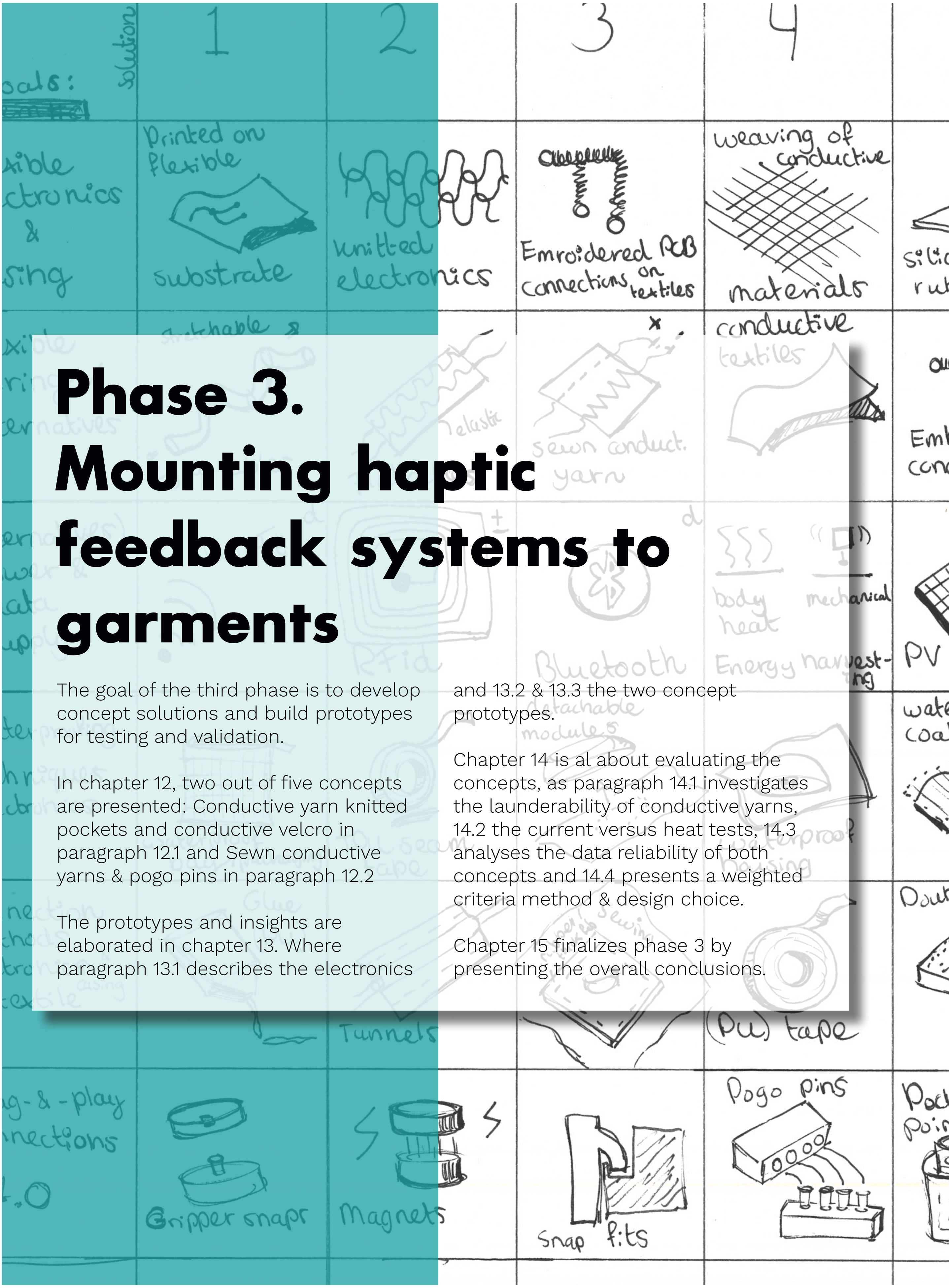
Initial tests

Basic test were performed with ERM motors used by Elitac Wearables. To ensure that the ERM motors will start and operate properly in future designs, the following values will be used: ***3V DC*** is the preferred voltage supplied at the motors. Moreover, a ***starting current of 192 mA (cylinder) and 120 mA (coin)*** and an ***operating current of 50 mA*** for both motors is considered to be normal. Resistance calculations showed that for a ***triangular constellation with cylinder motors is 6.85 Ohm and for coin motors 9.09 Ohm is the maximum circuit resistance.*** For a line constellation these values are 8.26 and 11.67 Ohm, and for a points constellation these are 10.42 and 16.67 Ohm for cylinder and coin motors respectively. The ***maximum resistance*** found ***in practice*** at which both motors still start to vibrate ***lies between 60-70 Ohm.*** This number is higher than calculated in theory, as the 3 Volts used is the optimal operating current.

Conductive yarns, velcro and inks were tested as potential data & power transporters. ***Conductive yarns*** and ***velcro*** showed a low enough resistance and practical processing methods.

System design

The system design divides the solution into four modules. ***Module A. Tactor*** contains the ERM and the driver PCB. ***Module B. The power & data transport system*** forms the electrical connection. ***Module C. The main controller***, contains the micro controller and power supply. Finally, ***module D. The textile carrier*** makes the technology wearable.



Phase 3. Mounting haptic feedback systems to garments

The goal of the third phase is to develop concept solutions and build prototypes for testing and validation.

In chapter 12, two out of five concepts are presented: Conductive yarn knitted pockets and conductive velcro in paragraph 12.1 and Sewn conductive yarns & pogo pins in paragraph 12.2

The prototypes and insights are elaborated in chapter 13. Where paragraph 13.1 describes the electronics and 13.2 & 13.3 the two concept prototypes.

Chapter 14 is al about evaluating the concepts, as paragraph 14.1 investigates the launderability of conductive yarns, 14.2 the current versus heat tests, 14.3 analyses the data reliability of both concepts and 14.4 presents a weighted criteria method & design choice.

Chapter 15 finalizes phase 3 by presenting the overall conclusions.

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Phone battery
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SSS heat press
PU cond.
PU
Lamination
vacuum lamination
air
TPU glue
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Phone socket
Twist & click friction
+ magnet
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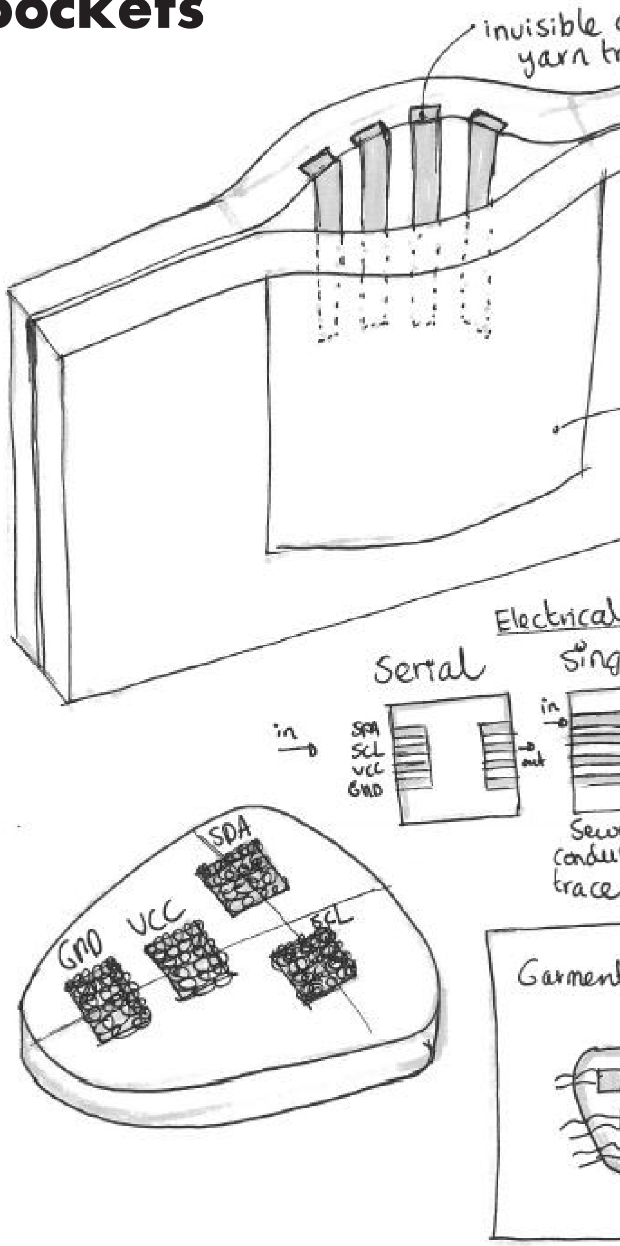
12. Concepts

*Two out of five concepts are presented, that according to Elitac have the highest potential. First a brief description will be given, together with an overall sketch of the concept. Moreover, the production processed involved will be described, together with the pros and cons. Elements of the concept that are changeable with other technologies presented in other concepts are shown in a table and **highlighted.** Next, two prototypes are elaborated and analysed in detail.*
To see all concepts, see Appendices A9 to A11.

12.1 Concept 1: Knitted pockets

General design

This concepts was inspired by Mehmann et al. (2015)'s ball-grid-array-like electronics-to-textile pocket connector. Through knitting pockets are created with conductive yarn traces inside. By knitting tight pockets, wireless modules including vibration motors can be placed inside during the production, and are enclosed by the knit. The vibration motor modules are powered and controlled through the conductive yarn traces transporting power and data. Design for play is in order, as the size of the ballpoint will be smaller compared to the width of the conductive traces. Also, each row of points represent one singular input our output, and could also come in the form of a singular metal stripe instead of different ballpoints. Each vibration motor module can either be connected in series or have its own circuit. De main control module encloses a battery, USB-C connection point and is made detachable before washing and to enable easy charging. See Figure 137 for a drawing of the concept.



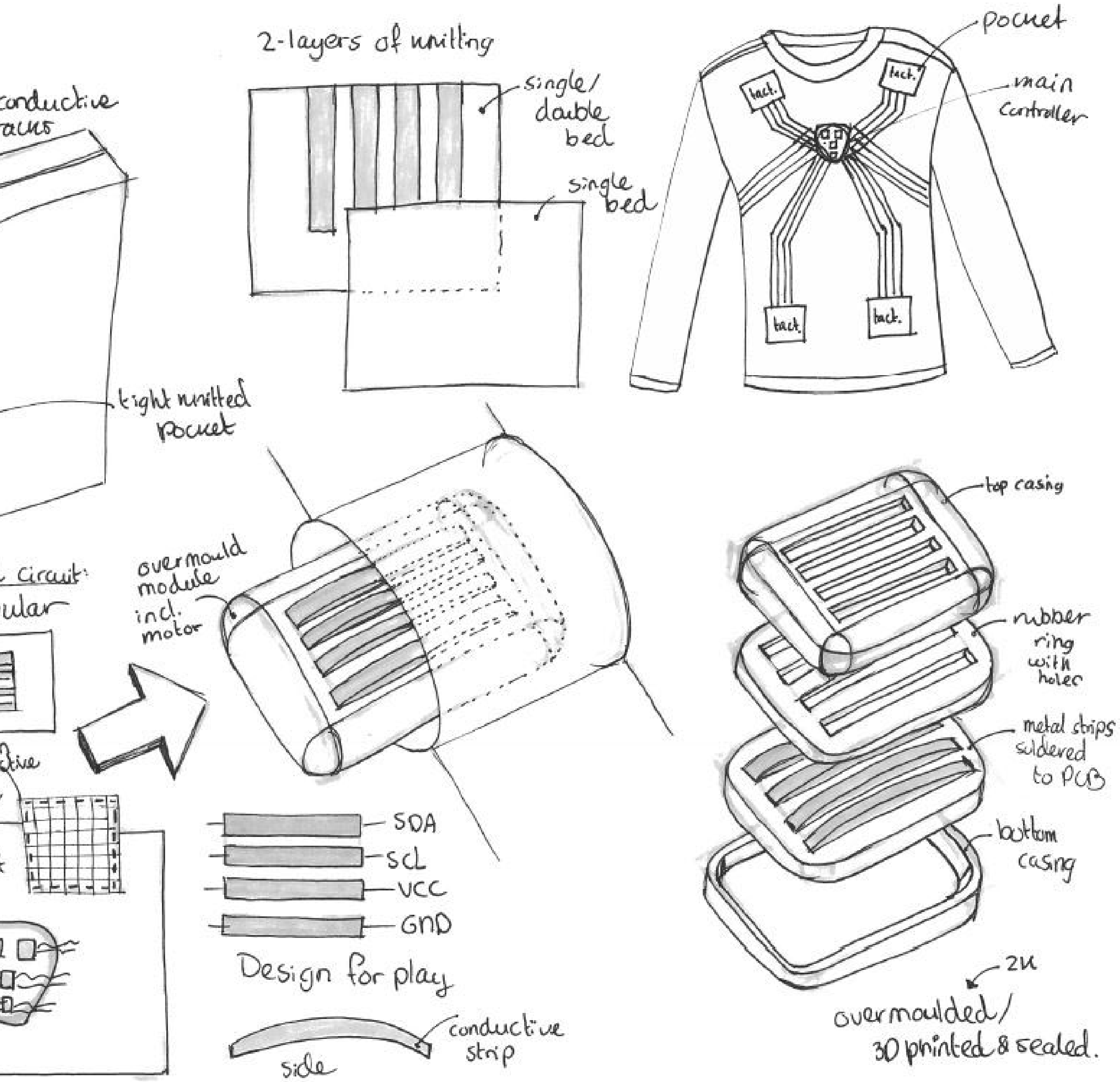


Figure 137. Concept 1 Knitted pockets explained in a drawing

	Module A: tactor	*Module B: power & data transport system*	*Module C: the main controller*
Connection of module to power & data transport	A1: Soldering of ***ballpoints*** or ***metal stripes*** to PCB. Through the clamping force of the knitted pockets, these conductive connections are pressed against the conductive knitted traces (B1).	B1: Conductive traces knitted with conductive yarn. 4 connections for ***SDA, SCL***, VCC & GND. data could be communicated via ***Bluetooth***.	C1: Detachable main control module by the use of conductive ***Velcro (snap buttons)*** attached to knitted conductive traces
Connection of module to protective casing	A2: Overmold casing under and on top of modules. 1k or 2k mold the conductive points/stripes.	B2: Isolation of conductive yarn by sandwiching between two non-conductive knits	C2: 3D printed/ Injection molded casing. closed through ***clicking/ glueing.***
Connection of module to textile carrier	A3: Though clamping force of the knitted pockets, enclosing the tactor modules and keeping them in place.	B3: Connected through integrated knitting with the non-conductive textile carrier	C3: The same as C1.

Table 8. Designed connections Concept 1, Knitted pockets

In Table 8 an overview of the modules designed for concept 1 is given. Interchangeable components are highlighted in black.

Production processes

In order to produce this concept the following processes are involved:

• Knitting (textile carrier, power and data transport).
• Overmolding (tactor module casing)
• 3D printing (main control module casing)
• Soldering (Electronics inside tactor and main control module)
• Glueing (main control module casing)
• Sewing (conductive Velcro)

Pros

1. This design avoids breakable connections of tactor modules to the textile carrier.
2. Conductive yarn traces can be isolated in between two layers of non-conductive knits.
3. Conductive yarn traces and pockets can be made almost invisible if desired.
4. Allows for additional design in which pockets can be opened and closed to remove electronics before washing or design for repairability.

Cons

1. To achieve tight pockets, either a 3-bed knitting machine is necessary, or the pockets will have to be sewn in.
2. If the conductive yarns has to be isolated, the thickness and warmth of the material increases at these locations.
3. If pockets are closed, tactor modules will need to be waterproof to withstand the washing machine.
4. Knitting might be an expensive tool for prototyping and requires new partners for Elitac Wearables.

Discussion & concerns

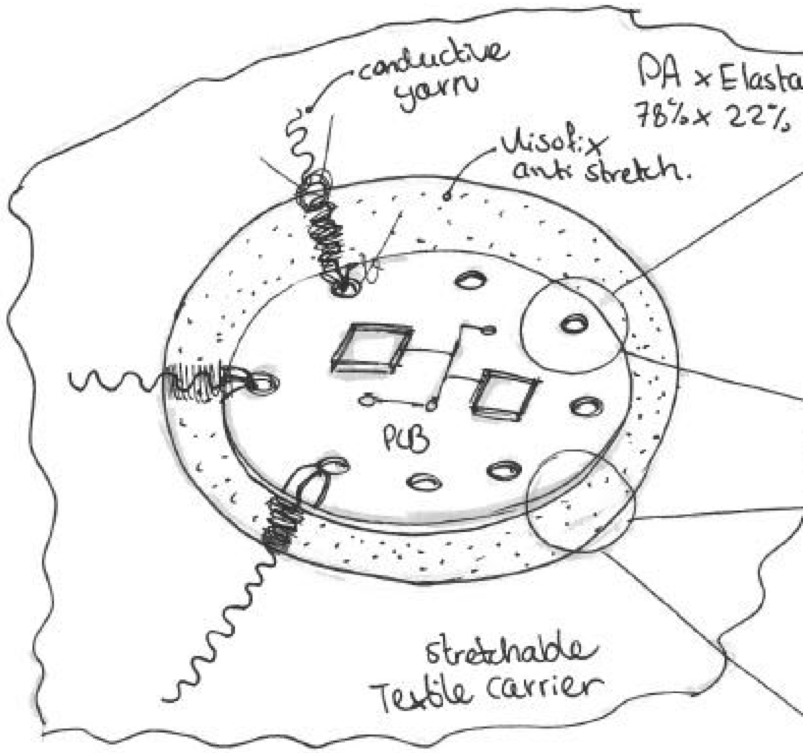
As discussed by Mehmann et al. (2015) the data & power reliability will need to be tested for this type of design. They mention increasing the tightness of the pocket to improve this reliability, however this could decrease the ergonomics of the design. Moreover D. Van Elteren (personal communication, May 17th, 2021) was concerned about the ability of sweat or sand ruining the connection. According to him, creating a stronger electrical connection has the preference. An idea is to create a hybrid design with adhesive interposer to fixate the connection more. Moreover, will the resistance of the yarns increase significantly during wear or washing? The design could be adjusted so that pockets can be opened up to remove electronics before washing or allow for repairability.

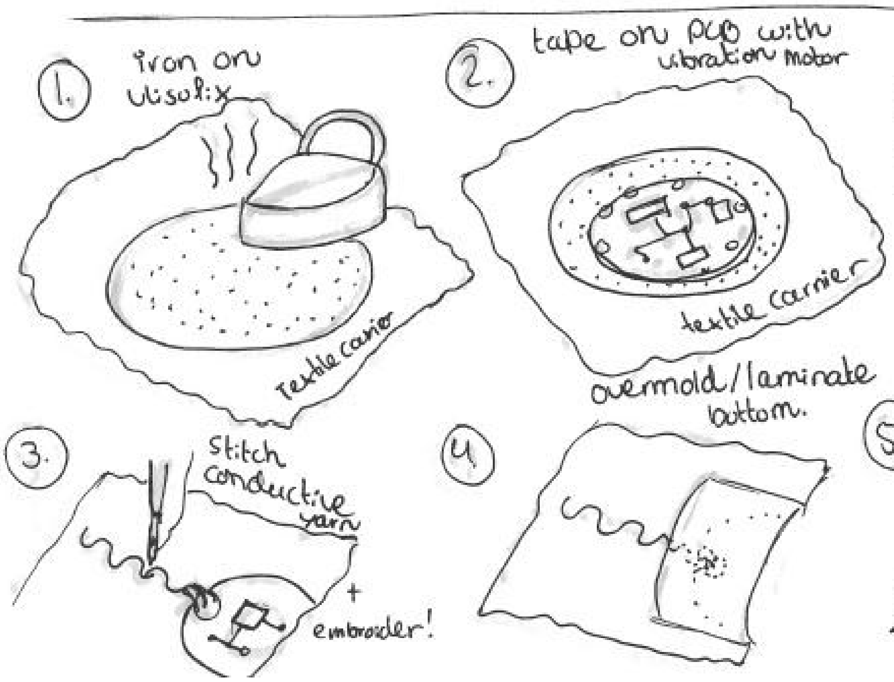
Prototyping of early designs will have to be done on the sewing machine/embroidery machine to show a partner company what the design should look like.

12.2 Concept 2: Sewn conductive yarn traces & pogo pins

General design

This concepts was inspired by the Arduino LilyPad and uses sewn conductive yarn traces as power and data transport system.
Since the original LilyPad connections are quite fragile, additional reinforcements are designed to connect the tactor to the shirt. See Figures 138 and 139 for a more visual explanation of the concept.





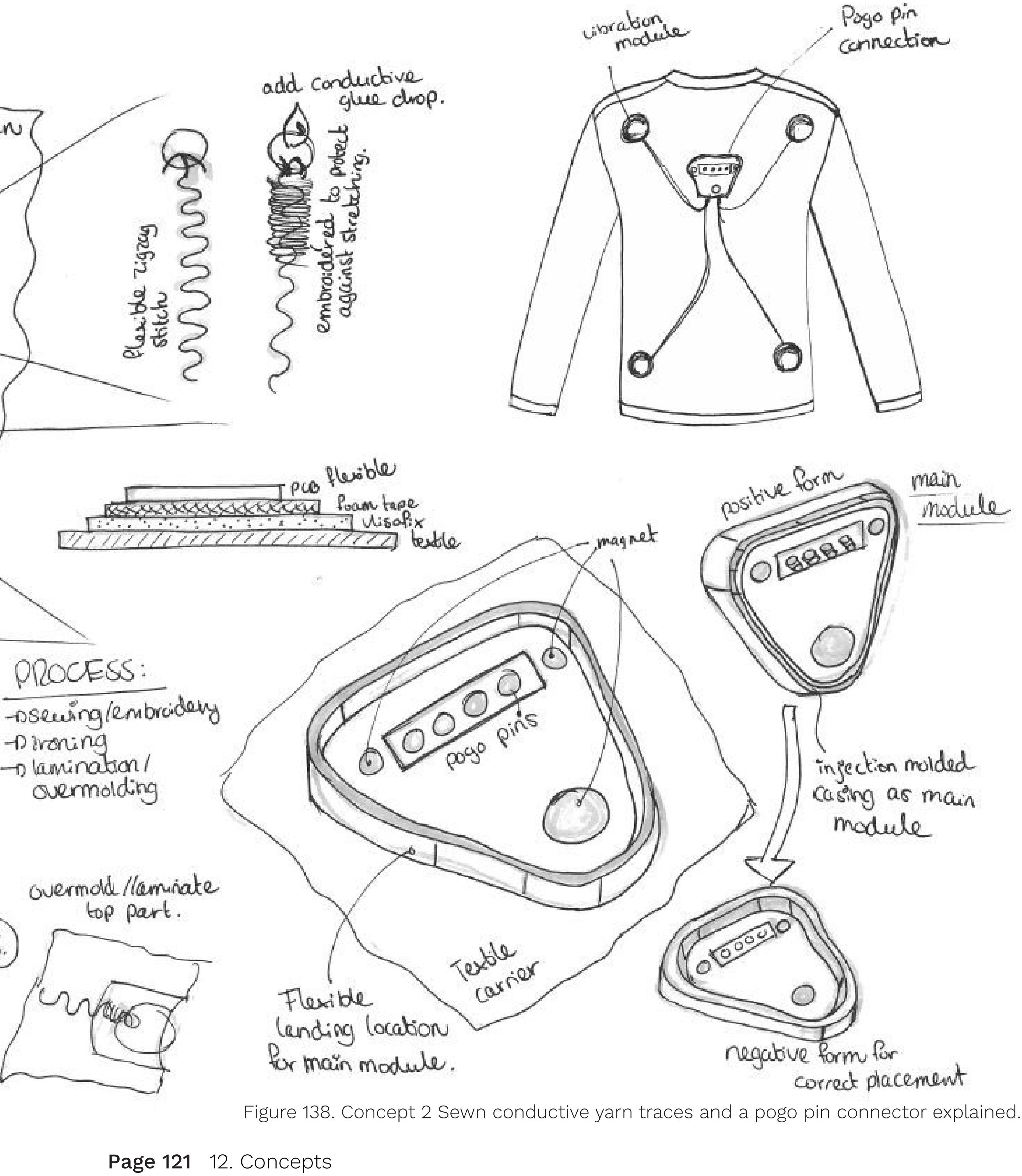


Figure 138. Concept 2 Sewn conductive yarn traces and a pogo pin connector explained.

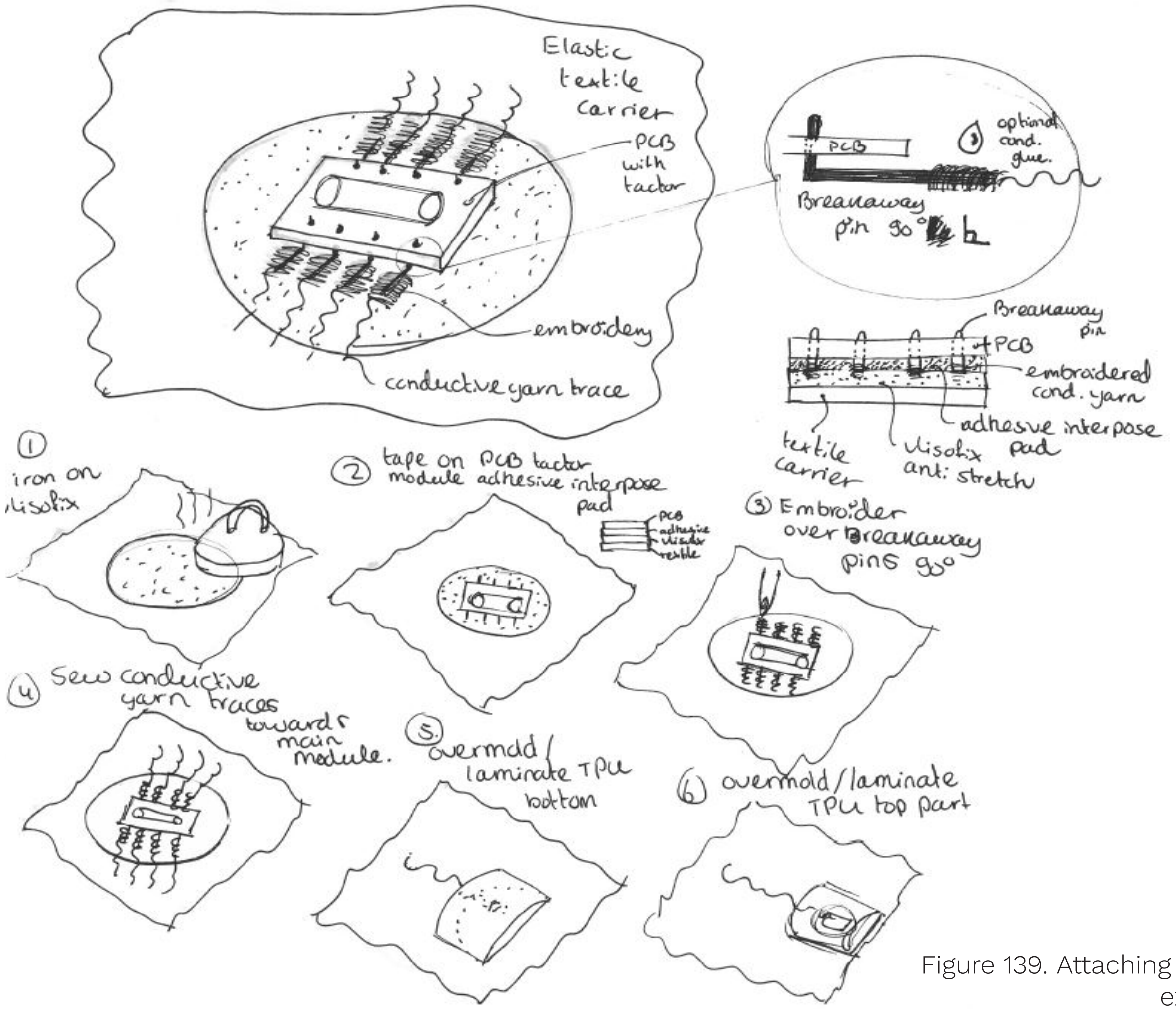


Figure 139. Attaching the PCB explained

	Module A: tactor	*Module B: power & data transport system*	*Module C: the main controller*
Connection of module to power & data transport	A1: Soldering of electrical components inside tactor. Using embroidery over conductive breakaway pins and adhesive interpose to attach PCB to power and data transport.	B1: Conductive ***yarn traces.*** Can be substituted by ***conductive ink*** or ***flat cables.***	C1: Detachable main control module by the use of ***pogo pins*** and magnets. Can be substituted by ***conductive Velcro or snap buttons.***
Connection of module to protective casing	A2: Overmolding of PCB an conductive traces	B2: No protective casing or TPU layers on top and bottom. Also lining and embroidery of traces is an option.	C2: 3D printed/ Injection molded casing. closed through ***clicking/glueing.***
Connection of module to textile carrier	A3:Combined by A1 & A2	B3: By sewing conductive yarns directly on the textile carrier	C3: The same as C1.

Table 9. Designed connections Concept 2, Sewn Conductive yarn traces and pogo pins

In Table 9 an overview of the modules designed for concept 2 is given. Interchangeable components are highlighted in black.

Production processes

In order to produce this concept the following processes are involved:

- Overmolding (tactor module casing)
- 3D printing (main control module casing)
- Soldering (Electronics inside tactor and main control module)
- Glueing (tactor module)
- Sewing (conductive yarn traces)

Pros

1. Conductive yarns traces sewn on textile carriers can be easily prototyped and tested through available equipment at Elitac Wearables
2. The conductive yarns allow for serial or singular circuitry of tactor modules.

Cons

1. Each conductive yarn traces needs to be sewn by hand on a sewing machine, requiring precision work and skilled sewers.
2. Not all conductive yarns are durable in terms of resistance when it comes to launderability.

Discussion & concerns

The pogo pins used to connect the main control module might not be strong enough. Additional magnets or click finger design might be necessary. A second design of the system could allow for detachable tactors as well, making it easier to repair and more washable.

Moreover, when implementing a large number of tactors, wire-crossing is almost certainly necessary. Prevention of short circuits by implementing isolated layering in the design is an option. This will result in the use of more fabric at some locations and make production more challenging.

Next, not all conductive yarns are as durable when it comes to washing, this should be tested when low resistance yarns are selected. In previous research performed by uz Zaman et al., (2019) source, silver coated yarns from AMANN Group still maintained their conductivity after multiple washing cycles. Another option to increase the durability is to select yarns with an additional protective coating. However, at the connection points this coating will have to be removed without damaging the yarn and decreasing the conductivity.

Moreover, a singular conductive yarn trace might be too fragile, and if it breaks no backup is available. However, if multiple conductive traces are sewn over each other, the total resistance will decrease and if one yarn breaks, the other sewn traces will take over and still close off the circuit. However, this will increase the production time and costs, as each line has two sewn multiple times.
By giving each tactor their own circuit, no additional micro controller per tactor module is necessary and a larger voltage drop is allowed, thus allowing an increase in length of the conductive yarn traces used.

13. Prototyped concepts

In this chapter first the prototyped electronics is presented in paragraph 13.1. Followed by the actual prototypes of the pocket concept in paragraphs 13.2, and the conductive yarn and pogo pins concept in paragraph 13.3.

13.1 Electrical prototyping design

Pulse-Width-Modulation control

To enable quick proof of concept, it was chosen to use Pulse-Width-Modulation (PWM) as motor control method. With this method, the supplied voltage to each vibration motor can be controlled.
An analog port is switched on/off x amount of times, within a certain time frame y, creating digital square waves. These digital square waves simulate voltages between the maxim VCC and 0V. The maximum VCC of the Seeeduino Xiao used in the hardware setup presented in Figure 142 equals 3.3V. In Figure 140 an example of different digital square waves can be found. According to Arduino (2021), the pulse width represents the duration of the "on-time" of an analog port. In order to create different square waves, one can vary the pulse width.
The "on time" can be set by varying the analogWrite() value from 0 (0% of the time on, resulting in no voltage) to 255 (100% of the time on, resulting in maxim power supply VCC). For example, if we want to simulate an output voltage of 1.5V in total , we can calculate the analogWrite() value that represents this value:

255/3,3 *1,5 = 115,9 = 116 (rounded off)

In order to simulate an output voltage of 1.5V, we will have to write analogWrite(116).

Pros of PWM

By using this method, only a few components are necessary to test the prototypes, also making it cheap. Moreover, it can quickly be programmed by using Arduino IDE.

Cons of PWM

Each vibration motor will need an individual PWM cable port to be controlled, requiring quite some additional connections if the number of motors increases. Also, only limited vibration motor control can be realised, compared to the use of I^2C communication and a driver including a library full of vibration patterns that is generally used by Elitac Wearables.

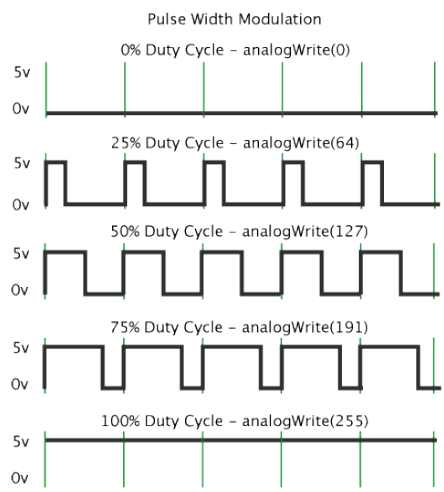


Figure 140. Pulse-width modulation square waves example (Arduino, 2021).

Hardware design

In Figure 141 the prototyped version of the quick and dirty hardware design presented in Figure 142 can be found.

A Seeeduino Xiao is used as the brains of the system. A 3.7V battery of 600 mAh delivers the power to the complete system to make it wireless. The Darlington Array ULN2003 is used to allow amplification of the low level input of the Seeeduino, in order to drive the ERM motors. A schematic overview of the hardware design can be found in Figure 142, showing the implementation of 3 motors. In reality a single Darlington Array would be able to power up to 7 vibration motors using PWM.

In Appendix A12 a short script of the Arduino test code can be found to power multiple motors at once. In the prototypes presented in paragraphs 13.2 and 13.3, only one motor is implemented at a time. However, during a quick test in which 3 motors were attached to an individual output of the Darlington Array, the maximum vibration intensity decreased significantly. This was to be expected, as 3 motors will now have to share 3.7V input. In reality, the goal is to have a 5V power supply to power motors. Also, the hardware components implemented are larger in size than Elitac Wearables would use in real products, making it harder to judge aesthetics and ergonomics of the prototypes.

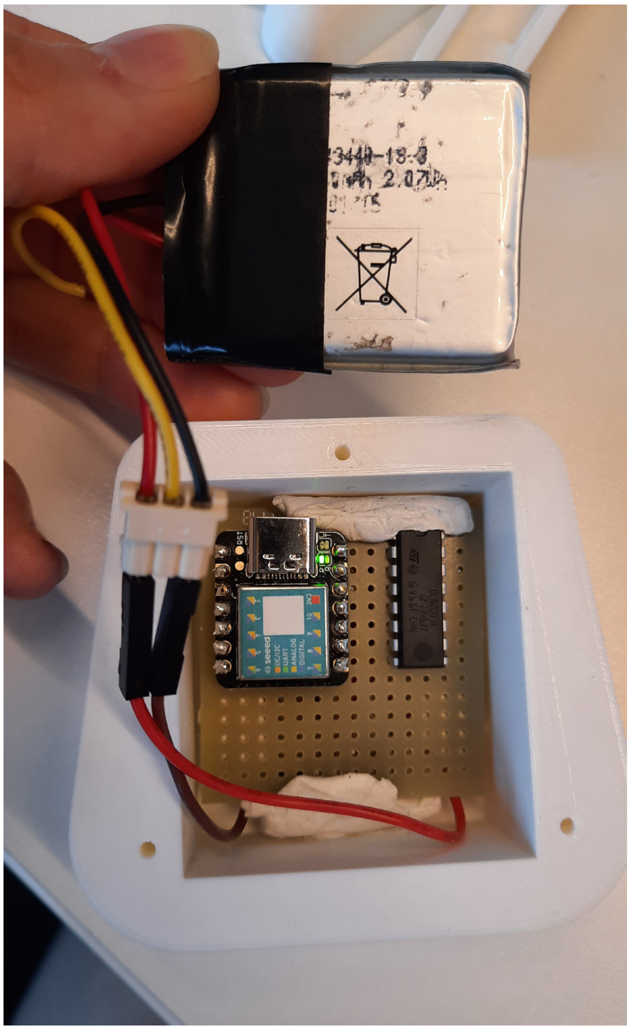


Figure 141. Prototyped hardware design with the Seeeduino Xiao, Darlington Array ULN2003 & 3.7V battery.

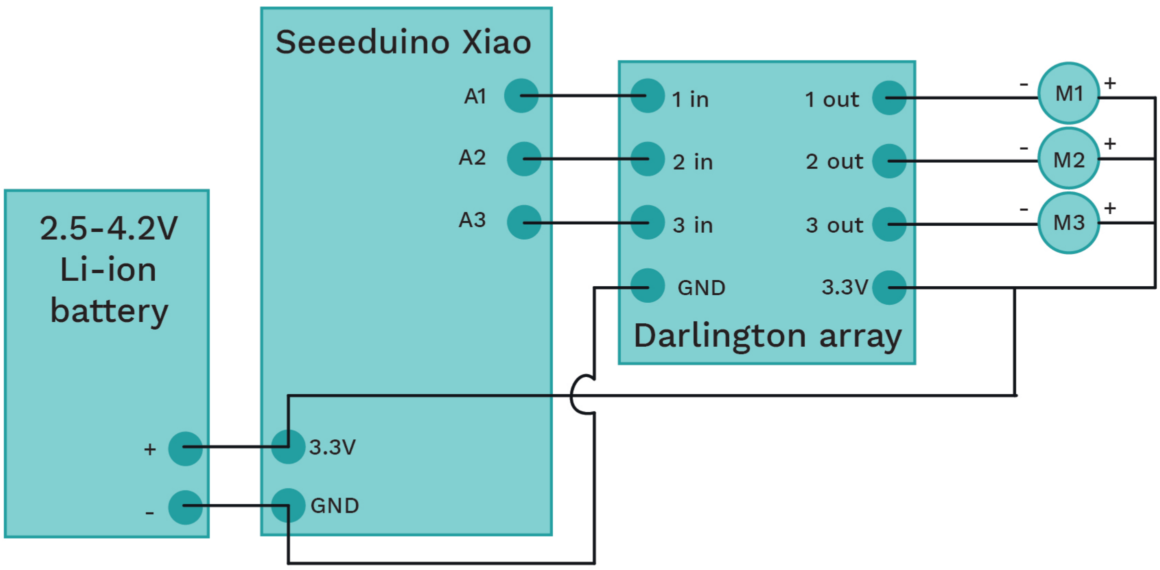


Figure 142. Schematic overview of hardware design

13.2 Prototype concept 1: All about pockets

Module A. Tactor

The tactor housing found in Figure 143 is 3D printed with PLA. The inside structure leaves cutouts for two metal strips made of spring steel, that are mechanically fastened to the casing via screws, and then soldered to the plus and minus of the vibration motor. The internal rib construction has a cut-out designed to enclose a vibration motor. This module is placed inside a tight pocket, that includes traces of conductive yarns. The metal strips are pressed against these traces to ensure an electrical connection between the main control module, see Figure 144.

Module B. Power & data transport

The original idea behind the concept was to knit conductive yarn traces throughout the textile carrier. Due to time limitations and resources, the conductive traces were sewn with conductive yarn instead. For this prototype Elektrisola 30004021L was used as Bobbin thread and AMANN Saba 80, 100% polyester grey as top thread, see Figure 145. To ensure proper sewing with the high tensions necessary for the conductive yarns. Solufix used on the side of the top stitch. This avoids wrinkling or pulling of the fabric, see Figure 147. Solufix can be washed off easily with cold water afterwards. The stitch used results in the conductive yarn only being visible at one side of the fabric. Some individual knitted pockets were tested as well, see Figure 148.

Module C. Main control module

The main control modules uses conductive Velcro pads of 10x10mm as mechanical and electrical connection to the rest of the system. By stitching the conductive Velcro contacts directly with the conductive yarn, the electrical connection to the rest of the system is ensured, see Figure 149.

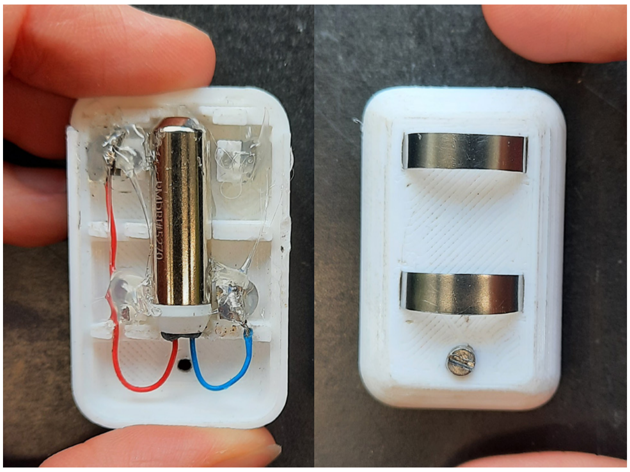


Figure 143. The vibration motor module placed inside the PLA printed casing (left) & metal spring strips pearcing through the cut-outs

Figure 144. The modul with metal strips making contact with the conductive yarns traces

Figure 145. Close-up of conductive Elektrisola yarn (left) & AMANN Saba polyester (right)

Module D. Textile carrier

For the textile carrier a thick 4-way stretch fabric was chosen, to give the stitches additional body. By using stretch fabric, it was possible to see how stitching conductive yarns would behave on these type of textile carriers. High tensions are necessary, and to avoid pulling of the fabric Solufix can be used as explained earlier.

An overview picture of the complete prototype pinned to a male mannequins' back can be found in Figure 146.

For a detailed production overview and the materials used, see Appendix A13.

Figure 147. Solufix placed on top of the textile carrier on the side of the AMANN top yarn

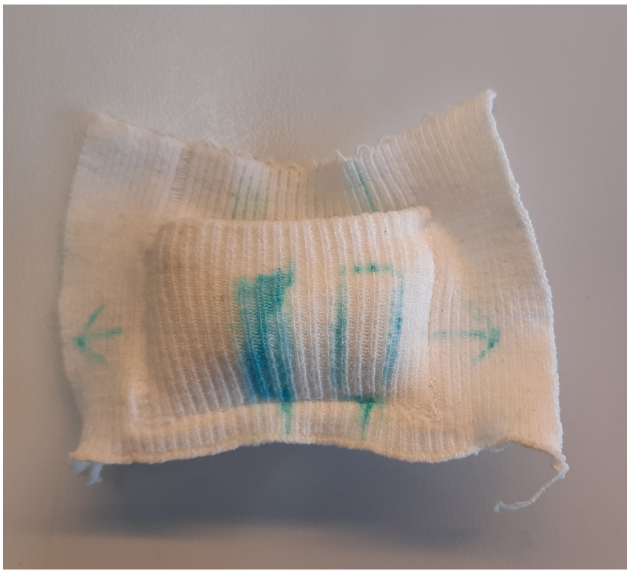


Figure 148. Knitted pocket test: Ottoman one-bed knitt with vibration motor module

Figure 146. Concept 1 pinned to the back of a male M running shirt

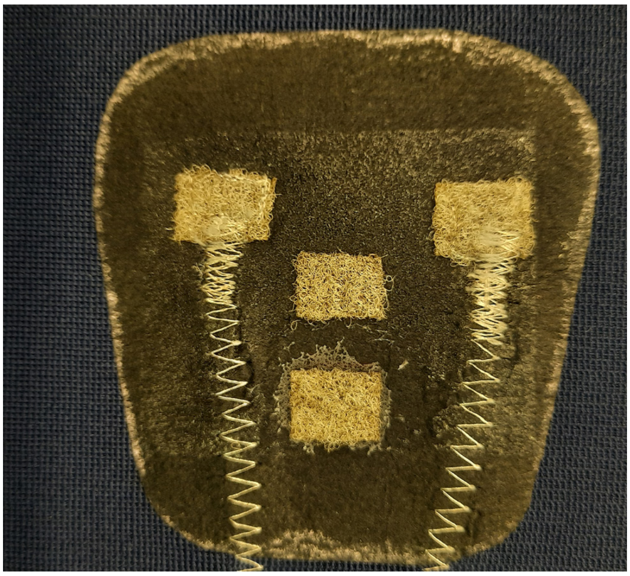


Figure 149. Conductive Velcro attached with conductive yarn

Knitted pockets

To test the feasibility of the knitted conductive yarn pocket, sample knits were made. Figure 150 shows an initial trial of a two-bed knit as researched by van der Valk (2020).

A second production test with a single-bed Ottoman pocket was performed, shown in Figure 151. The top picture shows all the trial knits starting from left to right. The pockets shown at the bottom left will first need to be stitched shut, to close the pocket, as shown in the figure at the bottom right. When supplying the knit with 3.7V the ERM motor vibrated properly.

Figure 150. Knitted conductive pocket trials (top), placement of tactor module in pocket (bottom left) & conductive pocket with tactor inside (bottom right)

Figure 151. Knitted conductive pocket trials (top), placement of tactor module in pocket (bottom left) & conductive pocket with tactor inside (bottom right)

Resistance & connection

Resistance

The resistance of the complete circuit was measured with a multimeter and was found to be 6.6 Ohm in total.

Connection

To test if the electrical connections work, a 3.7V battery was used to make the motor vibrate. Moreover, a short Arduino script was written to actuate the motor a bit. This short Arduino script can be found in Appendix A12. The connection functioned properly and the motor could be powered well. Even the pocket could be moved about and the motor would still continue to run.

Learnings & improvements

Conductive Velcro

- Placing and stitching the conductive Velcro is quite difficult, due to blind stitching of all surfaces. If top stitch could be used, this would make the production process a lot better. Also, the Vliesofix does not attach that well to the metal surface of the Velcro. It took multiple to fixate them before being able to sew them.
- The conductive Velcro spots look cheap and not robust. After using it X amount of time the conductive yarns holding it to the textile carrier could break from pulling forces.
- The conductive Velcro looses quite some material per hook&loop cycle.
- To improve the look of the conductive velcro, laser cutting them to the correct size and placing an overlay with cutouts on top of them could help. This overlay will also fixate the velcro for sewing. As only a small attachment is needed for electrical contact as found in paragraph 9.4 conductive velcro test Adafruit Hook & Loop. The loss of fibres per hook & loop cycle is not that important. However, the attachment also serves as a mechanical one for the main control module. Therefore, it is suggested to implement pieces of non-conductive Velcro around the edges of the main module. This will help secure the mechanical connection. It is also possible to look for an alternative mechanical-electrical connection that is more durable.

Sewing with conductive yarn

• A single zigzag stitch might be stretchable, but is still vulnerable. To improve the redundancy, stitch 3 conductive stitches on top of each other.
• Elektrisola is fragile, see if a stronger alternative is available on the market. Or protect the current stitch by placing a non-conductive embroidery stitch on top of it. This can also help to isolate the non-isolated conductive yarn.

Solufix, Vlieseline & Vliesofix

• Solufix avoids forming tensions in the fabric created by the high top tension used during stitching and easily dissolves with a bit of cold water afterwards.
• Vlieseline & Vliesofix can be used to improve the stiffness of a textile carrier and prevent stretching at critical contact places.

Vibration motor module

• The holes for the screws that attach the spring steels were not big enough and the screws available were too long. In the second module, the holes should be made bigger and fit for standard available screws: 1.6M x 8mm.
• Spring steel is difficult to solder, cut or drill holes in. Additional fixation with a hot glue gun was necessary to avoid the soldering points from loosening. A good alternative would be gilded soldering battery contacts with pre-made holes in them.

Knitted pockets

• The current way of knitting pockets pushes the knitting machine to its limits. As the knit should be pulled down to allow for proper knitting, while the Ottoman pocket requires the machine to let go of some parts of the knit, making it possible for it to crawl upwards and fail the knit.
• For mass production of above 1000 pieces, it might be interesting to develop a prototype with a professional knitting company such as Byborre or MyAnt.

Waterproofing of the design

• The current prototype of concept one is not yet waterproof, in a next design, this should be addressed as well. 3D printing with TPU & the use of waterproof coatings or glues could be an interesting direction. Also the implementation of gaskets or maybe even casting the casing might be interesting.

Ergonomics

• The current vibration module will create pressure points due to the spring steel strips sticking out of the casing that much. In a redesign this should be improved by making it stick out less, and creating a slightly curved module that follows the human body shape.

Opportunities:

• Electronics can be produced complete separate from the textile carrier in production. While still being properly integrated in textile carrier.
• Important electronics can be easily replaced or re-used when textile carrier is at end-of-life. Meaning that Elitac Wearables could create a product service design in which the client uses the textile carrier X amount of times, before replacing it, while re-using the Electronics.
• Design allows for removal of electronics before washing, or when changing from textile carrier.

13.3 Prototype concept 2: Conductive yarn and pogo pins

Module A. Tactor

The tactor housing found in Figure 152 is 3D printed with PLA. The inside structure leaves an open space for the vibration motor and PCB. The plus and minus of the vibration motor are soldered to two header pins on a small piece of breadboard. These pins are in turn slid underneath a conductive yarn zigzag stitch and cover with a drop of conductive glue to ensure proper electrical contact and fixation of the connection. Then the casing is placed on top of it.

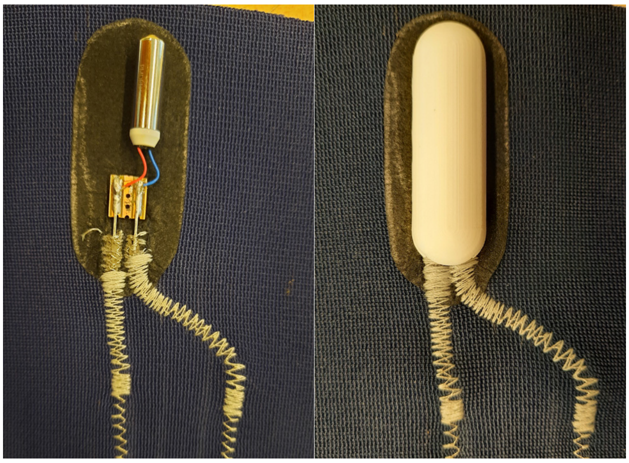


Figure 152. The vibration motor module connected with conductive yarn (left) & casing placed on top (right)

Module B. Power & data transport

For this prototype the exact same yarns and machine settings were used for the conductive yarn stitches as in prototype 1: Elektrisola 30004021L of 0.04 mm thickness was used as Bobbin thread and non-conductive AMANN Saba 80, 100% polyester grey as top thread. The stitch is a zigzag stitch to allow for stretching of the fabric and more comfortable wear. To avoid over stretching, an additional stitch with non-conductive yarns and a longer stitch length is stitched over the conductive trace, see Figure 153. The longer stitch length shortens the total length of the yarn significantly and, will prevent over stretching of the underlying conductive yarn stitch to a certain degree. If overstretched, the non-conductive stitch will break first as a warning for the user.

Figure 153. Additional longer stitch covering conductive stitch to avoid over stretching

Module C. Main control module

The main control module uses header pins (soldered to a PCB) that are slid underneath sewn conductive yarns as connection to the textile carrier. A drop of conductive glue is added to fixate the mechanical connection and strengthen the electrical connection, see Figure 154. The second part of this connector is the removable pogo pin connection. This is also soldered on top of the PCB and each pin is connected to an individual header pin. The complete PCB is then covered by the

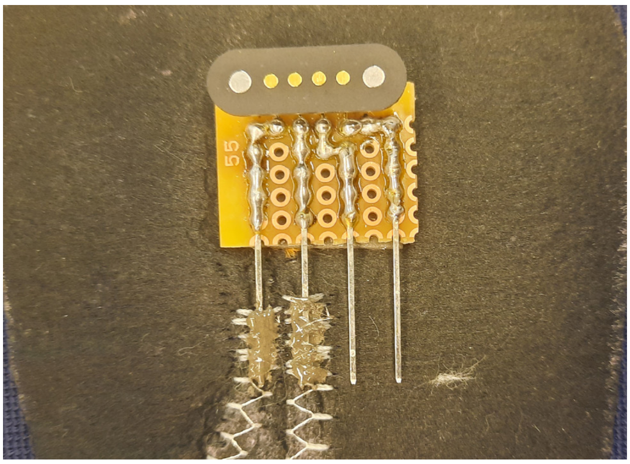


Figure 154. Close-up of conductive Elektrisola yarn (left) & AMANN Saba polyester (right)

landing plateau for the main control module as shown in Figure 156. Currently, this plateau is 3D printed, but in the real design should be overmolded or casted to fixate the underlying connections. In Figure 157, you can see the connection of the main control module. The design of the landing plateau and main control module only allow for one way of correct placement.
To protect the conductive yarn stitch from friction and mechanical stresses at the transition from the casings to the textile carrier, an additional dense zigzag stitch covers this critical point as shown in Figure 158.

Module D. Textile carrier

The same 4-way stretch textile carrier was used as in prototype one. The production in detail can be found in Appendix A13

An overview picture of the complete prototype pinned to a male mannequins' back can be found in Figure 155.

Figure 155. Concept 3 pinned to the back of a male M running shirt

Figure 156. Landing plateau main control module with pogo pins and magnets

Figure 157. Main control module with magnets ensuring proper placement & electrical contact..

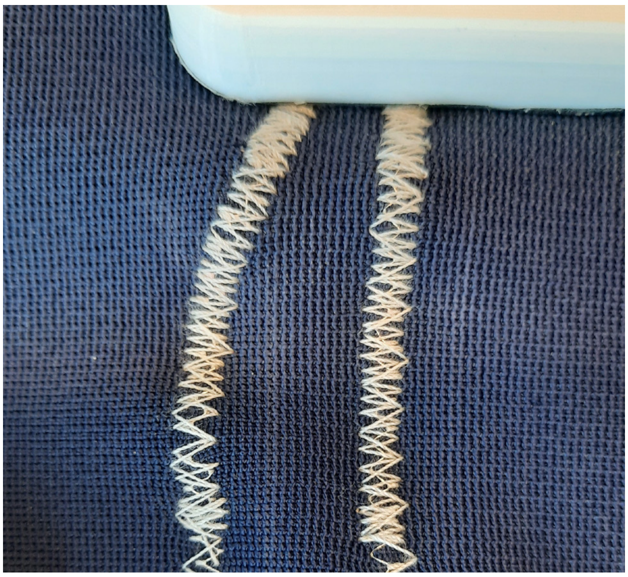


Figure 158. Additional dense zigzag stitch of non-conductive yarn to protect conductive yarn

Silicon overmold

In Figure 159 & 160 silicon overmold test can be found for both the landing spot area and the tactor module. The overmolds were done in two phases: first a layer of 1mm silicon was placed on top of the fabric (Sensitive© Evo) with a Micron-level adjustable film applicator.
After drying, the 3D printed mock-ups were placed on top of the fabric together with a mold, followed by the second overmold.
As the mock-up vibration motor was not fixated, it is now askew inside the overmold. The silicon tested was Rubber Silicon Shore 40 of the brand Resion. It does attach well to these Sensitive© fabrics, though it does not attach to the mock-ups, needing additional silicon kit to make the designs waterproof. Also, shore 40 is too flexible and it can push hard parts out. The molds were filled completely during injection, but by releasing the air bubbles in a vacuum oven, the volume decreased significantly. Resulting in the shiny canals that can be seen in Figure 159 & 160. For a complete overview of the test, see Appendix A14.

Figure 159. Silicon overmold landing spot with Rubber Silicon Shore 40 by Resion

Figure 160. Silicon overmold tactor module with Rubber Silicon Shore 40 by Resion

Resistance & connection

Resistance

The resistance of the complete circuit was measured with a multimeter and was found to be 3.5 Ohm in total.

Connection

To test if the electrical connections work, a 3.7V battery was used to make the motor vibrate. Moreover, a short Arduino script was written to actuate the motor a bit. This short Arduino script can be found in Appendix A12. The connection functioned properly and the motor could be powered well. The strength of the magnets was however not enough to keep the main control module and landing spot attached during vertical movement.

Learnings & improvements

Magnets

- The use of magnets can be really helpful to fixate an electrical connection in the correct alignment while also being waterproof.
- The strength of the current used magnet was not enough, as it was only a cheap hobby version. In the future, a professional stronger magnet should be implemented, from for example Supermagnete.nl.
By using a professional magnet, the size can also be decreased, making it more easy to implement. Moreover, additional changes in the landings pot should be made to improve the mechanical attachment.

Sewing with conductive yarn

- In the first production trial the tactor module and pogo pin module were first taped to the textile carrier and then sewing with conductive yarns was done. However, it was almost impossible to sew blind on top of the header pins. The modules got stuck in the transport of the machine. In the end, first the conductive traces were sewn and then the header pins were put underneath the zigzag stitch for electrical contact.
- The zigzag stitch is extremely stretchable, however, addition strain relief is necessary at critical points where the transmission from casing to textile carrier happens. This can be done by adding zigzag stitch with smaller stitch lengths.
- Over stretching of the conductive yarns

should be avoided. By adding a strong parallel stitch that is less stretchable, this stitch will help prevent over stretching to a certain degree. If over stretching happens, first the normal yarn will break and alert the user to stop.

Solufix & Vlieseline

• Solufix avoids forming tensions in the fabric created by the high top tensions used, during stitching and easily dissolves with a bit of cold water afterwards. This model was produced without Solufix and shows high tensions inside the textile carrier.
• Vlieseline prevents fabrics from stretching at critical points, such as the connection points of the tactor module or pogo-pin module.

Vibration motor module

• The first designed cutout in the casing of the vibration motor was to big, resulting in a loose fit around the vibration motor. This casing does not press the module tightly against the fabric, decrease the ability to feel the motor properly at all times. Especially during movement this could result in wrong interpretation of the user. In a future version, this fit should be tight, helping to press the vibration motor down on the textile. However, not to much to make it ergonomically uncomfortable.
• The hard casing results in loud noise when the motor vibrates. In future designs a softer material should be used to damp the sound a bit.

Landing spot and main control module

• The size of the current main control module and landing spot are rather big. In a future design, the sizes should be optimized according to the electronics used by Elitac Wearables. The estimation is that the height could be decreased by 50% through the design of a PCB. Moreover, the contact surface could be decreased as well, as only the connection points and magnets will require proper connection.

Header pins and prototyped PCBs

• The header pins now use prototyping PCBs that take up quite some space. In future versions, it would be interesting to research PCBS with these pins already included.

Waterproofing of the design

• The current prototype of concept 3 is not yet completely waterproof. In a next design, this should be addressed.
New overmolds with a higher shore value of silicon and silicon kit should be explored. Moreover, other overmold materials can be tested.

Ergonomics

• The current casings are still quite hard and might not feel ergonomic when worn tightly on the body. Using less hard materials for the casing could improve the situation.

Opportunities:

• The implementation of more flexible casings could increase the ergonomics significantly and improve the waterproofing of electronics
• The pogo pins connector has great potential to make important electronics easy to (re-)attach after washing or charging.
Not only for the main control module, but this could also be an interesting connection for tactor modules.
• By sewing stretchable conductive yarn traces, stiff and large cables can be left out of future designs. A good intermediate solution for now could be Amohr flat cables as well.

14. Concept evaluation

In this chapter the prototyped concepts are evaluated. First results of a washing test vs. the resistance of 3 conductive yarns is presented in paragraph 14.1. Next, a current vs. heat test is presented in paragraph 14.2, followed by a data reliability test in paragraph 14.3. Finally a weighted objectives analysis and a design choice is presented in paragraph 14.4.

14.1 Launderability test conductive yarns

Goal

Laundering tests were performed to monitor potential changes in resistance of the following three conductive yarns: Bekaert Bekinox VN 12.2.2. 175S (steel core strands), AMANN Group Silver-tech 30 Tex 96 (nylon core, silver coated) & Elektrisola 3004021L (copper core & silver plated). The goal was to test the durability & resistance of the conductive yarns after washing. This in turn can be used to support the feasibility of the use of conductive yarns and choose a conductive yarn for the final design.

Setup

Sewing

All yarns were stitched on top of a pure non-bleached piece of cotton in the setup shown in Figure 161. Each length was individually sewn to help evaluate the durability. The top yarn used was AMANN Saba 100% polyester and the conductive yarns were used as Bobbin thread. The straight stitch had a length of 2.5 mm and the zigzag stitch a length of 2.5 mm & a width of 3 mm. The total length sewn with the zigzag stitch was calculated to be the same length as the straight stitch, to see if the type of stitch would influence the resistance. An example calculation can be found in Figure 161. A size 80 universal needle of Schmetz and a Brother sewing machine was used.

Washing

The laundry machine used was a Miele Soft Care System W 3203 Watercontrol-System, with a silk wash setting of 30 degrees Celsius and 400 rpm. During washing, the conductive yarns were placed in a laundry bag, and air dried at room afterwards.

Resistance measurement

The Bekaert Bekinox and AMANN Group yarns were measured using a normal multimeter with a resolution of 0.1 Ohm. During each measurement, the resistance of the circuit was also taken into account.
For the Elektrisola yarn, a 4-point measurement was used to measure the resistance, as the resolution of the multimeter would have been too low to measure the low resistance accurately. Moreover, the resistance of the measuring circuit would have had a significant effect on the measured resistance. A 4-point measurement has a much higher resolution and eliminates the resistance of the measuring circuit, allowing for the measurement of small resistances.
An overview of the setup of a 4-point resistance measurement can be found in Figure 162. Rs represents the resistance of the conductive yarn measured between points 2 & 3. Rw represent the wire resistances of the measuring circuit which

are eliminated (Öhlund, 2012).
Single test hook clips were used to make proper contact with the conductive yarns during measurements.
The ends of each stitch were used to measure the resistance at a constant location. To protect these ends during washing, they were cover in hot glue gun, as shown in Figure 163. This method was abandoned after the first wash, as this would break or damage the ends of the yarns. A laundry bag was used for additional protection, see Figure 164.

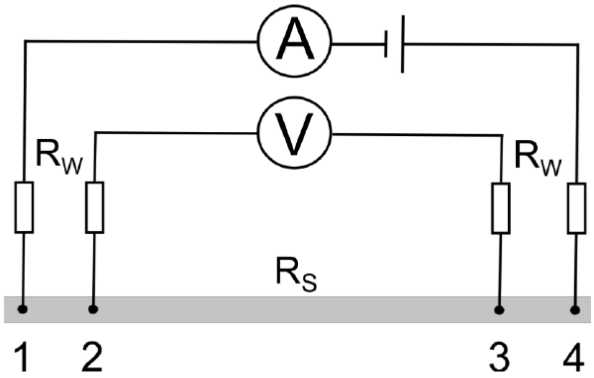
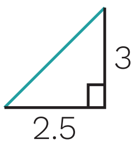


Figure 162. Setup of 4-point resistance measurement (Öhlund, 2012, p. 16)



$A^2 + B^2 = C^2$
$C = \text{sqrt}(2.5^2 + 3^2)$
C=3.905 mm
100/3.905mm = 25.6 stitches
25.6X2.5mm = 64.02mm

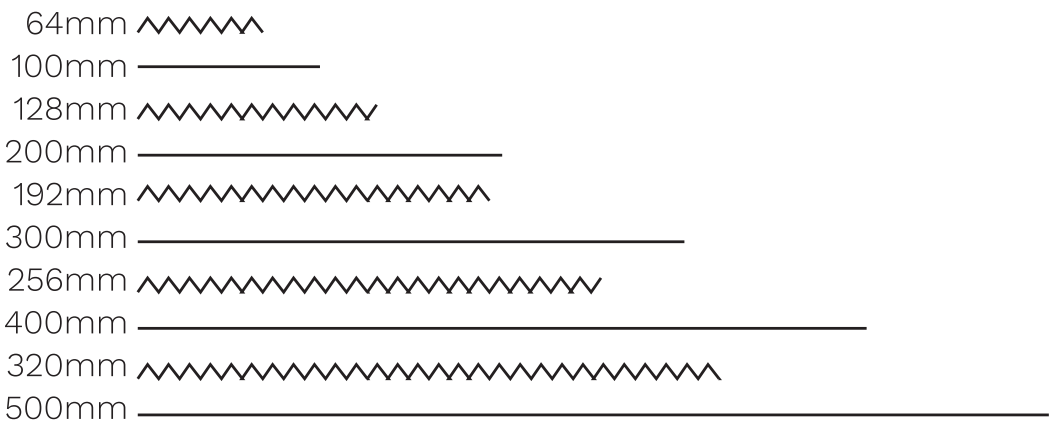


Figure 161. Schematic overview of washing tests with distances sewn

Figure 163. Conductive ends glued with a hot glue gun

Figure 164. Conductive yarn samples in laundry bag

Results

In Figure 165 to 172 the results for both the straight stitch and the zigzag stitch of the 3 yarns can be seen. Next to the different measurements, the equation of the linear lines can be seen, in which the slopes present the ohms/m of the yarns after each washing cycle. The Bekaert Bekinox yarn shows a higher resistance value before washing than after washing, but the general resistance remains more or less the same for both type of stitches. The AMANN Group Silver-tech shows increasing lines per washing cycle. The Elektrisola yarn shows similar behaviour as the Bekaert Bekinox yarn, having a higher starting resistance before washing, but remaining more or less constant over the overall length.

All resistances measured were higher for the straight stitches then for the zigzag stitches. During the measurements of the Bekaert and AMANN Group yarn, the resistance of the measuring circuit was also measured and subtracted from the values. The overall resistance of the circuit lied around 0.2-0.3 Ohms. The Y-axis intersection of each graph, saying something about the measurement error and resistance of the circuit, lied between -0.002 & -0.08 Ohm. For the detailed results, see Appendix A15.

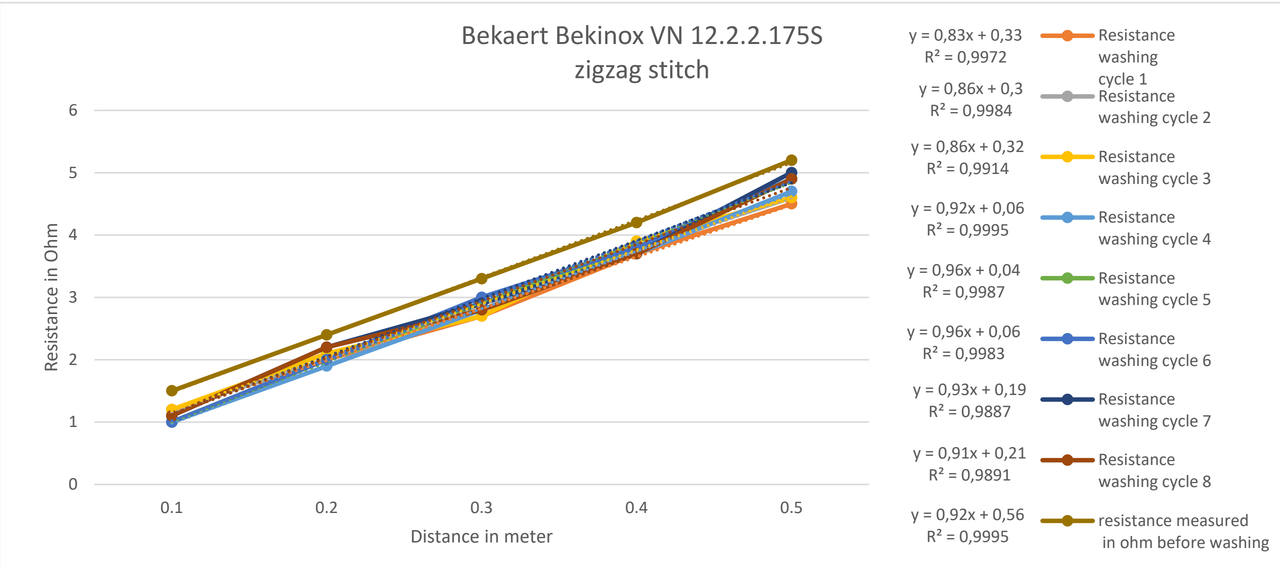


Figure 165. Results of the Bekaert Bekinox yarn zigzag stitch, remaining stable during all washing cycles.

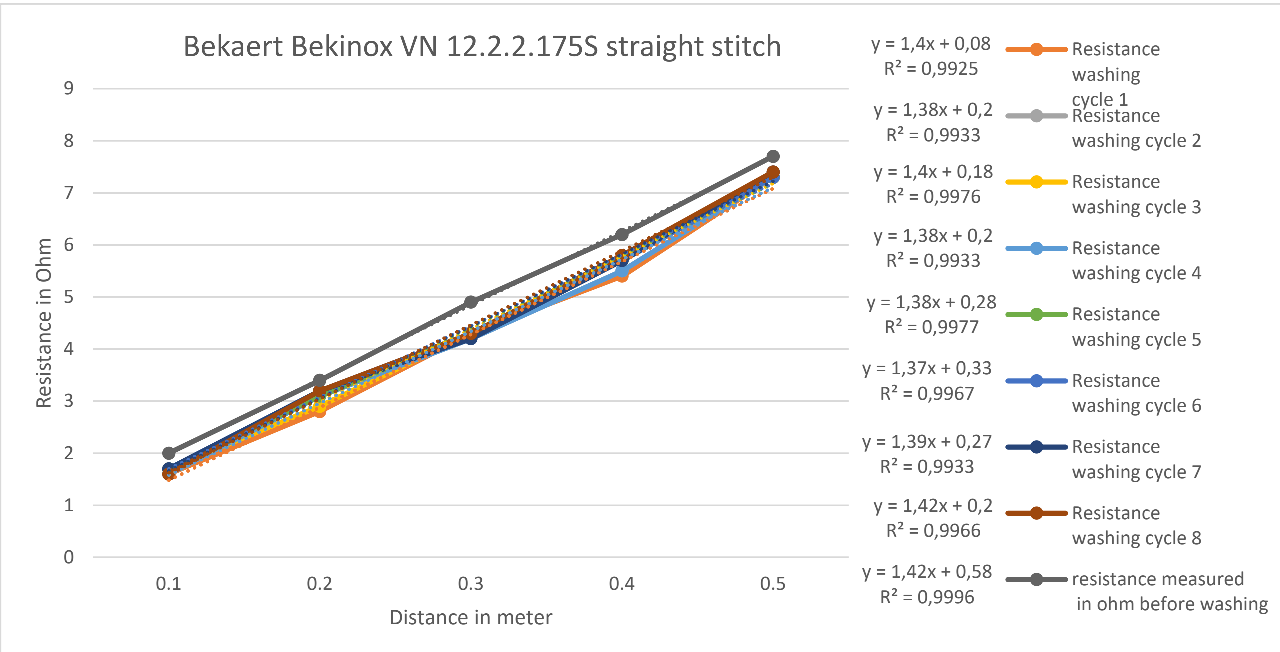


Figure 166. Results of the Bekaert Bekinox yarn straight stitch, also remaining stable during all washing cycles.

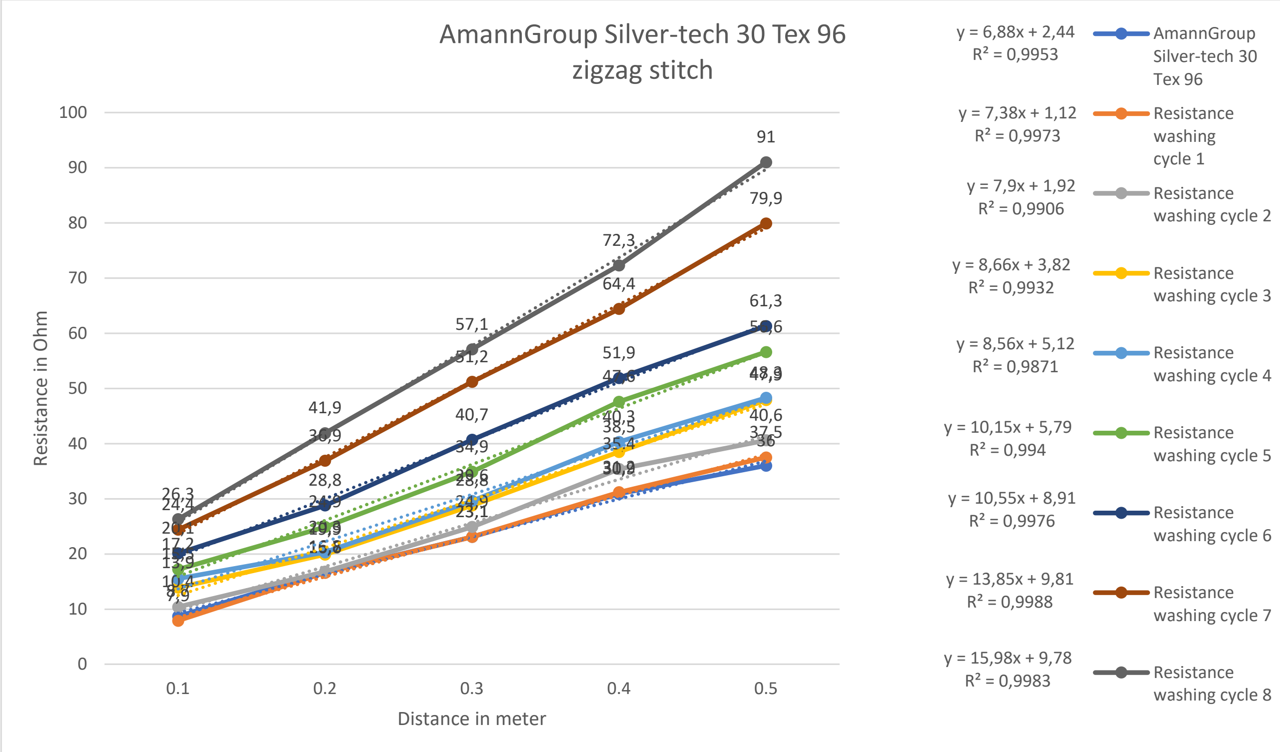


Figure 167. Results of the AMANN Group yarn zigzag stitch, showing a significant increase per washing cycle.

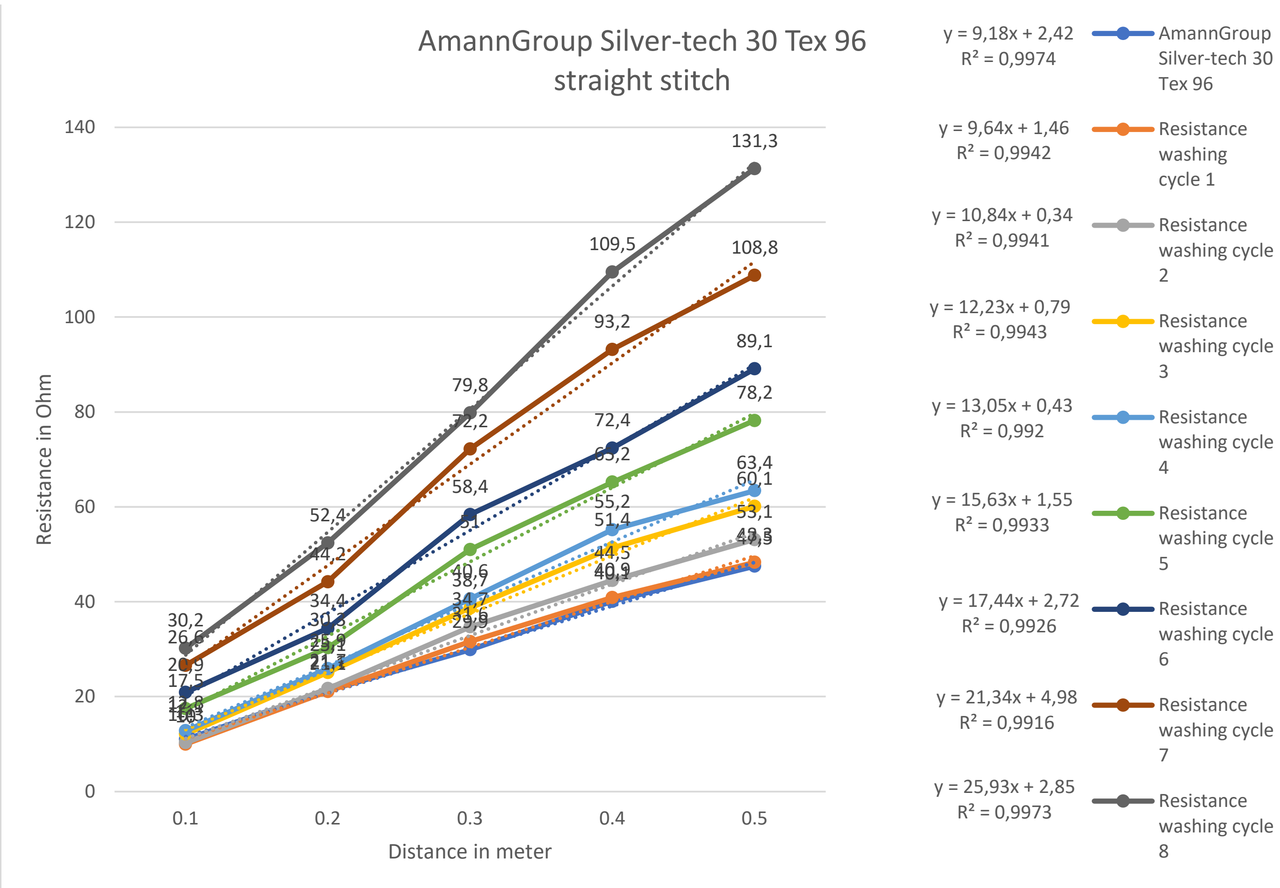


Figure 168. Results of the AMANN Group yarn straight stitch, also showing a significant increase per washing cycle.

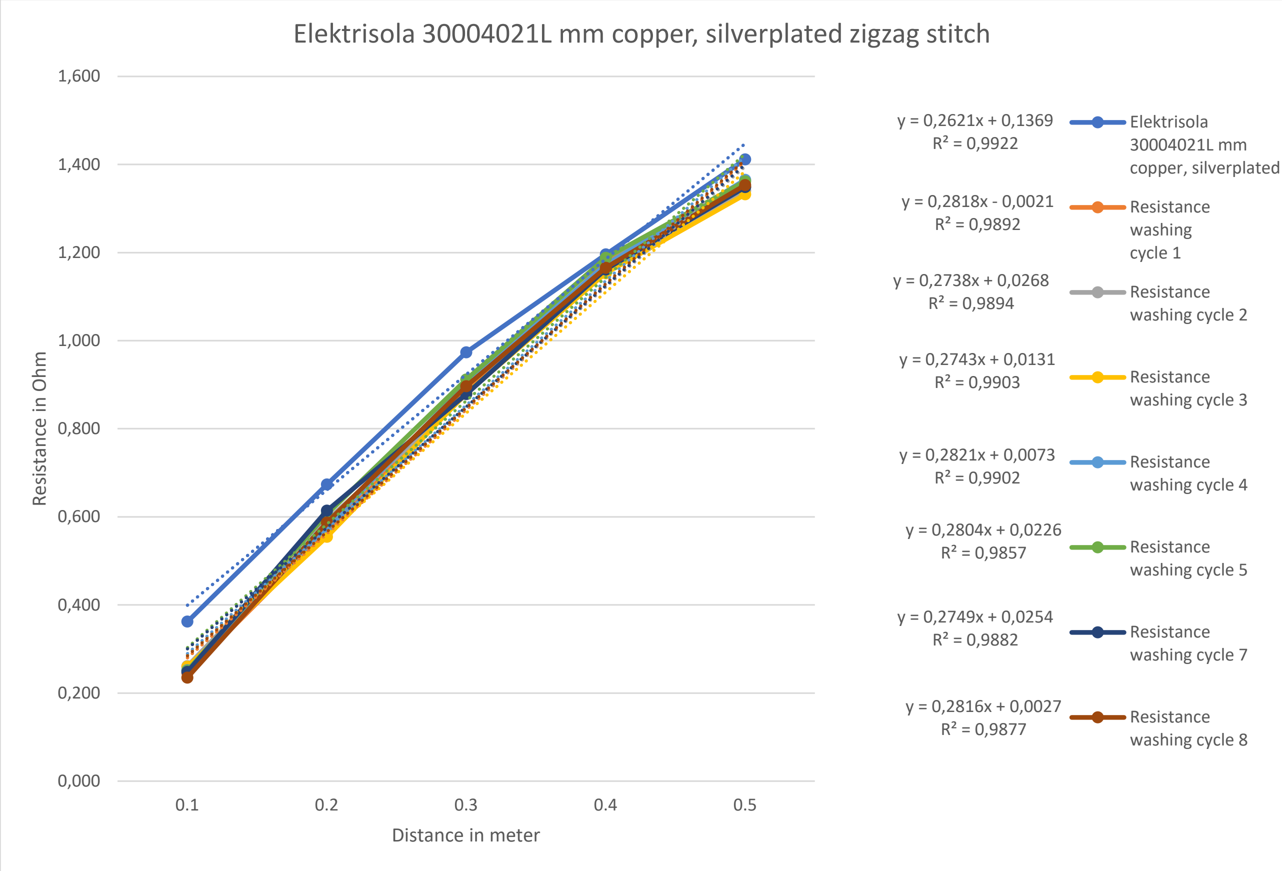


Figure 169. Results of the Elektrisola yarn zigzag stitch, remaining stable during all washing cycles.

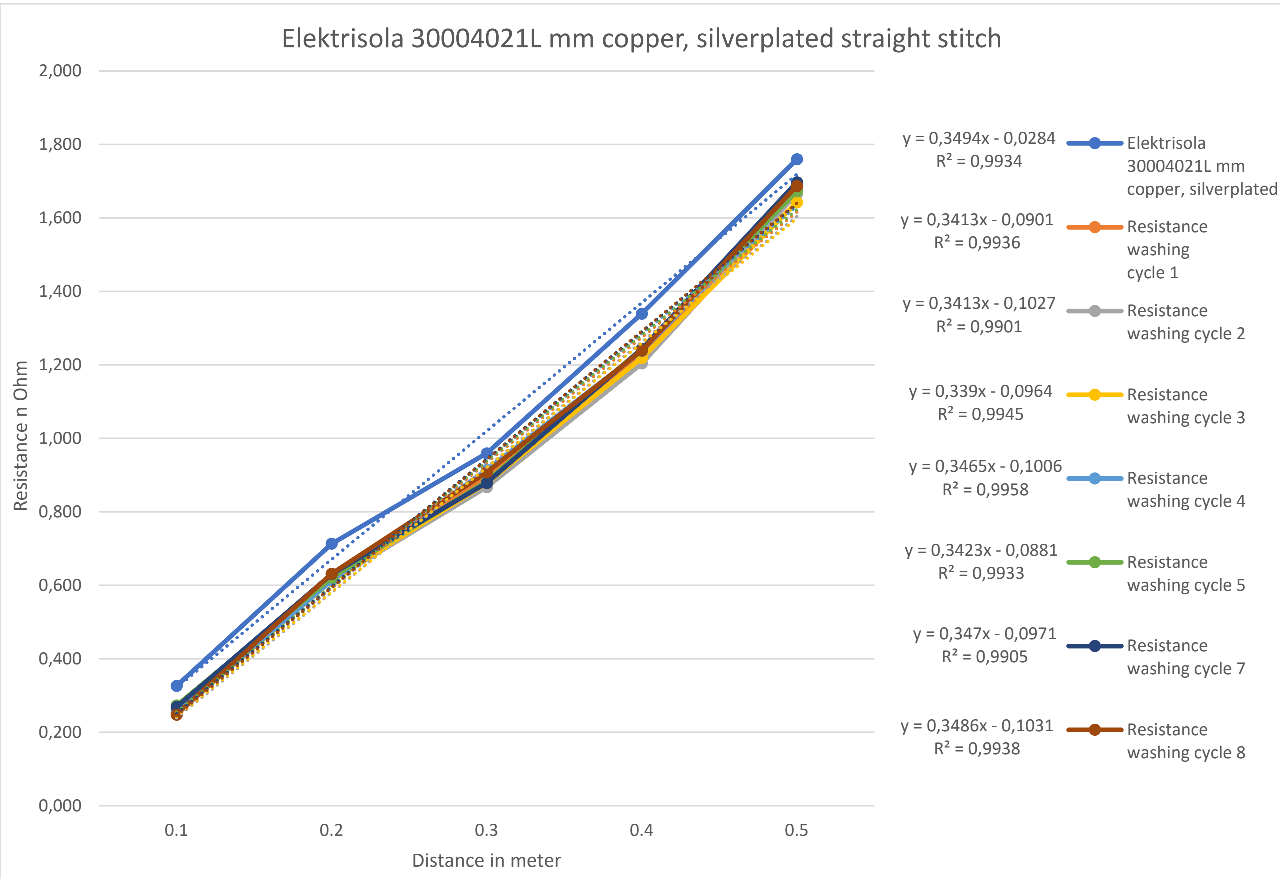


Figure 170. Results of the Elektrisola yarn straight stitch, remaining stable during all washing cycles.

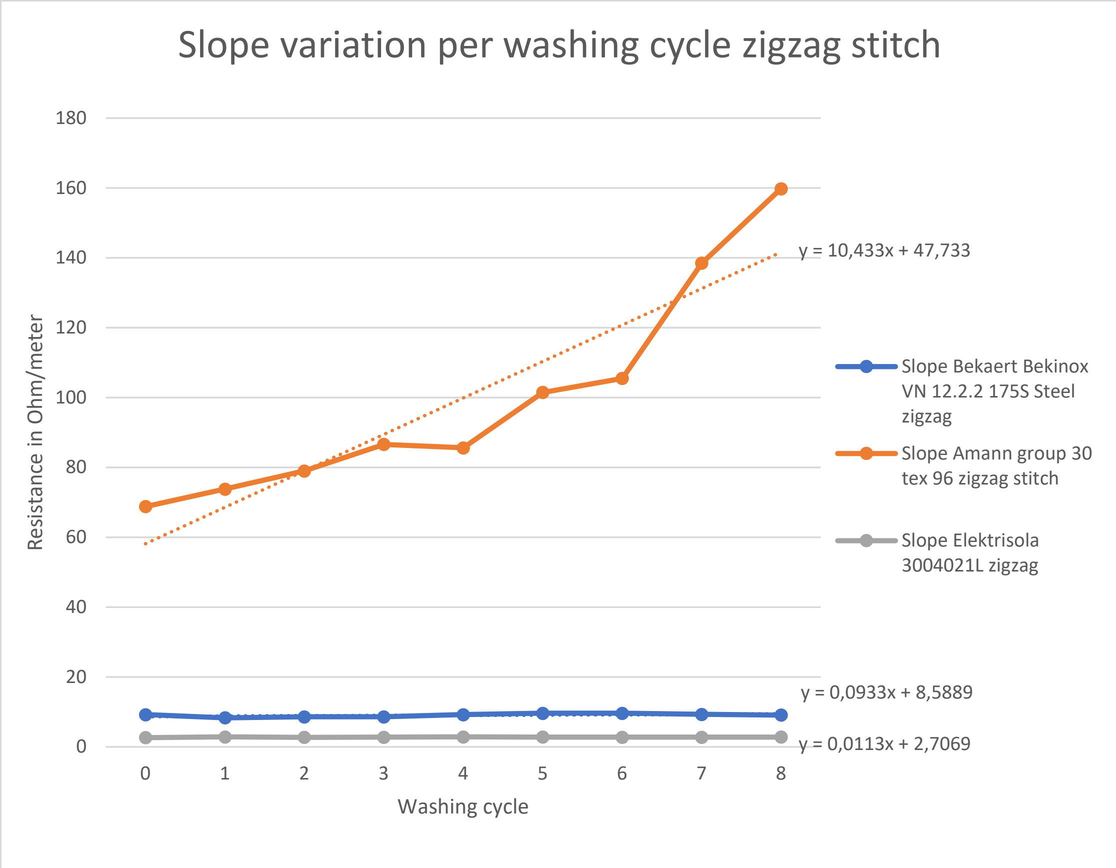


Figure 171. The overall slope variations per washing cycle for all three conductive yarns stitched in a zigzag.

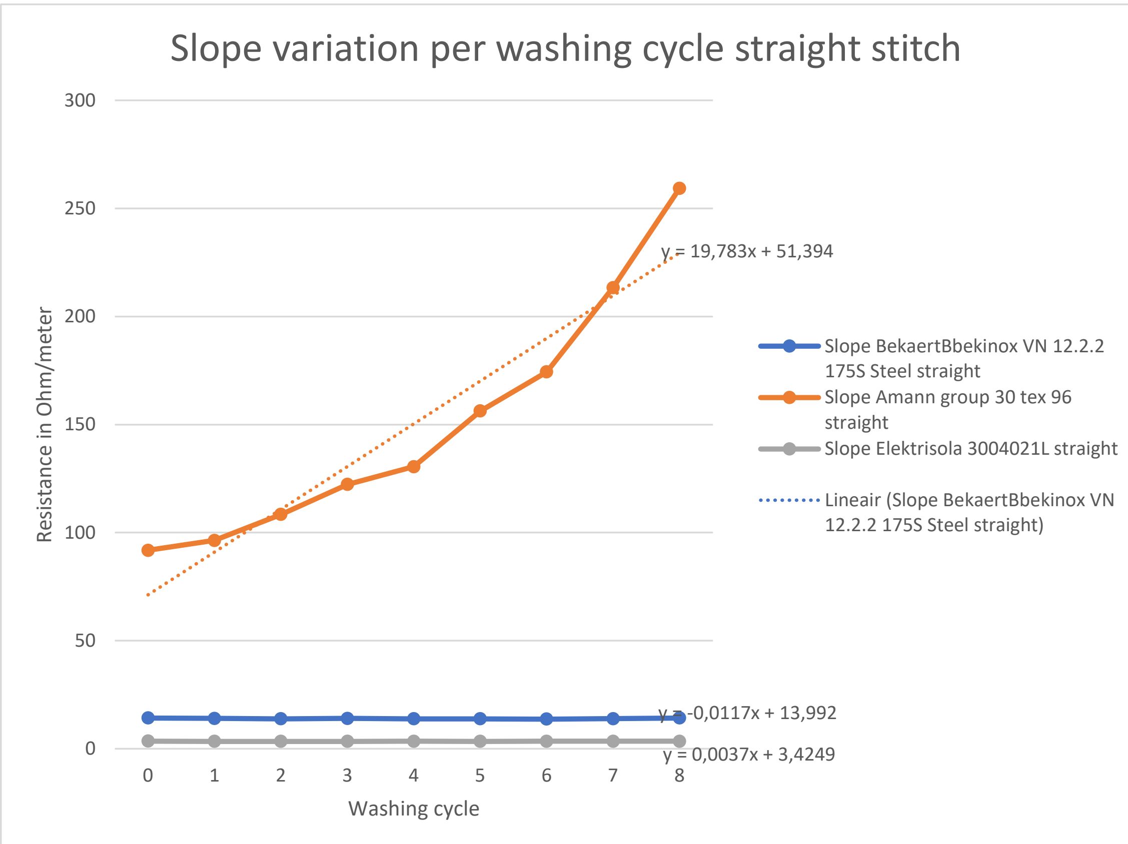


Figure 172. The overall slope variations per washing cycle for all three conductive yarns stitched straight

Discussion

Higher starting resistances

The Bekaert Bekinox and Elektrisola yarns show a higher starting resistance before washing and after the first washing cycle. This difference can be explained due to the fact that the initial hot glue protective layer damaged the yarns, having to measure the resistance at another location, shortening the total distance of the yarns.

Straight vs. zigzag stitches

The straight stitches seem to have a higher resistance per meter than the zigzag stitches tested. To stitch equal lengths of yarns in a zigzag stitch compared to the straight stitch, a calculation was made to stitch approximately the same amount of yarn. Although all the machine settings and materials used were exactly the same, not all yarns were sewn neatly in a zigzag stitch. Especially for the Bekaert Bekinox, the zigzag stitches looked more like straight stitches due to the thickness of the yarn, decreasing the processability. Therefore the zigzag stitch uses less yarn in total than the straight stitch, but the resistance is calculated over the same distance. This problem lessened as the yarns got thinner, so the Elektrisola showed this effect the least.

Y-axis intersection

The Y-axis intersection tells us something about the resistance of the measurement circuit and possible measurement errors in Ohms. These numbers were insignificant (-0.002 to -0.08 Ohm) and can be neglected. The reason why these values were so small, can be explained due to the subtraction of the resistance of the measurement circuit, or by the elimination of the circuit resistance due to the 4-point measurement.

Slopes

The slopes presented in Figure 165 & 172 represent the actual resistance/ meter measured. The Bekaert Bekinox and Elektrisola yarn show minimal to no resistance increase per washing cycle. The AMANN Group yarn however shows a significant linear and even a bit exponential increasing line. Changing the resistance up to multiple ohms per meter per washing cycle.

Strength of the yarns

The AMANN Group and Bekaert Bekinox yarn remained strong after 8 washing cycles and did not show points of weakness. Although, the Elektrisola yarn would break at some points after measuring too often at the same location. Therefore, the Elektrisola yarn is the most fragile of all when it comes to pulling forces and mechanical wear.

What other literature says

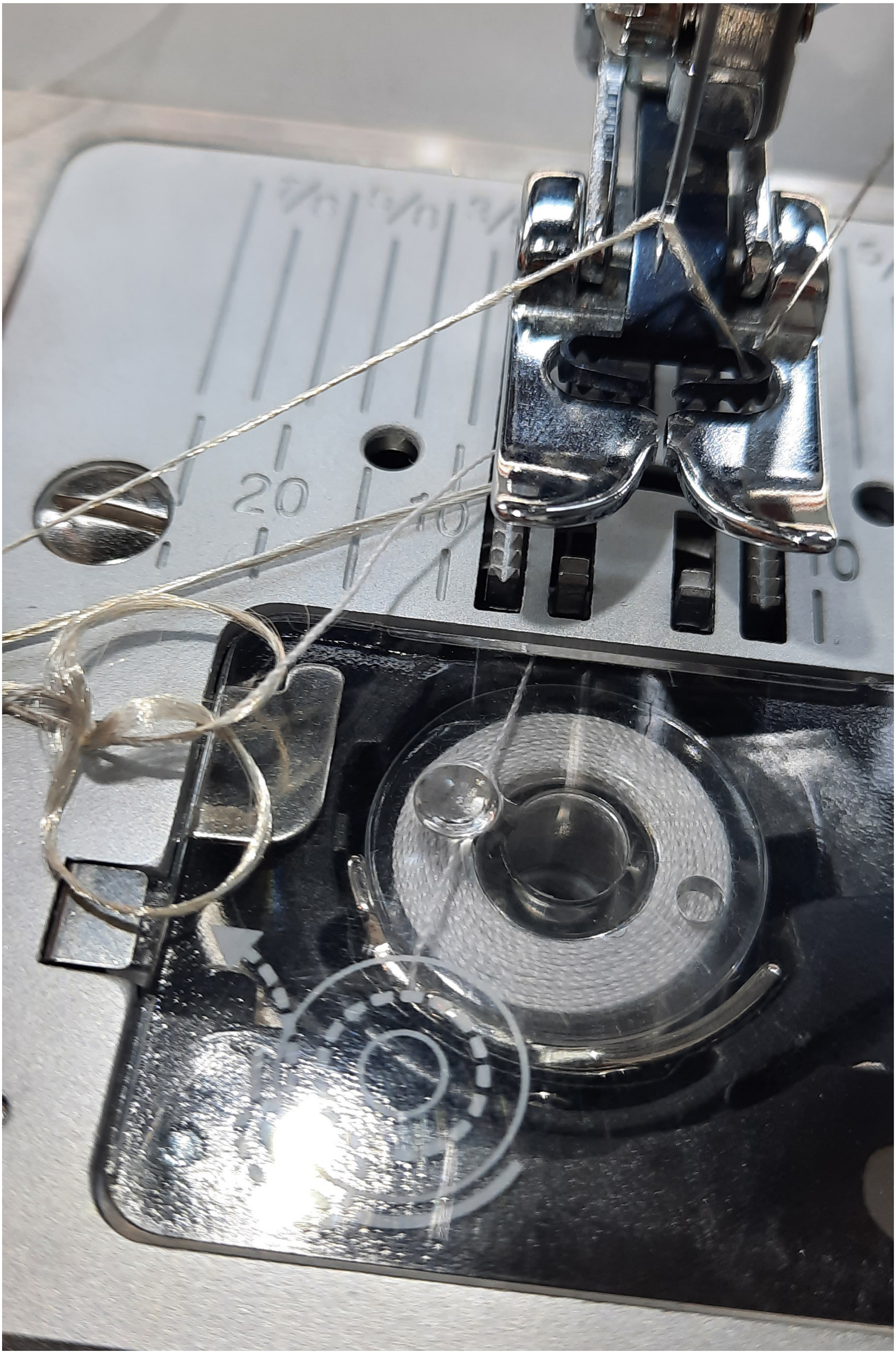
Zaman et al. (2019) also tested the launderability of multiple conductive polymer yarns, of which one was the AMANN Group Silver-tech 120, a thicker yarn than the 30 version tested in this experiment. Their results says the opposite, and show that the resistance should stay constant over a total of 10 washing cycles. This discrepancy can be caused by the use of different laundry detergent that could have washed away the silver coating. Special TexCare soap is advised by LessEMF (2021) to protect silver or stainless steel threads. They add that sulphur, minerals and fluorides can affect the yarns.

Second control test

A second conductive yarn laundry test was performed, in which one singular stitch´s resistance was measured at different distances. This test also enabled us to re-do the zero measurement before the first laundry cycle. This laundry test confirmed the findings of the launderabillity of the 3 types of yarns found as before. For the results of this test see Appendix A15.

Conclusion & Decisions

Based on the findings in this research, the ***Bekaert Bekinox and Elektrisola yarn tested are suitable for washing at 30 degrees Celsius on a silk washing program***, as this does not significantly increase the resistance. The opposite is true for the AMANN Group Silver-tech yarn tested. However, this effect could possibly be prevented by using a ***special laundry detergent such as TexCare***. The ***Elektrisola*** yarn was concluded to be the ***most fragile***, however ***neat reliable stitches*** could be produced. The Bekeart Bekinox yarn is stronger, however, more difficult to sew in a stretch zigzag stitch.



14.2 Current vs. heat test

Goal & Setup

The goal of this experiment was to see if the conductive yarns selected would become warmer than the 43 degrees Celsius allowed by the IEC (IEC 60601-1) when trying to power 3 ERM motors. This restriction applies for medical electrical devices directly worn on the skin. The three yarns tested are the AMANN Group Silver-tech 30 tex 96 (<85 Ohm/m), Bekinox 12.2..2 175S (14 Ohm/m) and Elektrisola 20042021L (~2.1 Ohm/m)
As found in chapter 9.2. The maximum Ipeak of three cylinders is 292mA and 220mA for cylinder and coin ERM motors respectively. If the three motors are running, the general operating current Iopp will lie around 150mA for both type of motors. Half a meter of three different yarns were supplied with a set current for X seconds in total. The yarns ware placed on top of non-bleached cotton fabric to mimic the surroundings of a textile carrier. A FLIR camera was used to measure the temperature changes in real-time. The maximum temperature measured was noted in an Excel. For the raw data, see Appendix A16.

Results

In Figure 173 the current versus maximum temperature after 10 seconds of power is presented. In Table 10 an overview is given of the maximum temperature versus a current supply of 150 and 300 mA in a total of 60 seconds.

Discussion

All three conductive yarns tested remained below the 43 degrees Celsius boundary when supplied with up until 300 mA. However, the AMANN Group yarns seem to warm up the most after increasing the current or applying the current for a longer period of time. This was to be expected, as this yarn has the highest resistance of The other two yarns remain far below the boundary presented, though it must be noted that the power in watts also remains rather low for these two yarns. Presenting the power supplied versus temperature would have been a better representation of the heat formed, as the unit of power is Joules/second. However, as power is directly related to the current and voltage supplied according to the following formula:

$P=U*I$

it was difficult to create a neat graph such as in Figure 173 for power versus degrees Celsius. These graphs can however be found in Appendix A16 for the measurements performed.

Moreover, it is important to note that next to current, many more factors play an important role that determine the temperature. Examples are the thickness of the yarn, directly linked to the surface area through which warmth can be dissipated, or the surrounding environment that can be highly conductive or insulating. Therefore, it is important to perform more safety tests once the complete design is finished.

Conclusion & Decisions

Of the three yarns tested, the ***Bekinox and Elektrisola seem to stay far below the 43 degrees Celsius when 300 mA*** is supplied for 10 seconds and even 60 seconds in a row. The AMANN Group yarn also stays below the required boundary, but heats up the most of all yarns as it has the highest resistance. For now, the Elektrisola and Bekinox yarns are safe enough for implementation. Future tests should be performed to show that a design is completely safe to use. To be even more safe, the final design should protect the user from coming into direct contact with the conductive yarns.

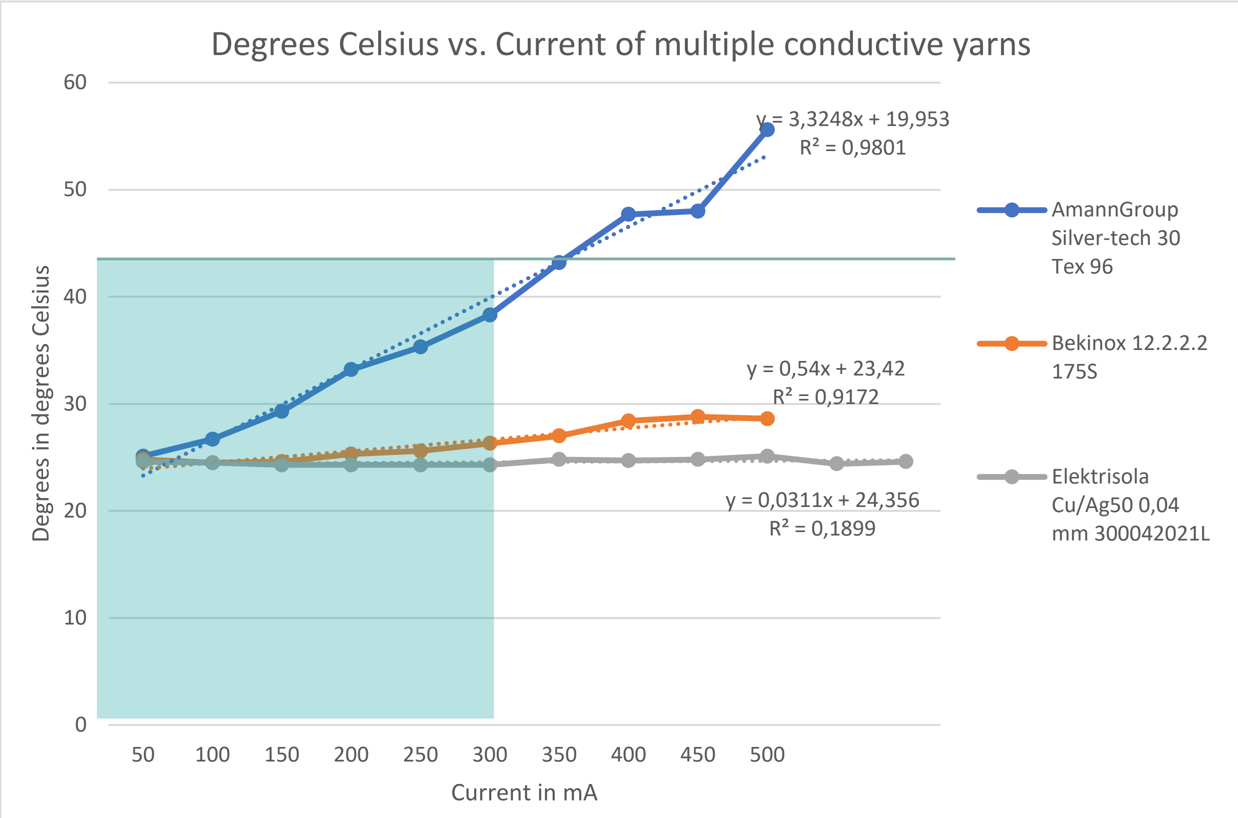


Figure 173. Temperature versus current supply for 10 seconds in total with the safety window shown in blue.

Yarn	*Current in mA (for 60 seconds)*	*Max voltage in V*	*Max temperature in degrees Celsius*	*Power in Watt*
AMANN Group Silver-tech 30 tex 96	150	3.37	28.5	0.506
AMANN Group Silver-tech 30 tex 96	300	7.35	40.5	2.205
Bekinox 12.2.2 175S	150	1.08	25.1	0.162
Bekinox 12.2.2 175S	300	2.2	28.3	0.660
Elektrisola 20042021L	150	0.174	24.4	0.864
Elektrisola 20043021L	300	0.351	24.6	0.855

Table 10. Temperature versus current supply for 60 seconds in total for different conductive yarns

14.3 Data reliability test

To validate if both concepts are reliable during dynamic use when it comes to data transport, experiments were performed with two Arduinos sending data to one another.

In Figure 174 the setup of the first prototype is shown. Two Arduinos are connected through the electrical components and communicate via Serial communication. The electrical connection is established through either the use of gripper clamps as shown in Figure 175, 176 & 177, or the soldering of wires (Figure 178).

Setup

The first Arduino sends 3 numbers over the conductive Velcro traces, through the conductive yarn and then through the contact points of the tactor to the second Arduino. Next, the second Arduino mirrors the received number and sends it back to the first Arduino the same way. The first Arduino then compares the sent 3 numbers with the 3 received numbers. If these numbers are not the same, the system will count this as an error and add +1 to the error count, see Figure 179. The first numbers are the time-stamp of the moment of measuring (left). The zero directly next to the arrow is the number of errors counted. Next, on the right, the first three numbers are the one's send by the first Arduino, and the next three numbers are received back from the second Arduino. The speed used to send information was 4800 baud, which is equal to 480 bytes per second.

The two scripts used for this test can be found in Appendix A17 and were written by Kooijman (2021).
During these tests, the concepts were shaken around, folded, stretched, etc. for a full minute to see how many errors would occur, see Figures 180 & 181.

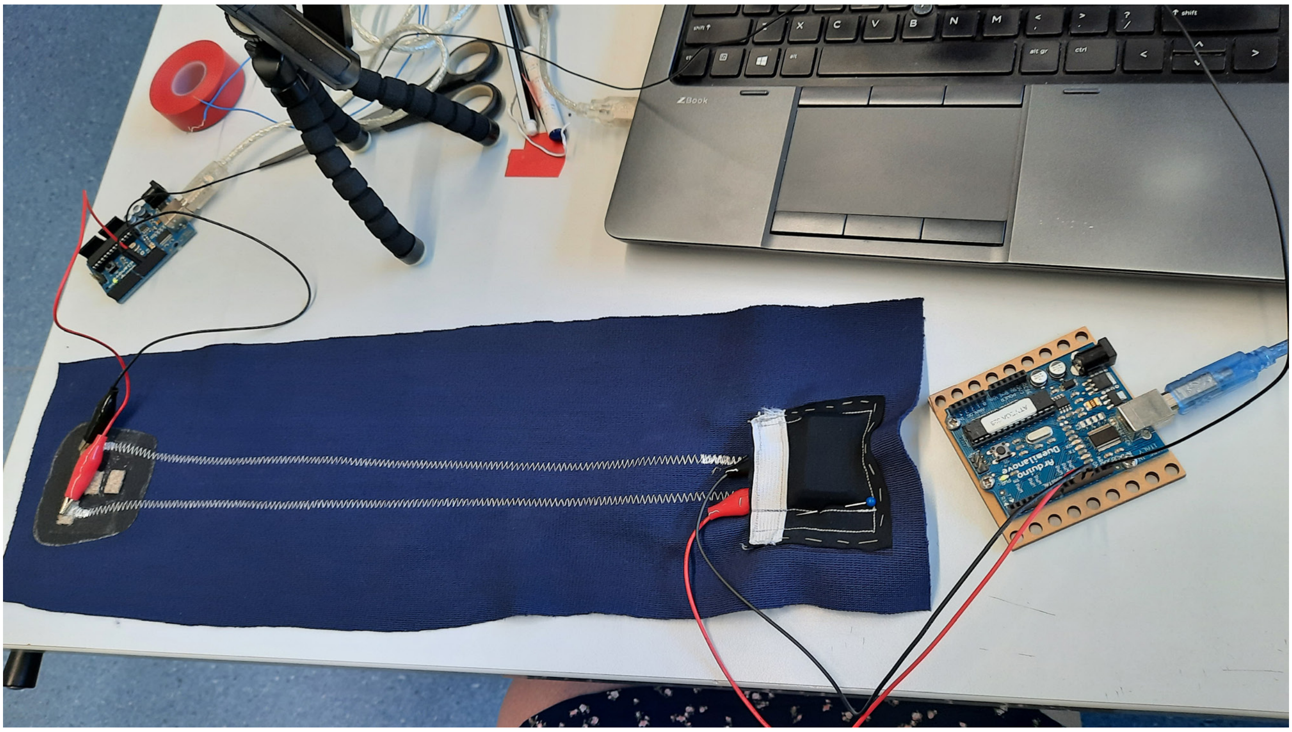


Figure 174. Temperature versus current supply for 10 seconds in total with the safety window shown in blue.

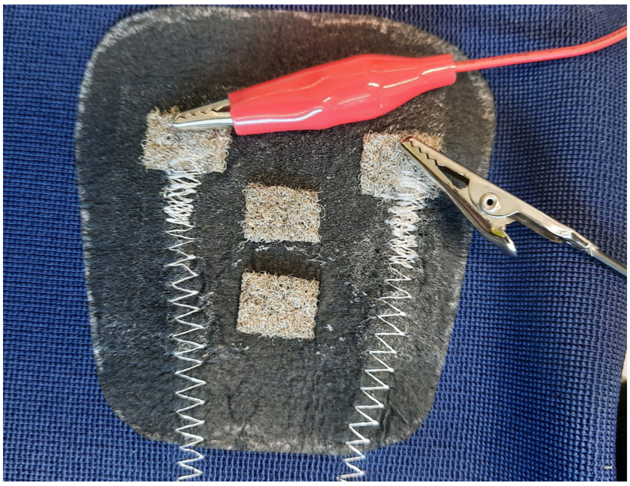


Figure 175. Gripper clamps connected to the conductive Velcro of concept 1

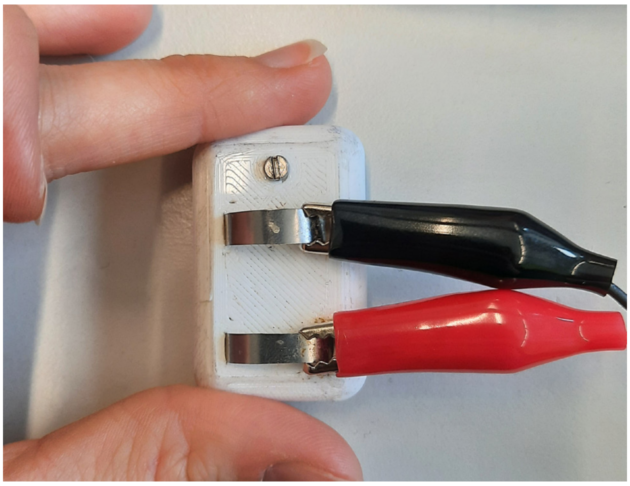
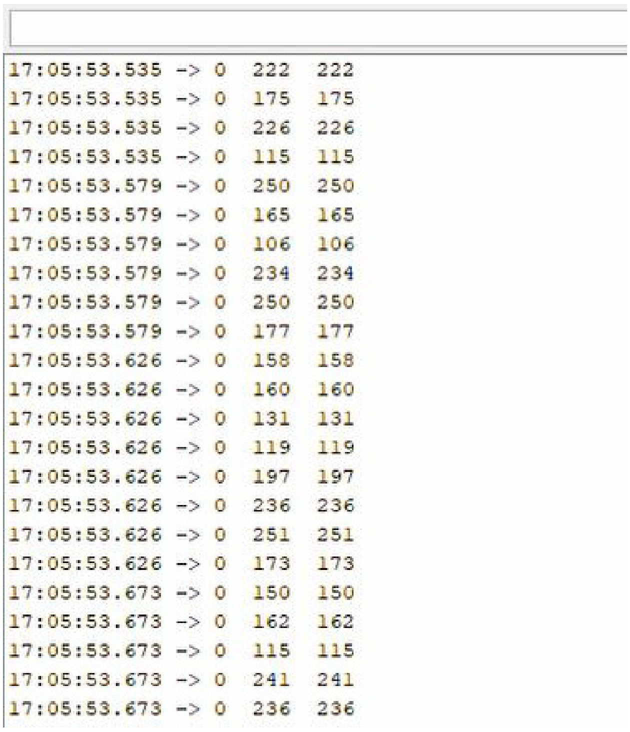


Figure 176. Gripper clamps connected to tactor module of concept 1

Figure 177. Gripper clamps connected to tactor module of concept 2

Figure 178. Soldered wires connected to pogo pin connector of concept 2



```
17:05:53.535 -> 0  222  222
17:05:53.535 -> 0  175  175
17:05:53.535 -> 0  226  226
17:05:53.535 -> 0  115  115
17:05:53.579 -> 0  250  250
17:05:53.579 -> 0  165  165
17:05:53.579 -> 0  106  106
17:05:53.579 -> 0  234  234
17:05:53.579 -> 0  250  250
17:05:53.579 -> 0  177  177
17:05:53.626 -> 0  158  158
17:05:53.626 -> 0  160  160
17:05:53.626 -> 0  131  131
17:05:53.626 -> 0  119  119
17:05:53.626 -> 0  197  197
17:05:53.626 -> 0  236  236
17:05:53.626 -> 0  251  251
17:05:53.626 -> 0  173  173
17:05:53.673 -> 0  150  150
17:05:53.673 -> 0  162  162
17:05:53.673 -> 0  115  115
17:05:53.673 -> 0  241  241
17:05:53.673 -> 0  236  236
```

Figure 179. Screenshot of Serial communication data during the reliability test

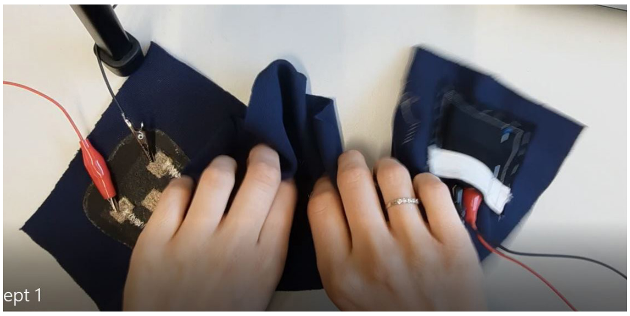


Figure 180. Folding and moving of concept 1 during the data reliability test

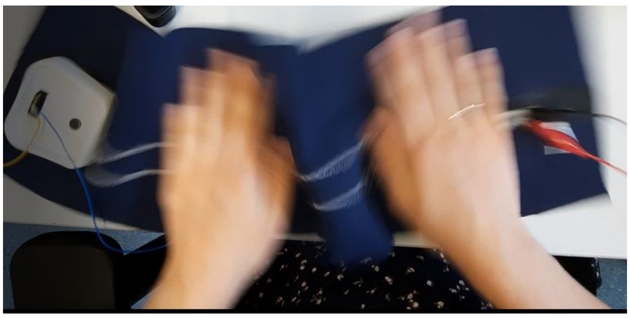


Figure 181. Folding and moving concept 2 during the data reliability test

Results

The screen prints of the error tests can be found in Appendix A17. A total of 0 errors were registered after 60 seconds of moving both concepts.

Discussion

This results make both concepts seem reliable when it comes to data transport during wear and human movement. However, the speed of the test could have been faster.

According to B. Bicknese, personal communication, April 20, 2021), one action of an ERM motor takes about 150 ms to be received, performed and finished. This would mean that a single tactor module would be able to perform 1000/150 = 7 actions per second. Meaning it could give 7 signals of haptic feedback to its user within one single second.

A brief calculation:
The Serial communication speed is equal to 4800 baud = 480 bytes per second, and 1 byte contains 8 bits.

The driver DRV2604 I2C communication consists of 3 bytes (3x8 bits) for a single command, see Figure 182. So for 7 actions we will need to transport 7x3 = 24 bytes in total. The Serial communication speed was set to 480 bytes per second, which is faster than the 24 bytes required per tactor.
Five tactors would for example required 5x24 = 120 bytes per second to be actuated.

This leaves 480-120 = 360 bytes to request and read sensor data from for example an IMU.

In a final test, it would be interesting to increase the speed of the Serial communication and see if it is still as reliable.

Conclusions

Based on the data reliability test performed ***both concepts seem reliable enough*** when it comes to data transportation over the designed system connections. In future tests, increasing the Serial communication speed would be an interesting parameter to change and see if the design is still reliable.

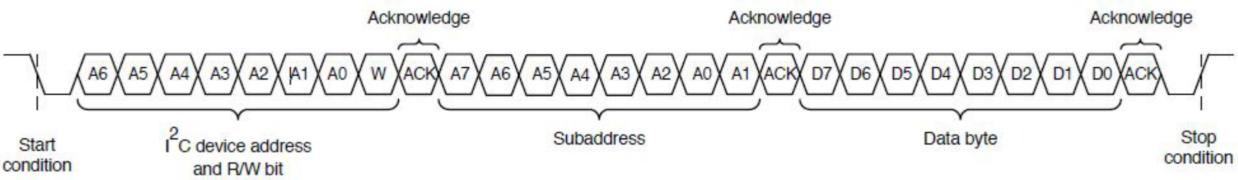


Figure 18. Single-Byte Write Transfer

Figure 182. I2C communication of the DRV2604, using 3 bytes per command (Texas Instruments, 2018, p. 22.)

14.4 Weighted objectives & Design choice

Both concepts including prototypes were evaluated with the Weighted Objectives method as described in the Delft Design Guide. This method allows us to increase the weight of more important requirements, and reduce the weight of less important requirements, so a better comparison can be made, compared to when all criteria would have the same weight.

The Program of Requirements Weighted Objectives can be found in Table 11.
For an explanation of the individual scores, please see Appendix A18.
Requirement R1.6 was not taken into account, as no tests with human sweat where performed. This could be an interesting test for the final prototype created during the final embodiment design phase.

Discussion

Based on the program of requirements weighted objective, Concept 2, the sewn traces of conductive yarn & pogo pin connections is tested as the best design with a total of 487 points. However, concept 1, the knitted pockets follows rather close with 452 points.
Both concepts have pros and cons. Whereas Concept 1 scores well on not restricting the user's movements and the flexibility of the textile carrier, Concept 2 scores well on ease of use and not being too hot to wear. Concept 1 is not that suitable for batch production of 25 due to the need of a knitting pattern that is rather expensive. Both concepts do not have IP54 at the moment.

Since both concepts score rather high, it is interesting to evaluate a potential combination of the two concepts:
The sewn conductive traces were shown to work as well for Concept 1, when prototyping the pockets. Instead of knitting, sewing could be used, improving the producibility for small batches. For mass production, knitting can still be considered in the future.
By using the pocket connection, the design allows for better integration of technology and more easy production, as electronics can be produced separately from the textile carrier. If we then combine this with the pogo pin connection, which looks cleaner and automatically outlines the contacts perfectly due to the magnets involved, we get the best of both worlds. As this connection is more robust, durable and easy to use than the conductive Velcro version.

Conclusions & design choice

The results of the Weighted Objectives score ***Concept 1, The knitted pockets, on 452 points*** and ***Concept 2, The sewn traces & pogo pins, on 487*** points in total. Since these numbers are rather close to each other, it is decided to create a ***hybrid version*** of the concepts for the final embodiment design. This hybrid will ***mainly consists of Concept 2***, however, ***the overmolded vibration motor module is replaced by the pocket design.*** This will allow for ***separate production*** of the ***electronics*** and the ***textile carrier*** due to the ***modularity of the design***. Moreover, Elitac Wearables will be able to design products that can ***easily take out/ replace/repair/re-use electronics*** in the future.

			CONCEPT 1 All about pockets		CONCEPT 2: Sewing with pogo pins	
Type	*Objective*	*Weight (1= Low & 5=High importance)*	*Score*	*Total*	*Score*	*Total*
Performance & implementation	R.1.1 Connect 7 vibration motors, of which 3 max at the same time.	4	6	24	8	32
Performance & Implementation	R.1.2 Vibration motor strength	4	7	28	8	32
	R.1.3 Implementation of other sensors	2	8	16	8	16
	R1.4 Robustness mechanical stresses	4	8	32	6	24
	R.1.5 Stretching of textile carrier	3	9	27	7	21
	R.1.7 Max. resistance 6.85 to 9.09 Ohms	4	8	32	9	36
	R.1.8 Max. voltage of 20V	4	8	32	8	36
Production & Processing	R2.1 Suited for batch production of 25 pieces	4	4	16	7	28
	R2.2. Uses widely available technology	3	7	21	8	24
Cost	R.3.1 Less than 2x expensive current design	3	5	15	7	21
Cleanability	R4.1 IP54	4	2	8	4	2
	R4.2 25 delicate washes	3	8	24	8	24
Ergonomics	R5.1 Not restrict users in movement	4	9	36	7	28
	R5.2 Technology integrated	4	7	28	8	32
	R.5.3 Aesthetics	3	7	21	8	24
	R. 5.4 Comfortable to wear	3	6	18	7	21
	R. 5.5 Not too hot to wear	2	7	14	9	18
	R.5.6 Ease of use	4	7	28	9	36
	R5.7 <43 degrees Celsius	4	8	32	8	32
	TOTAL			***452***		***487***

Table 11. Program of Requirements Weighted Objectives method as described in the Delft Design Guide used to evaluate the two concepts

15. General conclusions phase 3

Concepts

In phase 3, two concepts chosen by Elitac Wearables for further development were presented. The ***first concept*** discussed in this chapter was the ***Knitted pockets***, which uses knitted conductive yarn traces for data and power transportation. A tactor module with 4 metal contacts piercing through the casing is pressed against these conductive yarn traces, by placing them inside tight pockets.. Conductive Velcro is used as mechanical and electrical connection of the detachable main module.

The ***second concept*** discussed was the ***Sewn conductive yarns & pogo pins***. This concept also uses conductive yarn, but the conductive traces are then sewn on top of a stretchable textile carrier. A PCB is connected to these conductive yarns via sewing and the use of conductive glue. The main module is connected to the textile carrier by placing it on top of an overmolded landing spot including pogo pins

Prototypes

Both concepts were prototyped and the communication method implemented was PWM for quick-and-dirty testing.

Opportunities of concept 1 are the ***complete separate production of electronics and the textile carrier***. Also, important ***electronics*** can be ***easily replaced/repaired/re-used.*** Finally, the design ***enables removal of electronics*** before washing, when charging or changing from textile carrier.

Opportunities of concept 2 are the ***implementation of flexible casings***, which could improve the ergonomics of the technology. Moreover, the ***pogo pin connector*** makes it possible to attach and remove important electronics when necessary. Also, the ***stretchable conductive yarn traces*** have great potential to ***replace stiff and large cables*** currently used in products by Elitac Wearables.

Evaluation

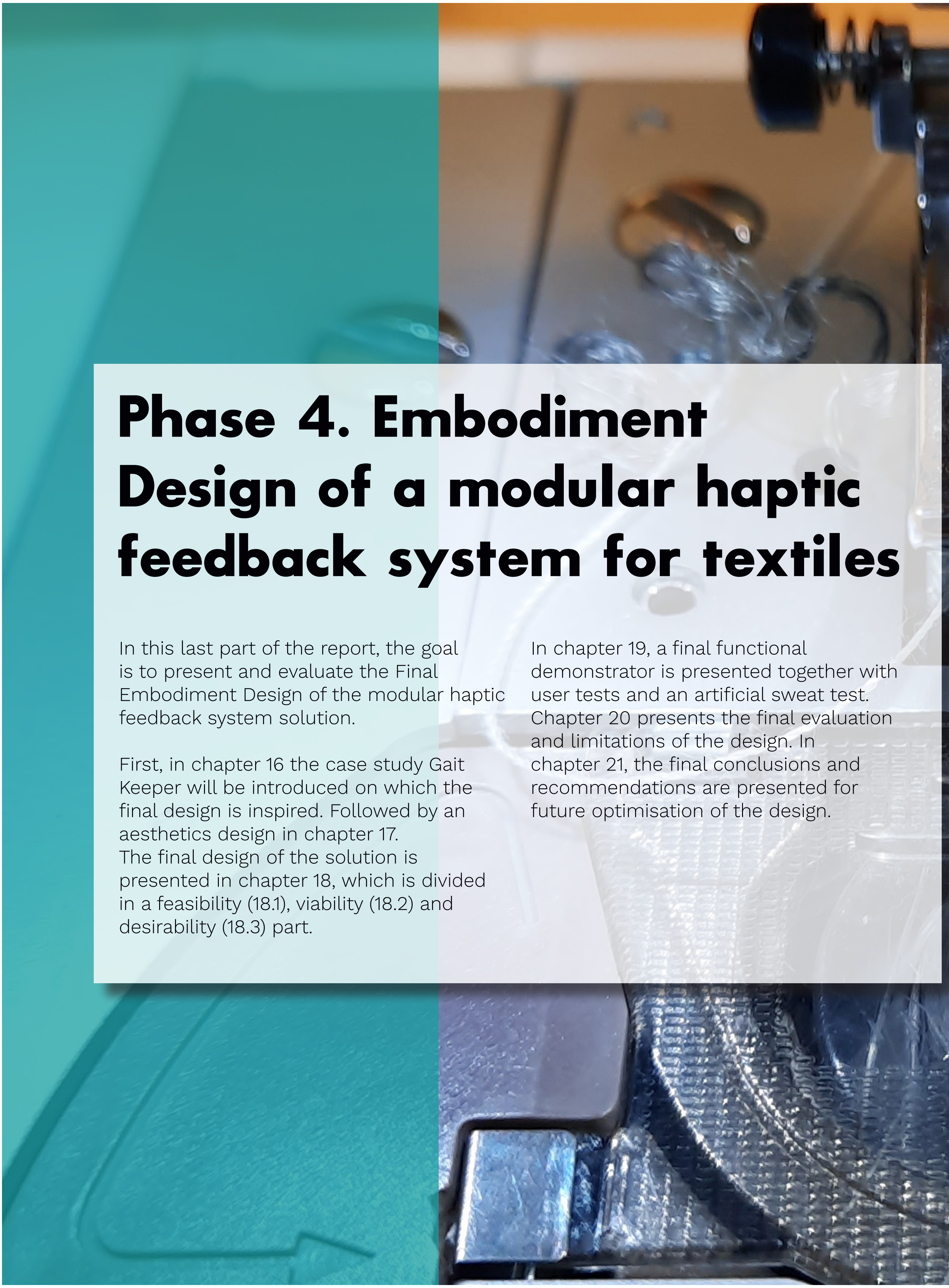
Multiple tests were performed to evaluate the concepts. First, the launderability of conductive yarns was tested. Both the ***Elektrisola and Bekaert Bekinox yarn proved suitable for washing at 30 degrees Celsius on a silk washing program***, as they maintained a stable resistance. The opposite was true for the AMANN Group Silver-tech yarn.

The ***Elektrisola yarn was most fragile to sew***, but with some practice ***reliable and extremly stretchable stitches*** could be created. The ***Bekaert Bekinox yarn was not that suited for sewing*** due to its thickness and roughness. No neat stitches could be created with this yarn.

The current vs. heat test showed that the tested ***Bekinox and Elektrisola yarns seem to stay far below the 43 degrees Celsius when 300 mA*** is supplied. In addition, both concepts seem reliable when it comes to data transport and the prototyped connection methods.

Concept choice

The weighted criteria assessment performed showed a small favour towards the second concept. However, as both concepts have good qualities, it was decided to create a ***hybrid version*** that combines the best of both worlds. This hybrid concept will mainly consist of concept 2. However, ***the overmolded vibration motor module is replaced by the pocket design.*** This will allow for more ***separate production*** of the ***electronics*** and the ***textile carrier*** due to the ***modularity of the design***. Also, electronics can be more easily ***taken out/replaced/repaired/re-used***

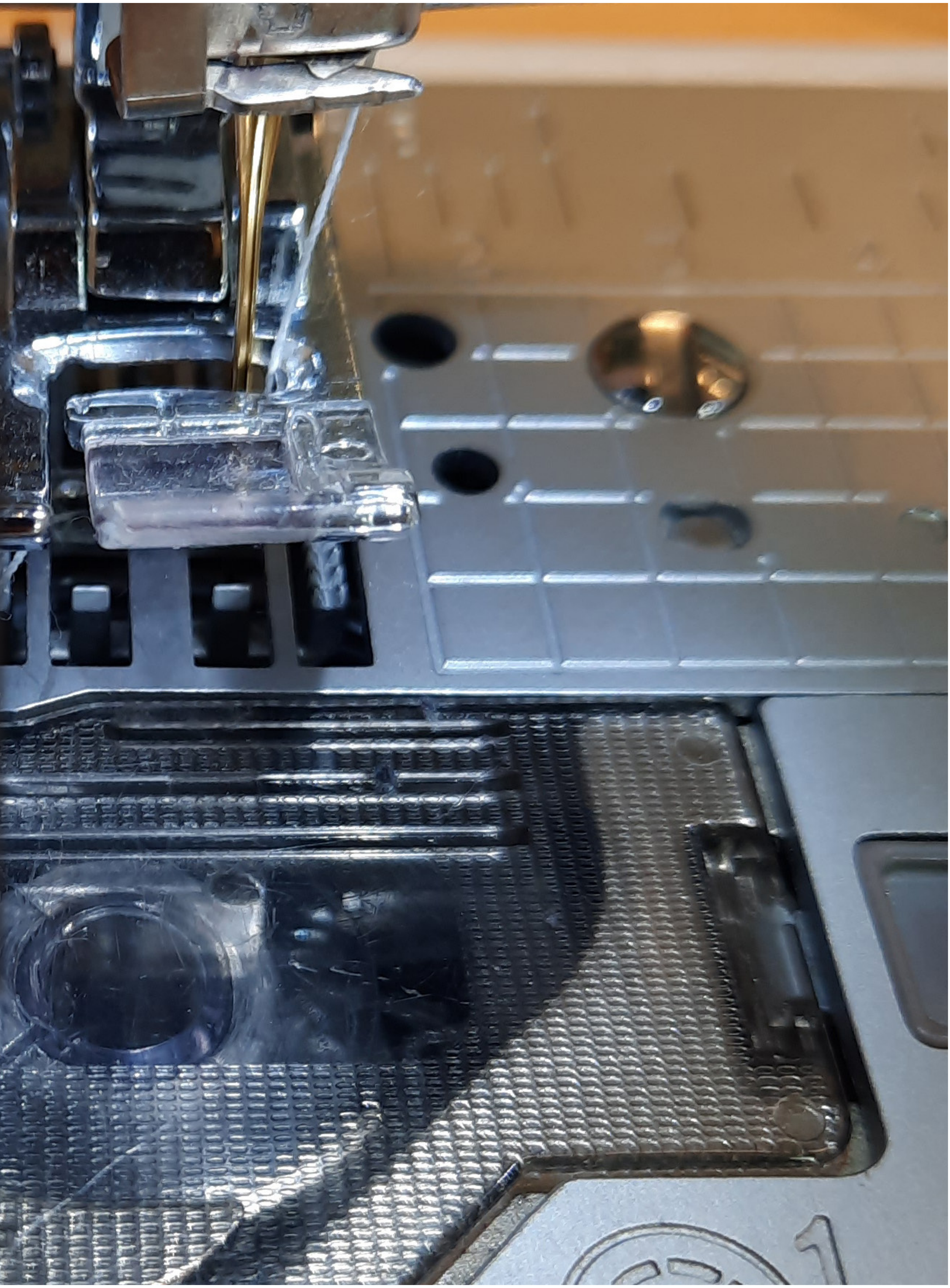


Phase 4. Embodiment Design of a modular haptic feedback system for textiles

In this last part of the report, the goal is to present and evaluate the Final Embodiment Design of the modular haptic feedback system solution.

First, in chapter 16 the case study Gait Keeper will be introduced on which the final design is inspired. Followed by an aesthetics design in chapter 17.
The final design of the solution is presented in chapter 18, which is divided in a feasibility (18.1), viability (18.2) and desirability (18.3) part.

In chapter 19, a final functional demonstrator is presented together with user tests and an artificial sweat test. Chapter 20 presents the final evaluation and limitations of the design. In chapter 21, the final conclusions and recommendations are presented for future optimisation of the design.



16. A case study: Gait Keeper

In this chapter a case study is presented for which the final embodiment design will be created. A brief introduction to the project will be given, followed by the technology involved.

The project

Recently Elitac Wearables has launched a Eurostars funded project called the Gait Keeper, in which they are to design a SMART haptic feedback wearable that improves the process of people learning to walk with a prosthetic leg. The goal of this project is to design a product that learns people how to walk with a prosthetic leg faster, easier and safer. The functionality of the product will be to provide the user with real-time haptic feedback on the use of their prosthetic leg, based on data collected from IMUs.

The partners involved in this project are: TNO, GaitUp and Ottobock. Elitac Wearables is responsible for the design and embodiment of the smart garment that provides haptic feedback to the prosthetic leg user, see the scope in Figure 183. The blue areas highlight what is inside the scope: The embodiment design of the feedback wearable. The data collection, processing and feedback is not part of the scope.

Technology involved

The sensors used in this project will be an IMU, also known as an Inertial Measurement Unit. This unit includes multiple sensors (accelerometers, gyroscope & magnetometer) with which the exact movements of a persons body can be determined.
Tactor modules will be integrated to provide the user with haptic feedback on their walking behaviour.
To power the product, a wearable power supply should be integrated

Translation to project

This project will be used as a case study to finalize and implement the technology designed, in a smart textile wearable.
However, it is to be kept in mind that the company is looking for a solution that is not only suitable for this case study, but also implementable in other products as well.
As mentioned by the creative director of Elitac Wearables:

> *"If the design can be implemented in about 80% of the projects, that would be great " - G. de Hoog (personal communication, 1 July, 2021)*

The type of wearable to be developed for the final product, is an upper body garment, as decided together with Elitac Wearables.
An upper body garment will be a good demonstrator of the possibilities and limitations of the designed technology. As it will show how well it can be worn, used and how comfortable it. Moreover, it will demonstrate that the design can cover larger distances when it comes to power & data transport, and how it reacts to the uneven stretching of a garment on a human body. It will also facilitate the implementation of larger and more complex constellations, thus giving more design freedom than a belt, which only facilitates point or line constellations.

To create a final smart prototype a single IMU will be implemented in the main control module. Quick-and-dirty prototyping will help to translate the data into real-time feedback on the movement recorded by the micro controller. Moreover, a basic 3.7 V battery will be implemented, or a small power bank, to provide the system with power.

Constellation

As it is unclear yet what specific feedback is necessary, a cross constellation of 5 tactors is designed on the back pattern of a vest, to allow for many different forms of feedback (see Figure 184). This constellation enables the use of virtual tactors in between the tactors.

Conclusions & Design choices

The ***Gait Keeper project*** will be used as a ***case study*** to continue development of the technology and create a final prototype.
An ***upper body garment*** will be designed to ***explore the ergonomics, ease of use and opportunities & limitations of the design.***

The ***main control module will include an IMU for data collection*** to mimic the data collected by IMU's on the prosthetic leg. Also a ***3.7V battery*** will be included, or an ***small external power bank***. ***Tactor modules*** will be implemented to provide the user with real-time feedback.

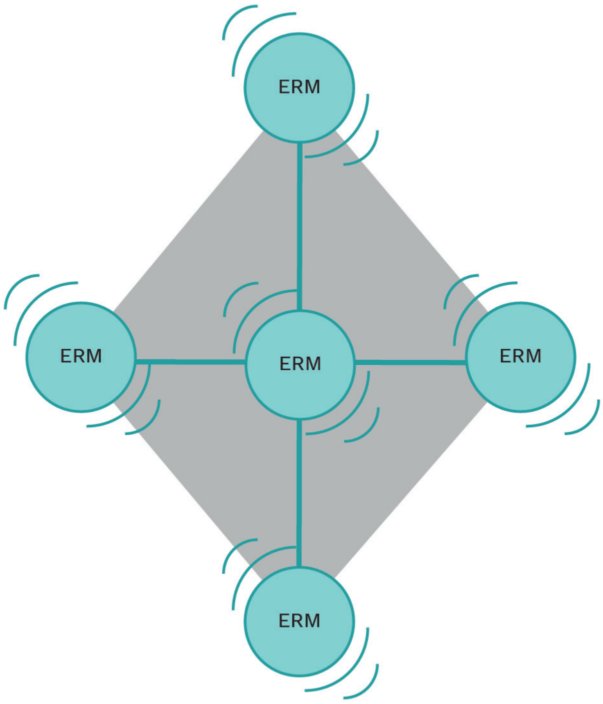


Figure 184. The constellation of the 5 tactors in a cross constellation, where the grey areas represents the possible location of the virtual tactor.

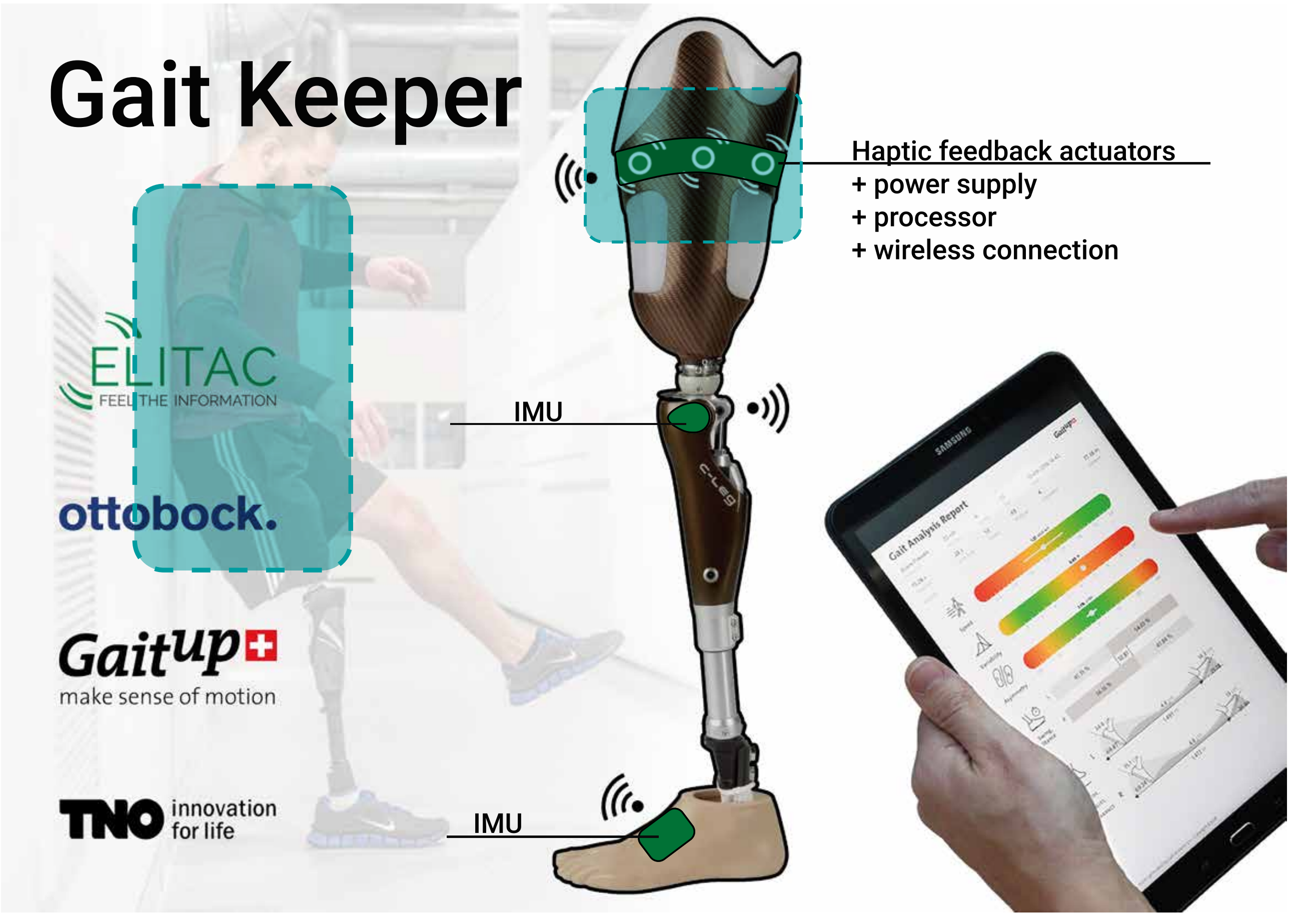


Figure 183. The Scope of the Gait Keeper project (de Hoog, 2021)

17. Aesthetics design

In this chapter the aesthetics and technology configuration of the final product is developed.

To ensure the product is aesthetically pleasing for future users, a mood board was created, see Figure 187 Products from Elitac Wearables, smart textile wearables on the market & sports wear were used for inspiration. This mix allows us to create a professional and appealing design, that is still in line with the company of Elitac.

Form language & materials

From the mood board it can be concluded that the use of breathable, stretchable textile carriers is common in the field of (smart) textile wearables. Often smooth surfaces and clean finishes are seen as well. Textures are small and smooth and a tight fit seems to be the uniform language.

Main control modules often have a landing spot with a cove, to enable easy, stable and correct placement. These components use smooth edges and fillets to make them more ergonomically and visual appealing. A matt to semi-matt finish is mainly used for both the textile carrier and the electronics.

Colours

The colours used in smart textile wearables are often black or dark grey, with an additional highlight colour. In sports the designs are more dynamic and colourful. The colour chord shown in Figure 185 is based on the logo of Elitac Wearables (Figure 186). Some in-between blue and greys are added to give more variety possibilities and inspire some of the fresh sports look in future designs.

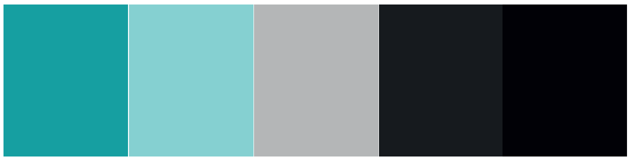


Figure 185. Colour chord for the final design in line with te colours used by Elitac Wearables

Figure 186. Logo Elitac Wearables (2021).

Figure 187. Mood board for aesthetical inspiration

Design

In Figures 188 & 189 some possible designs for an upper body garment can be found that were inspired by the mood board of Figure 187. The designs can either hide or show the electrical traces. According to the marketing manager of Elitac Wearables D. van Weert (personal communication, May 27th, 2021) showing off the electrical system is what people in general like. However, the physical appearance of a product will have to be tuned to each specific target group.

Conclusions & decisions

Stretchable and breathable materials should be used in the final design. Moreover, smooth edges and fillets for electronics are mainly used in smart material products. Also clean finishes and smooth matt surfaces can be found. The use of a cove to allow proper placement of electronics is also regularly used. The colours in the final product design will be based on Elitac Wearables' colours, but with a bit more variation to allow for more playful designs that also match the sports sector more. In the final design, The locations of the conductive sewn traces should be highlighted.

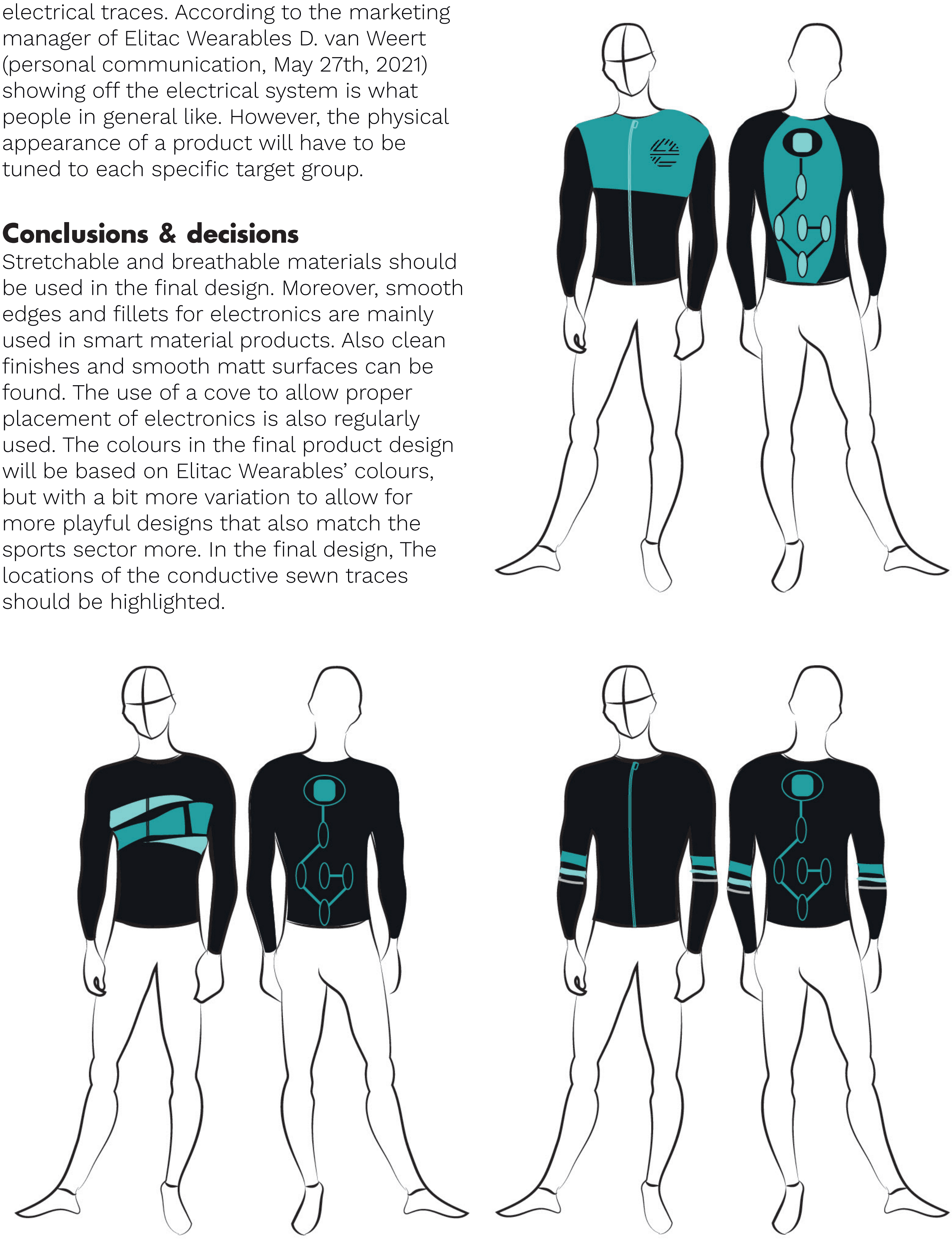


Figure 188. Aesthetics design sketches for possible inspiration for future projects.

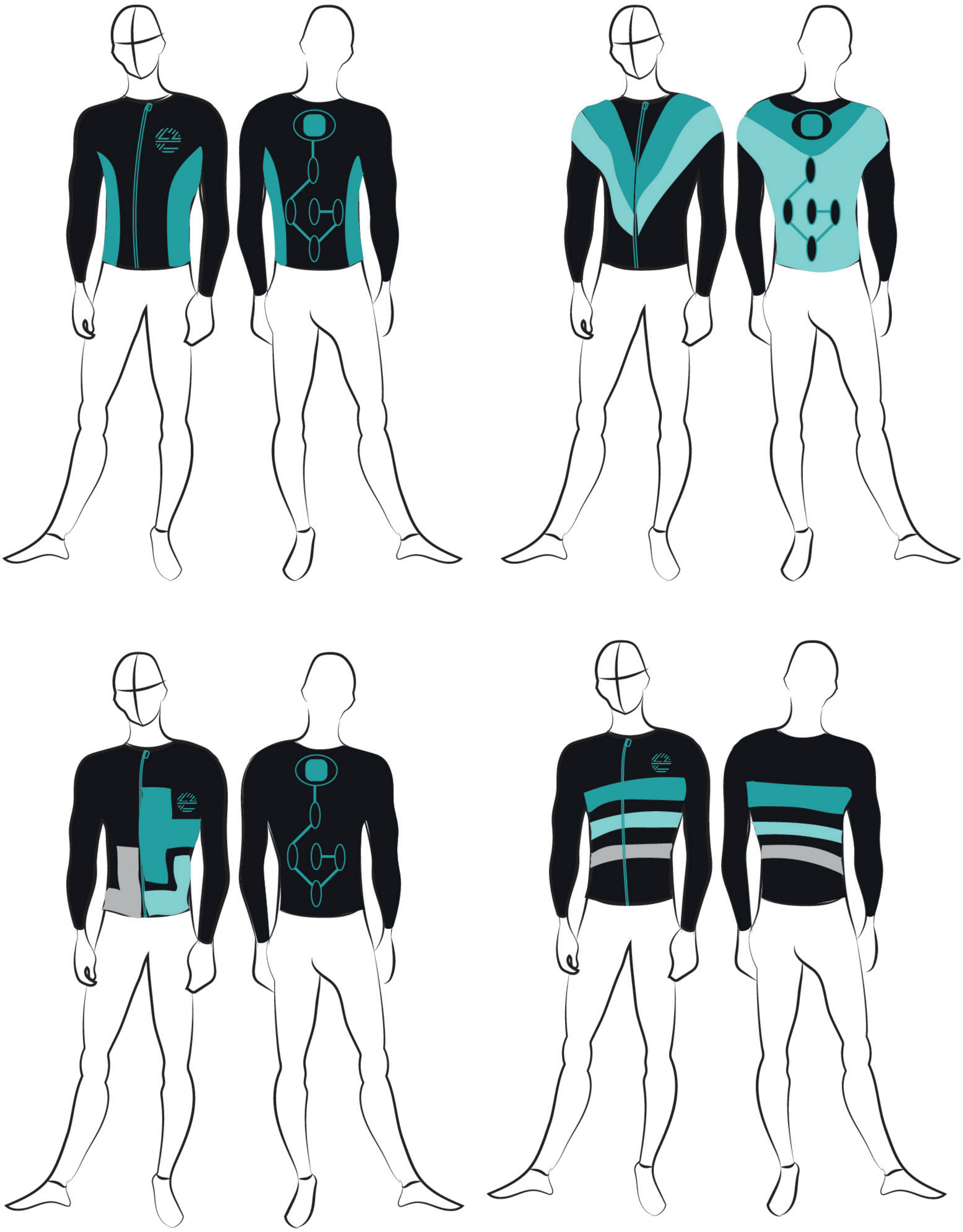


Figure 189. Aesthetics design sketches for possible inspiration for future projects.

18. Final design

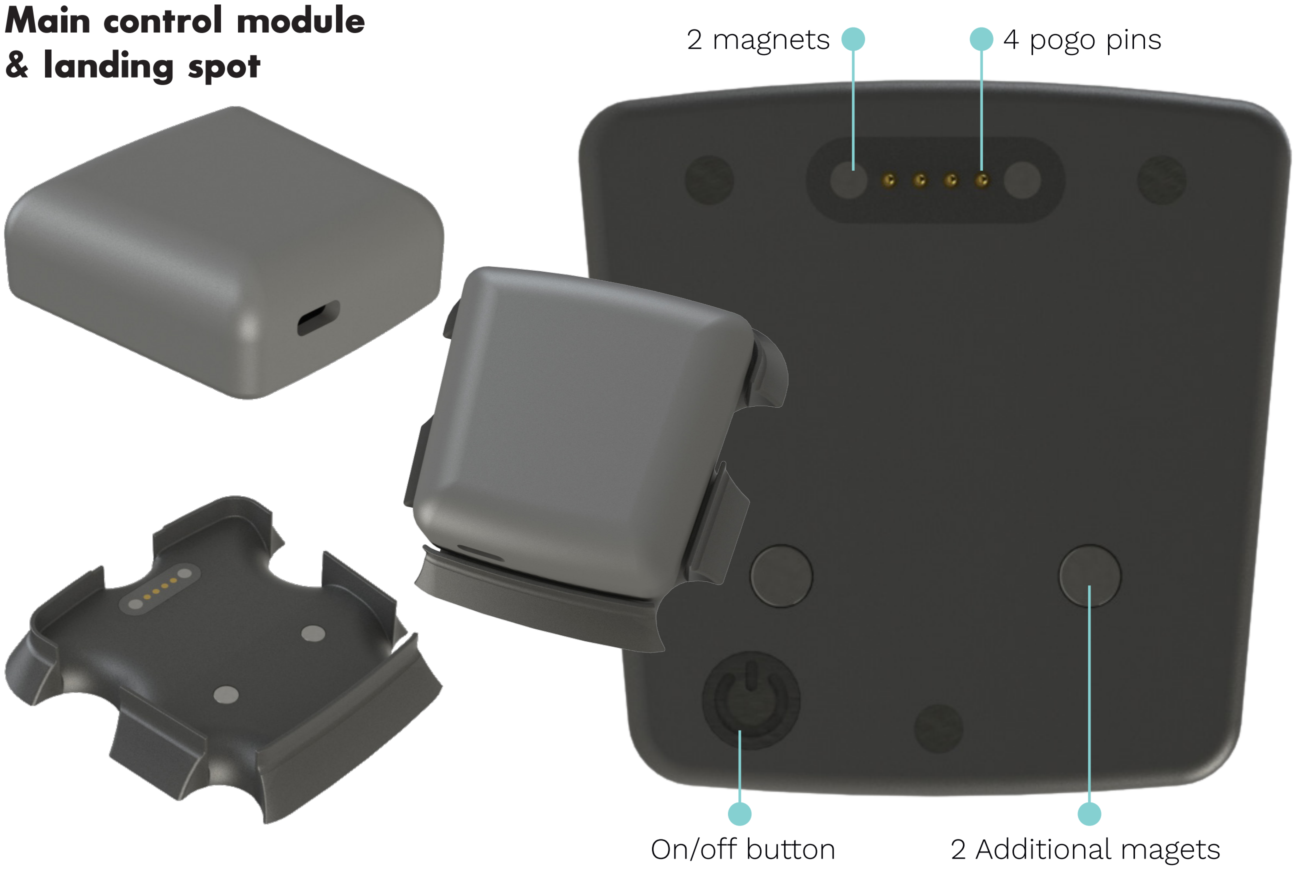
In this chapter the final embodiment design is presented. First a general product overview is given. Next, the technology used is elaborated by using the headers feasibility, viability and desirability.

The design presented in Figure 190 shows the implementation of the technology system in an upper body smart textile wearable. This design is specified for products that implement a small amount of tactors (up to 5) that can be taken out of the pockets by the user itself. In the desirability part, more application possibilities of the technology system will be discussed.

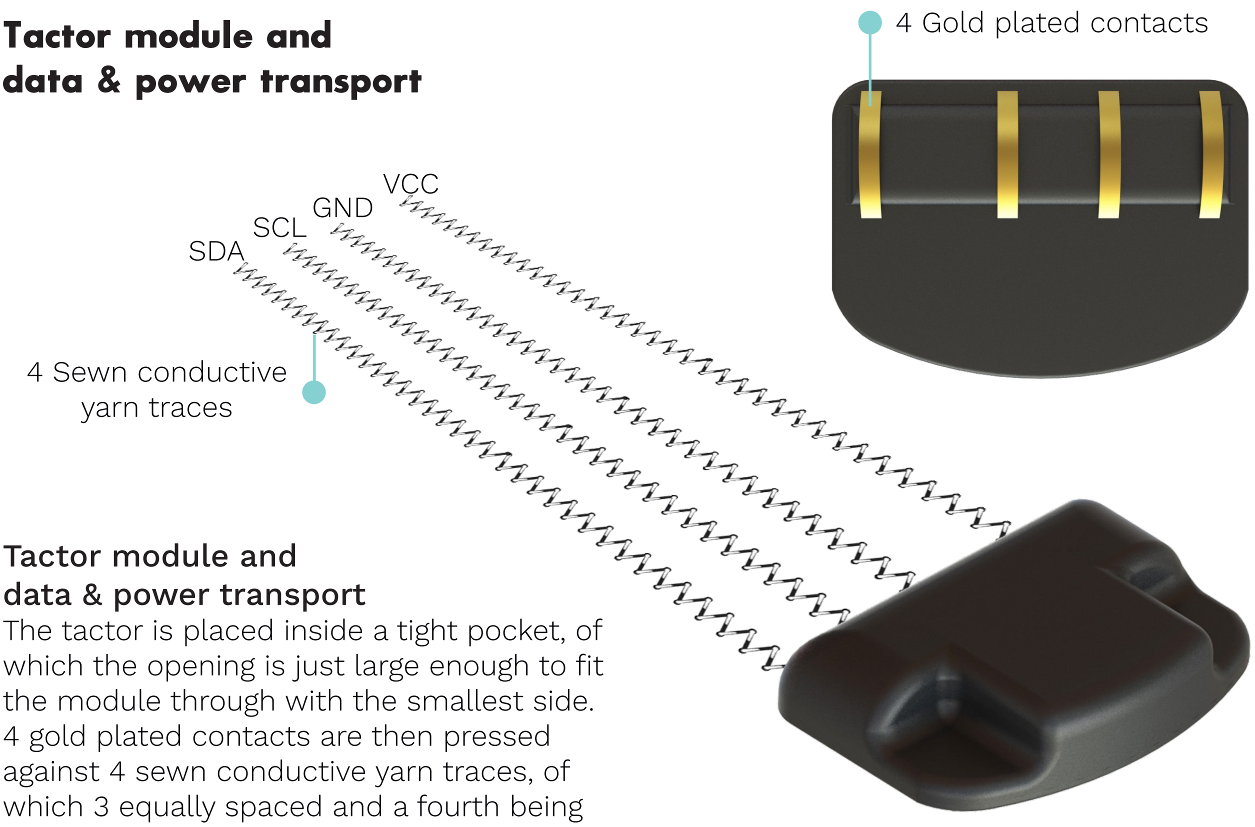
Main module casing & landings pot
The main module is connected through pogo pins and magnets to the landing spot. The walls of the landings pot will also provide additional support for the placement of the main module. The trapezium design facilitates one correct way of placing the modules.

Figure 190. Final embodiment design of a vest that facilitates the removal of 5 tactors due to the pockets

Main control module & landing spot



Tactor module and data & power transport



Tactor module and data & power transport

The tactor is placed inside a tight pocket, of which the opening is just large enough to fit the module through with the smallest side. 4 gold plated contacts are then pressed against 4 sewn conductive yarn traces, of which 3 equally spaced and a fourth being placed on a different distance. The general communication method facilitated is I^2C, which is currently used by Elitac Wearables. This methods requires a data (SDA), clock (SCL), positive (VCC) and ground (GND) line.

18.1 Feasibility

The feasibility of the design is discussed in this part of the report. Production and materials are explained, together with how the design builds on strengths and capabilities of Elitac Wearables.

General technology system

In Figure 191 a schematic overview of the technology system is given. It shows all the components integrated in the textile carrier. In total three textile layers are present: A robust base layer, a flexible layer for pockets and a Framis® layer, to attach the pockets and protect the conductive yarn traces. The base layer contains the sewn conductive yarn traces and the landing spot will be overmolded on this layer as well. The Framis® layer glues the base and flexible layers together to form pockets for the tactor modules. Also, strokes of Framis® are used to protect the conductive yarn traces from mechanical forces. A small opening is left at the top of the pockets, through which the tactor modules can be placed and removed by the user if desired.

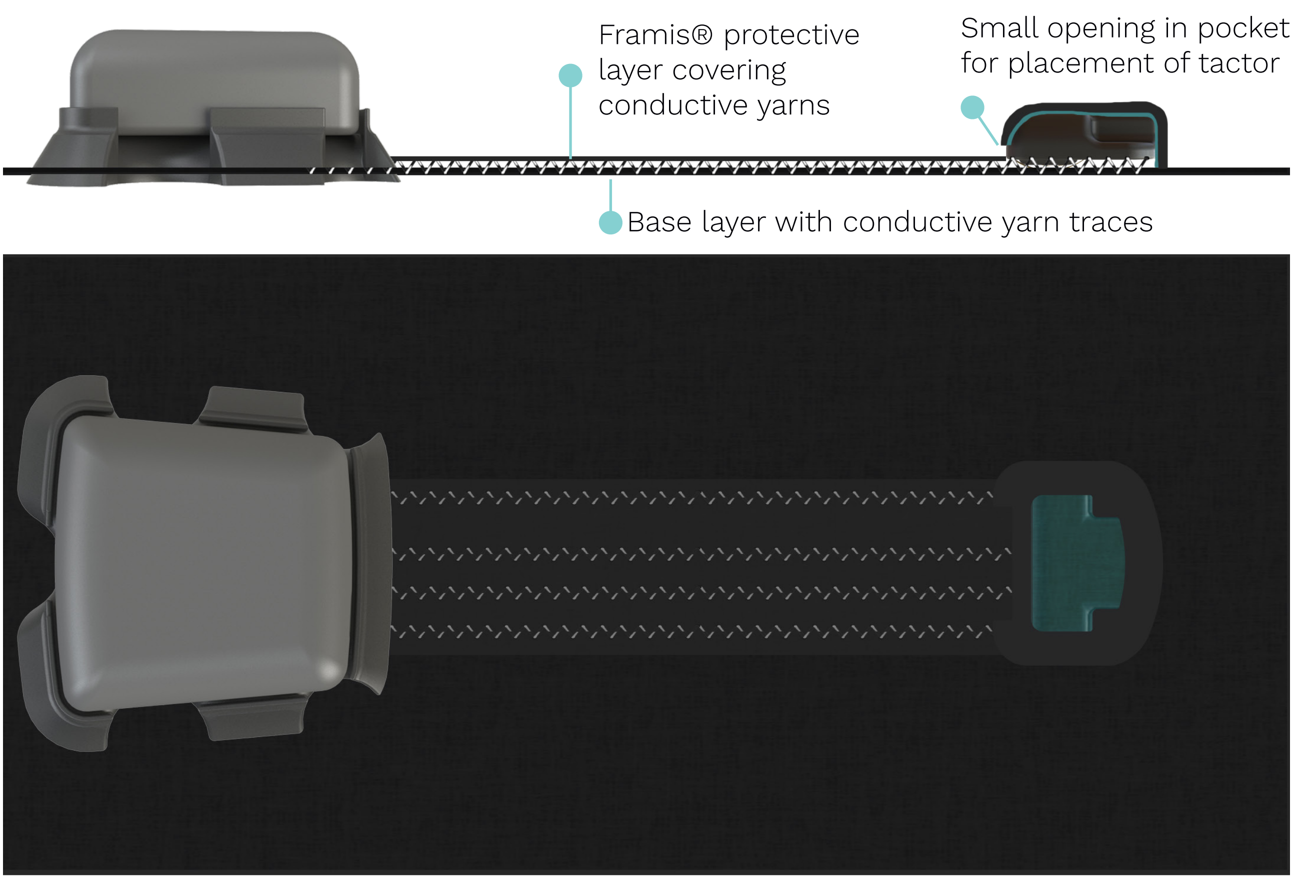


Figure 191. General system in top and side view that shows the connection of all component and the textile carrier. The T-shape of the pocket is a usecue for correct placement of the tactor module.

The modules

A. The Tactor

An exploded view of the tactor module is shown in Figure 192. It consists of a small T-shaped waterproof casing that encloses the following electronics: A PCB with a micro controller to change the address of each tactor module, a motor driver and an ERM cylinder motor. Moreover, it has 4 metal gold plated strips, that are pressed against the power & data transport conductive traces, to ensure the electrical connection. This connection is facilitated by a tight textile pocket that keeps the module in place and by the slightly sticking out gold plated strips that are always pressed against the silver conductive yarn traces.

Materials & Production

An overmold of Technomelt PA 646 is used to encapsulate the electronics in a waterproof casing. This material is easily moldable, hard, strong and has an excellent moisture and environmental resistance (Overmold, n.d.). As metal does not attach properly to the PA overmold material, additional waterproof glue has to be placed at the entrance points to make the casing conform IP64. 4 gold plated contact strips are implemented, as gold is known to be highly conductive, corrosion resistant and does not react with other materials since it is a precious metal. During production of this module, first the top part of the casing is overmolded, followed by the placement of the metal strips that are pushed through the holes and folded inwards, see cross section view in Figure 192. Next, the driver is fixated with double-sided tape and the SDA, SCL, VCC and GND lines are soldered to the 4 strips. The ERM motor is then also fixated in place with tape and the bottom part of the overmold is done on top of the first, encapsulating all the electronics.
The overall dimensions of the module can be found in Figure 193.

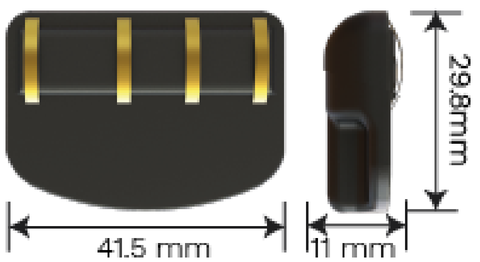


Figure 193. Exploded view of the tactor module

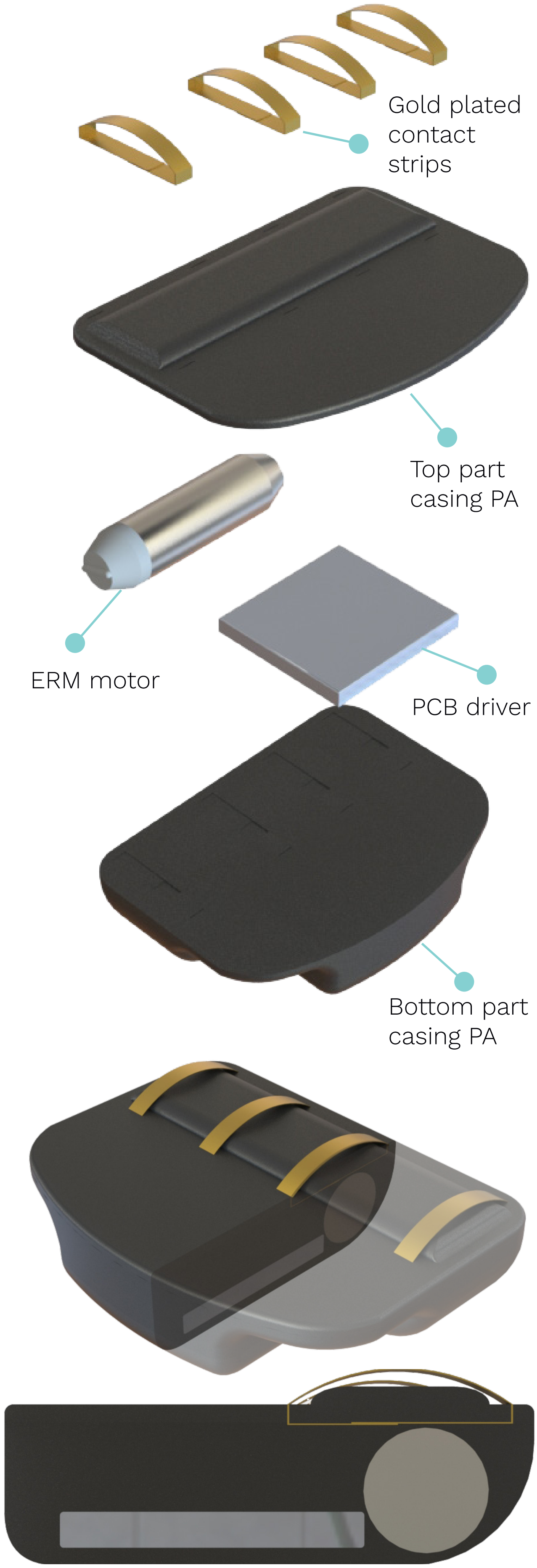


Figure 192. Exploded view and cross section of the tactor module

B. Power and data transport

The power and data transport lines are created through the sewing of conductive yarns. These traces will have a width of 6mm and a step size of 2mm, with an equal spacing of 4mm in between 3 of the traces. The fourth trace will have a distance of 7mm, to ensure that the tactors will only make contact in one possible way with all 4 wires, see Figure 194. To check if the spacing is correct during sewing, a mock-up of a tactor module was created, see Figure 195.

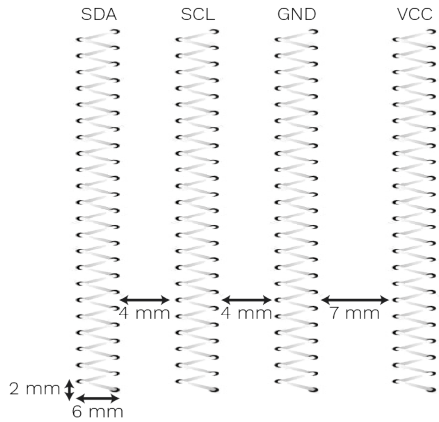


Figure 194. Production division of yarns

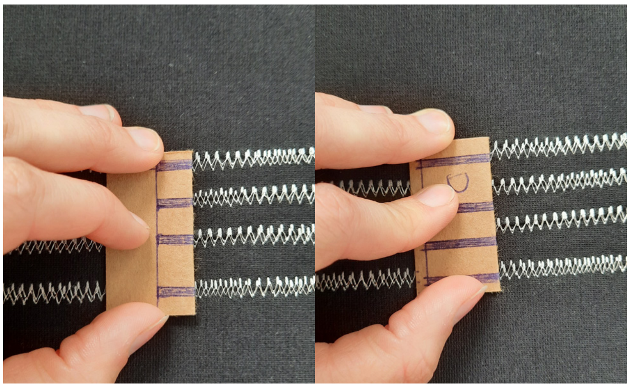


Figure 195. Correct placement (left), when rotated 180 degrees 2 lines make no contact (right)

Production & Materials

The yarn used is Elektrisola 3004021L 0.04mm consisting of a pure copper core which is silver coated. Silver is also considered to be a precious metal, however it does corrode in contrast to gold. Though, the conductivity of corroded silver is almost equal to non-corroded silver. The thickness of the yarn makes it fragile, however, sewing multiple lines over one another in a zigzag stretch stitch and protecting it with an additional Framis® layer, makes it durable and robust in design. The Framis® layer will also help prevent over stretching of the stitches. The launderability of the yarns was found to be excellent when it comes to maintaining a constant resistance of about 2.1 Ohms/meter.

The conductive yarn is used as Bobbin thread and a 100% polyester yarn of Gütermann is advised to be used as top thread. The sewing machine settings should use high top tensions as learned in chapter 13.2/13.3 and Appendix A13. To compensate for these high tensions and add extra stiffness to the textile carrier, Solufix Vlieseline is placed on top of the textile carrier before sewing, see Figure 196.


Figure 196. Elektrisola 3004201L 0.04mm sewn (left) and Solufix taped to top side (right)

In order to improve the production process, 1:1 scale molds of the pattern pieces will be made from cardboard with 1mm cut outs for the conductive traces. Tailors chalk can be used to draw the sewing line guides directly on the fabric with correct spacing. See figure 197 for an example.

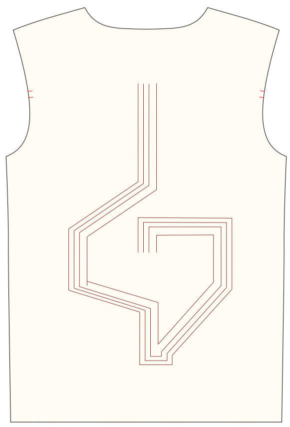


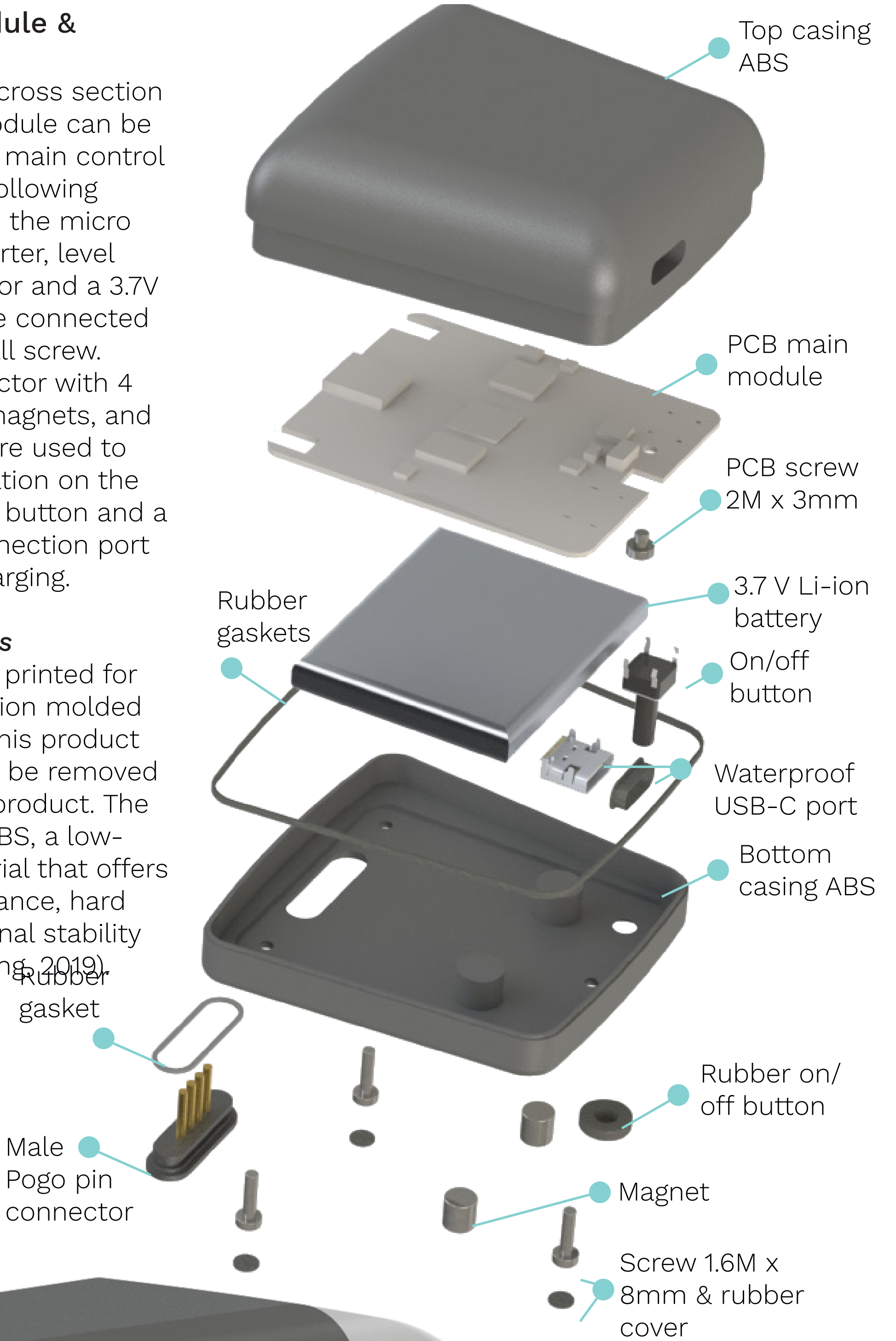
Figure 197. Special cardboard molds to chalk on conductive yarn traces in equal spacing.

C. Main control module & landings pot

An exploded view and cross section of the main control module can be seen in Figure 198. The main control module encloses the following electronics: A PCB with the micro controller, boost converter, level converter, an IMU sensor and a 3.7V battery. The PCB will be connected to the casing via a small screw. Also, a pogo pin connector with 4 contact points and 2 magnets, and 2 additional magnets are used to ensure mechanical fixation on the landing spot. An on/off button and a waterproof USB-C connection port is implemented for charging.

Production & materials

The casing is either 3D printed for small batches or injection molded for mass production. This product will have IP54, as it will be removed before laundering the product. The material will be matt ABS, a low-cost engineering material that offers a good chemical resistance, hard surfaces and dimensional stability (Dielectric Manufacturing, 2019). Silicon rubber gaskets will be used to close-off possible entry points of water and dust. A waterproof USB-C port is implemented just as in the newest smart phones.



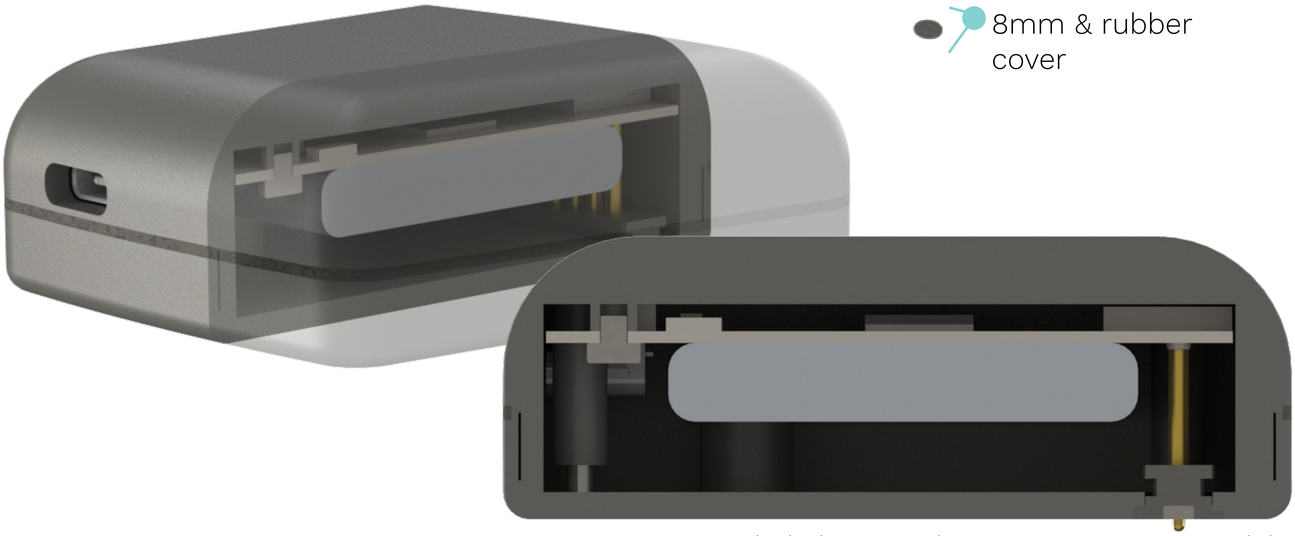


Figure 198. Exploded view and cross section main module

Figure 199 shows an exploded view and cross section of the landing spot, which consists of two components: the Technomelt PA 646 overmold and a PCB with the female pogo pin connector and 4 header pins.
First the PCB is connected to the electrical circuit by placing it underneath conductive traces and glueing it, see paragraph Production Steps. Next,it is overmolded from both sides for fixation and protection of water (as the overmold material will go through the fabric)

In Figure 200 the general measurements can be found of the main module and the landing spot together.

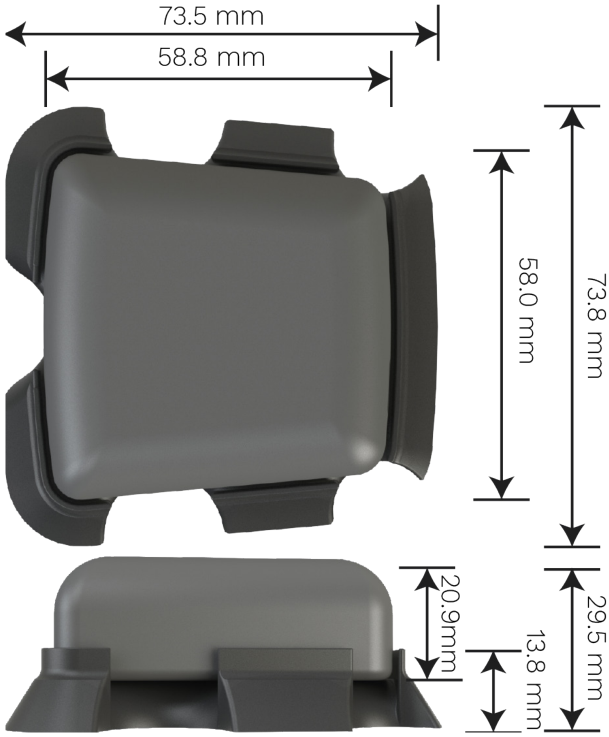
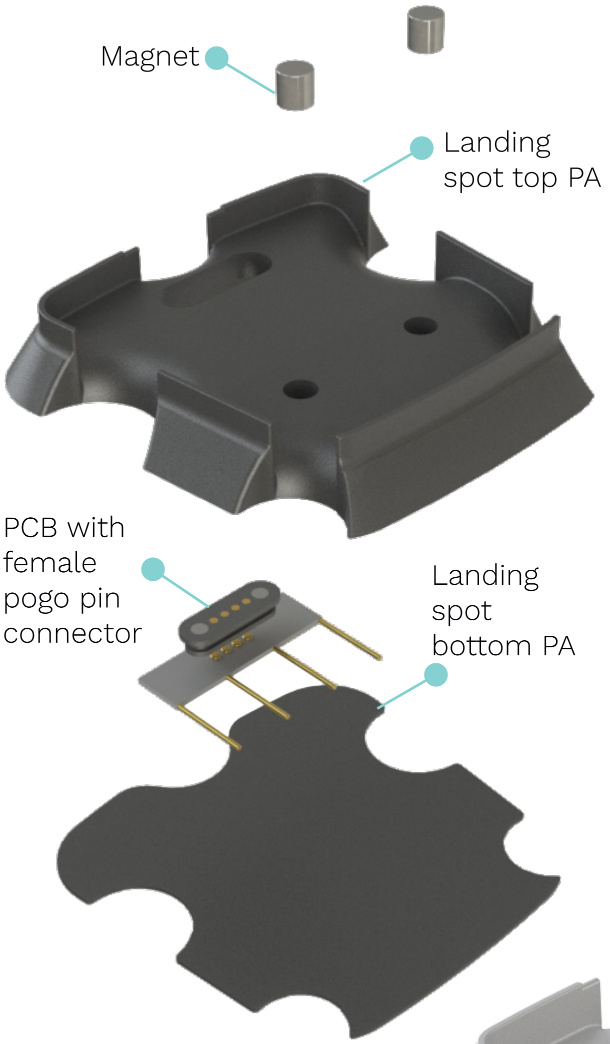


Figure 200. Overall measurements of main module and landing spot



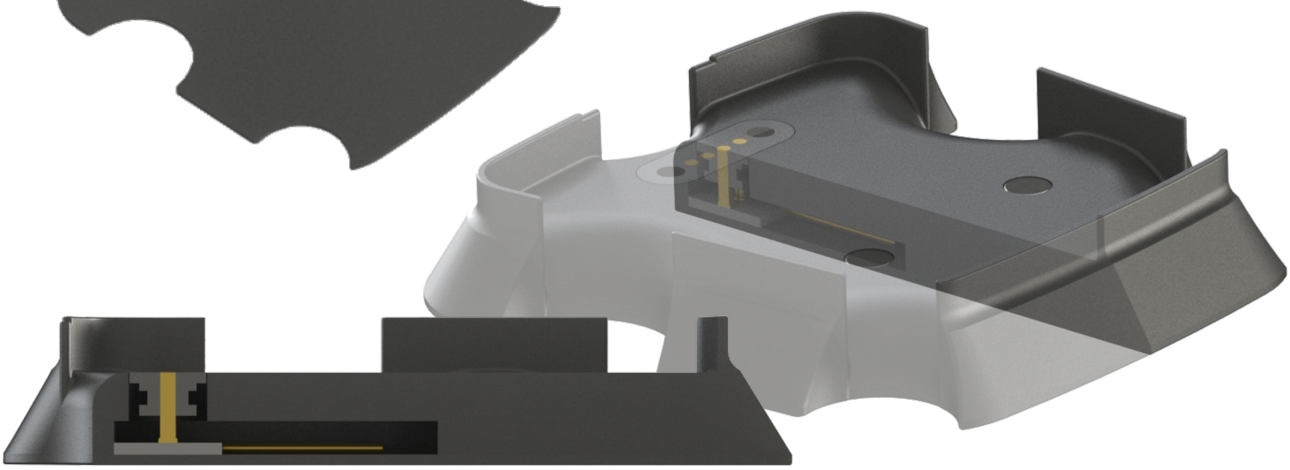


Figure 199. Exploded view and cross section landing spot

D. Textile carrier

The textile carrier is based on a male sewing pattern made of multiple layers, as shown in Figure 201. The first layer is the base layer, made of Sensitive® Bonded fabric consisting of 72% & microfibre PA & 28% EA (LYCRA®). A layer of Solufix Vlieseline will be attached to the wrong side of the fabric, which will avoid tunnelling (as a result of too high thread tensions) when sewing the conductive yarn traces. On top of these conductive yarn traces, Framis® material will be heat pressed for protection of mechanical forces and over stretching. This material has a TPU glue layer attached to it, and the same material will be used glue the pockets of the tactor modules to the base layer. The pockets consist of a Sensitive® Power Evo (74% & microfibre PA & 26% EA) coloured layer and a Framis® cut out, see Figure 202. These materials are heat pressed on top of the base layer with conductive yarns. The top part of the pocket will remain open for placement of the tactor. The pockets will be colour coded or a number will be added that overlaps with the tactor module, to ensure placement of the tactors in the right order for I²C communication. See Appendix A19 for the the pattern pieces of the back panel.

Figure 202. The two pocket layers Sensitive® Power Evo (blue) and Framis®® (black)

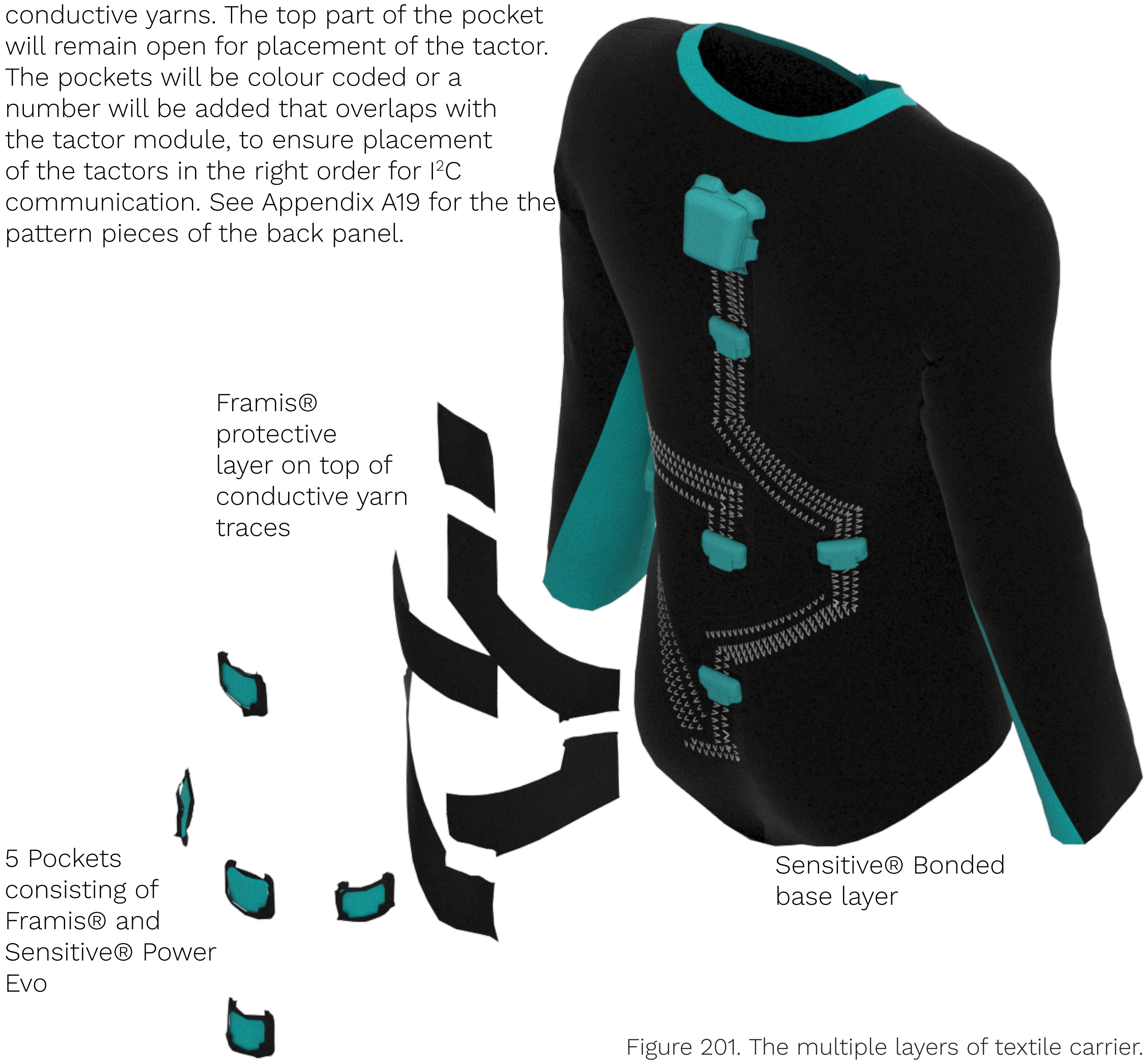


Figure 201. The multiple layers of textile carrier.

Production steps

The general production steps necessary to produce a smart textile wearable with the designed technology system implemented in explained in Figure 203.

Playing on the strengths of Elitac

The electronics integrated in the design were already developed and produced by Elitac Wearables. Furthermore, the production processes such as 3D printing, overmolding, sewing, laser cutting and soldering are all well-known to Elitac Wearables. Machinery to perform these processes are already in-house. Moreover, Elitac has a wide range of expertise, from hardware & software design to textile and research & development. All this information combined enables in-house development and production of products that integrate the modular technology developed during this thesis. At least small batches should be possible and for larger quantities new partnerships for injection molding and textile production should be established. Luckily, one of the strengths of Elitac is to find new partnerships for the development of products.

General production steps

1. Manufacture the Main module & Tactor module as shown previously in the images in this paragraph. The overmolding of the tactors is explained in chapter 19. Program each tactor with their own address

2. Decide on the total number of tactors and their locations on a 2D pattern pieces on the computer (CLO3D or Adobe Illustrator).

3. Cut out cardboard molds on where the conductive yarn traces will be located by laser cutting the 2D patterns as explained in Figure 197.

4. Cut out patterns pieces from the Sensitive® fabrics & Solufix by also using the laser cutting machine.

5. Tape the Solufix to the inside of the base fabric pattern piece where the conductive traces will be located.

6. Place cardboard mold over pattern piece and use tailors chalk to draw the lines on the pattern piece.

7. Sew conductive traces with the Solufix facing upwards and check correct distancing and connection with functioning tactor module.

8. Rinse off the Solufix material with cold water by hand and hang pattern piece to air dry.

9. Slide the landing spot PCB including pogo pin female connector with the header pins underneath the sewn conductive traces. Add drops of conductive glue at the connection points. Use double-sided tape for temporary fixation of the PCB if necessary.

9. Overmold the thin layer of the landing spot on the wrong side of the fabric at the height of the PCB.

10. Overmold the landing spot on the good side of the fabric over the PCB including pogo pin female connector.

11. Heat press a unique number to each pocket top layer.

12. Heat press the pocket top layers to the base pattern piece in the correct order.

13. Sew the rest of the pattern pieces together and finish it off with all the trims included.

14. Place the tactors inside the pockets with the corresponding numbers.

15. Place main module to test the product and tactors.

Figure 203. General production scheme

18.2 Viability

The viability of a product talks about the profitability and sustainable business models. In this part of the report, advantages of the designed technology compared to the current business models of Elitac and their future goals are discussed. Moreover, the scalability of the design is briefly elaborated together with critical materials or components. Finally, a cost analysis will elaborated of the final prototype.

Business models

From B2B towards B2C

Most product sales of Elitac Wearables are business to business (B2B) or high-end business to consumer (B2C), while offering technical assistance and repair. Expensive electronics are often completely embedded, making re-use and repair of components time intensive, costly and often nearly impossible. Together with the short life-times of smart textile products found in the consumer market (e.g.. 25 laundry cycles for the Nadi X), prices are often too high to enter B2C markets. With the mission of Elitac Wearables in mind of helping at least 1 million people by 2035, selling B2C is essential.

The new technology design helps facilitate B2C sales, as easy replacement and re-use of the expensive electronics is enabled due to the modular design and production process. Moreover, if the textile carrier is worn-out, the old electronics can be transferred to a new version, either by the user or Elitac Wearables. Keeping the value of the expensive electronics alive longer in a way that both benefits the company and the user in terms of money and resources. As users now pay one time for all components, but only a small amount over time for the replacement of the textile carrier.

Product service design & subscription based business model

The design of products can be created in such a way, that the user can replace the textile carrier regularly as this will naturally wear over time. By transferring of the old electronics to a new textile carrier can be part of a product-service system of Elitac Wearables. The company could even start thinking about new business models in which consumers pay a monthly fee, and in return always have a working product including maintenance.

Scalability

Small batches & mass production

Small batch production of products up to 100 pieces is something Elitac Wearables is capable of. The required production processes used such as sewing, 3D printing, overmolding PA , soldering and laser cutting are all in-house at Elitac Wearables. However, for mass production, investment costs will increase, as casing parts should now be injection molded. A company that can help facilitate the step to mass production and injection molding is for example Pezy Group. This is a Dutch based company that can injection mold parts up to 5000 pieces per batch. The textile carrier could also be fabricated through knitting during mass production. A knit pattern can directly integrate the conductive yarns, removing the need of time consuming sewing. This could be developed by a professional knitting company such as ByBorre or Myant, which are already known to Elitac Wearables. Other processing techniques of conductive yarns such as weaving or embroidery might also be interesting. See Appendix A20 for more information on the different process methods of conductive yarns.

Availability materials

The availability of materials on the market is important to analyse for the viability of a product. We consider materials or components to be critical when: There is only one company that can supply this material/component, and there are no good alternatives available. When looking at the design, the following materials/components could become critical for production:

1. Electronics hardware.

In 2021 a global shortage in computer chips has delayed the production and availability of many hardware components according to Sweney (2021). Such a large crisis is something small companies have little to no influence on. However, Elitac Wearables could reduce the risk by minimizing the amount of electronics used, and by choosing components that can be easily substituted by alternatives available on the market Also, investing in the design of textile based sensors and actuators can help reduce this risk.

2. Gold plated metal contacts

Gold is an expensive an valuable metal. A good alternative material would be silver or copper, as both materials are cheaper and also highly conductive. Silver would be the best alternative, as copper corrodes faster and loses more conductivity. (Helmenstine, 2019).

3. Low resistance conductive yarns

Low resistance sewable conductive yarns are hard to find. Alternatives next to Elektrisola yarns could be the ones produced by Syscom Advanced materials. In particular the Liberator 40 or Amberstrand 166 that are twisted 4.5 times/inch have a low enough resistance and can still be used in a sewing machine. Though optimisation of thread tensions and the use of a suitable top thread should be investigated further. Also the launderability should be tested for these materials as well.
A positive thing to note is the quick development and growth of the conductive yarns market. As the smart textile wearables market trend is increasing, so does the supply and demand for these materials increase.

Cost analysis

A cost analysis for the materials used in the ***final prototype*** of the technology design was made, see Appendix A21 for the detailed overview. The total costs were found to be ***109.76 Euros excluding VAT.*** This design includes one main control module and 3 tactors. See Table 12 for a summary of all the costs..

The 3D printed landing spot and the implemented BN0055 compass are already good for a total of 57.73 Euros of the 110.14 in total. The costs of each ***tactor module is 9.02 Euros*** and for the ***main control module without the BN055*** this is ***16.79 Euros.***

Due to time limitations, the number of man hours invested in the production was not taken into account during this cost analysis. Also, because these numbers would not be a good representation for a more optimised design fit for large batch production or even mass production. When the technology design is optimised for market implementation and large batch production, a new more accurate cost calculation should be made. Taking into account bulk prices and the number of man hours invested in production as well.

Component	***Costs in Euros excl. VAT***
Total costs complete prototype incl. complete main control module, 3 tactors and 3D printed landing spot	109.76
Tactor module	9.02
Textile carrier	8.34
Main module incl. BNO055	53.11
Main module excl. BNO055	16.79
Landing spot 3D printed	21.41
BNO055	36.32
Total costs incl. 3 tactor modules, main module, without BNO055 & landing spot overmolded instead of 3D printed	54.70

Table 12. Summary of cost analysis final prototype

18.3 Desirability

The desirability of a product analysis the need for the product and the desired aspects for both the company and the user. In this part of the report the different design possibilities of the haptic feedback system are elaborated. Moreover, the different steps of use are given to show the interaction of the technology system with the user.

As explained in the viability part, the modular design allows for easy repair/replacement/re-use of the expensive electrical parts. This is both cheaper and more sustainable than designs that irreversible fixate electronics inside the textile carrier.

A tool for the design of smart textile haptic feedback wearables

The haptic feedback system is designed to be used as a tool to develop smart textile wearables. The company can decide on the type of garment, the number of tactors and their locations, and then use a digital 2D pattern to draw the 4 conductive sewing lines and placement of pockets for production.

However, each specific project will have its own requirements when it comes to the type of garment, the number of tactors and the placement of these tactors. The fixation or ability of removing the tactors plays a large role in de design. There are two potential scenarios: ***Removable tactors and fixed tactors***

Removable tactors

Removing tactors could be desirable if for example industrial washing programs are required, or the user wants to use the technology in another textile carrier while the first one is dirty. For a small number of tactors, say up to 5, it is still okay to take out the modules individually. Numbering the modules and helping the user place them correctly is important for the I2C system. The pocket system can use colour coding or numbers to ensure proper placement.

For larger number of tactors (more than 5), it is desired to take out the tactors all at once if required. To enable this, an inner-outer construction of the textile carrier can be used. The inner construction can be detached and taken out, and the outer layers provide protection from dirt and mechanical stresses. Products of Elitac Wearables that already apply this type of structure are the NeuroShirt and Mission Navigation Belt. See Appendix A3 for a more detailed explanation of the NeuroShirt and Mission Navigation Belt and their construction.

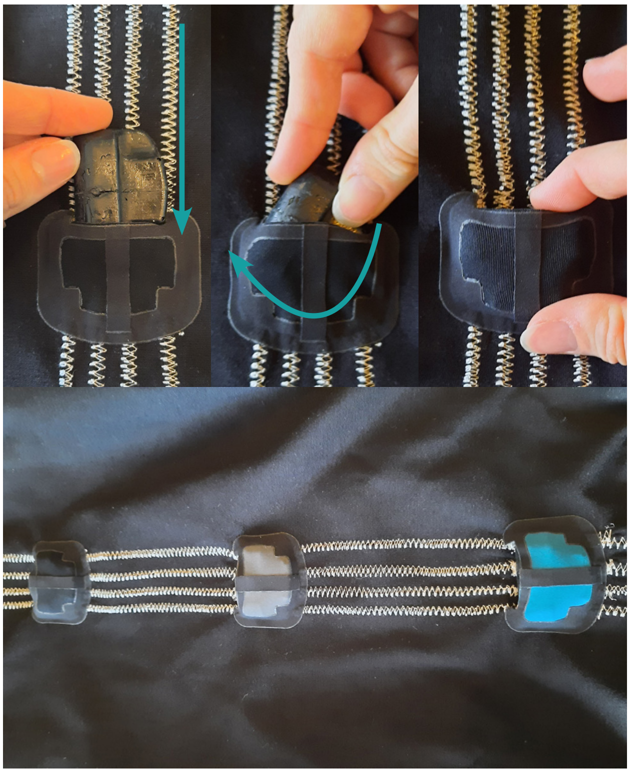
Fixated tactors

It can also be favourable not to take out the modules to improve ease of use. Waterproof electronics and quick drying materials are preferable here for multiple uses in a short period of time. The original design system can be used, where the main module is removed and the waterproof tactor casings are used. The textile carrier can also remain the same, but now the openings of the pockets can be closed-off in a way that would still facilitate easy repair & re-use of electronics. The pockets can be heat pressed as usual, only the Framis® layer opening will be enlarged, so it can seal the pocket completely. The complete sealing can be prevented by placing a piece of backing paper in the opening during the first heat press action. Then the tactor module is placed inside the pocket, and finally, the pocket closed by ironing shut the last piece of Framis® material that was left open before.

Steps of use

In Figure 204 the different steps of the use of a product designed with the modular haptic feedback system are shown. In the scenario where the tactors remain fixated, steps 2 and 9 do not need to take place.

1. Charge main module if necessary via the USB-C port



2. Place the tactor vertical in front of the opening of the pocket, push it in and rotate 90 degrees. Place the tactors in the correct order.

3. Turn on main module and pair with external system if required

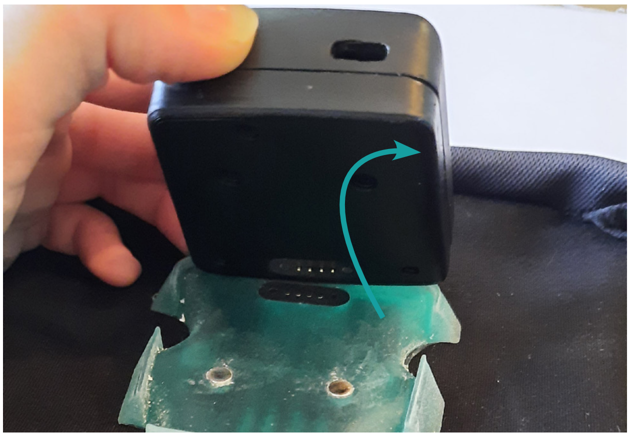
4. Place main module on landing spot

5. Put on garment

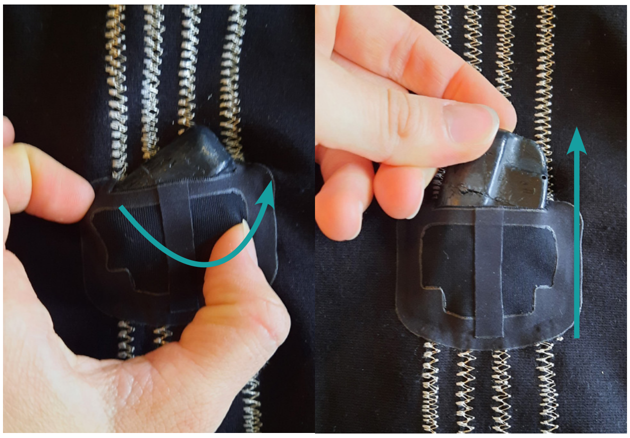
6. Perform acivity X (PNGKit, n.d.)

Figure 204. Steps of use visual

7. Remove garment



8. Remove main module from landingspot



9. Remove tactor modules

10. Place the textile carrier in a laundry bag, wash it on a delicate laundry setting and hang to air dry

Conclusions

The designed ***modular technology system*** in this chapter can be used as ***a tool to design smart textile haptic feedback wearables.*** The number of tactors and the placement can be adjusted per project. Furthermore, the modular design can also help ***facilitate the implementation of other sensors and actuators.***

Feasibility

In terms of ***feasibility, small batch production*** is facilitated by making use of ***in-house production technologies*** of Elitac Wearables. Also, already ***known companies*** to Elitac Wearables are advised as ***partners*** for taking the next step ***towards mass production***.

Viability

In the ***viability*** part new business models are discussed, advising a ***shift from B2B towards more B2C*** to help realise the goal of Elitac Wearables to help 1 million people by 2035. This can be achieved by changing the business model towards ***product service design*** or even ***subscription based business models.***

Desirability

When looking at the ***desirability*** of the technology, it can both be applied in products that require ***fixation or removal of electronics***. All by leaving an opening in the pockets or by completely closing them after placement of the modules. For more than 5 tactors it is advised to create a second design in which an inner-outer construction is created, if all the electronics need to be removed before laundering. This method can be copied from the NeuroShirt or Mission Navigation Belt. Since Elitac Wearables already has experience with this, no further detailing was done on the matter. Finally, a steps of use visual was created to show the interaction with the technology system and the user.

19. Final Demonstrator

The final demonstrator is presented in this chapter. The materials, electronics and production are elaborated. Followed by user tests and an artificial sweat test.

The goal of the demonstrator was to show that the system designed can actually power 3 tactor modules at the same time. Moreover, testing the experience of the interaction with the pockets, the main module and landing spot was also a wish from Elitac Wearables. The overall ergonomics was also briefly tested. The goal of the artificial sweat test was to see how corrosion sensitive the conductive yarns with gold plated contacts actually is. See Figure 205 for an overview of the final demonstrator.

Figure 205. Final demonstrator with 3 tactor modules, 0.5m of conductive yarn traces and a main module with an IMU embedded.

Electronics

In Figure 206 a schematic overview of the hardware electronics used in the final demonstrator can be seen. The components try to mimic the hardware electronics used in the actual products of Elitac as best as possible. Due to the limited amount of time and resources, it was not possible to code and implement the real hardware components. Figure 207 show the soldered electrical components in the prototyped main module. An additional

The final demonstrator facilitates I2C communication, just as the current products of Elitac. A total of 3 tactors were implemented. However, address changers are currently not available on the market due to a world wide chip shortage. Therefore, the different tactor modules cannot be individually actuated. A basic Arduino script was used to make them vibrate based on sensor input from an IMU. See Appendix A21 for the basic Arduino script.

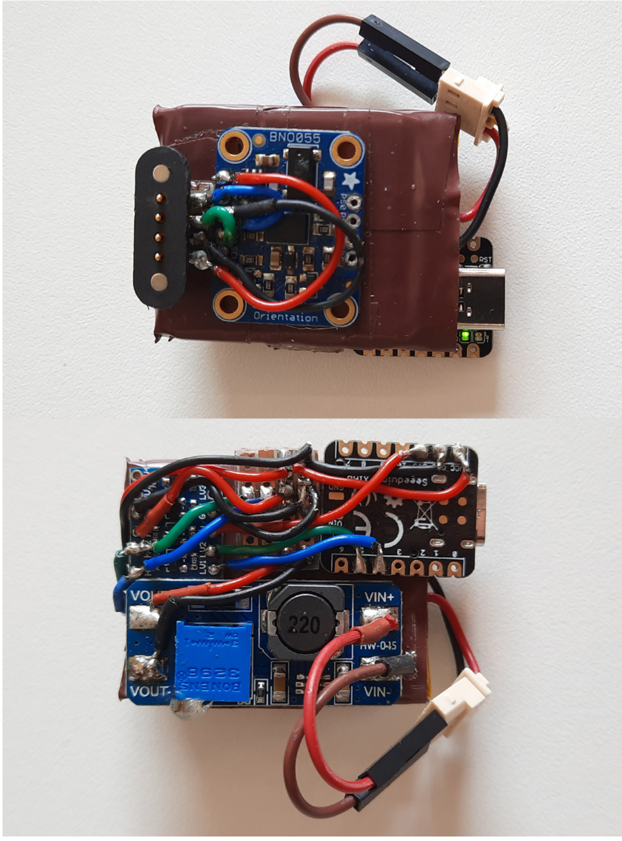


Figure 207. All electrical components of the main module soldered together.

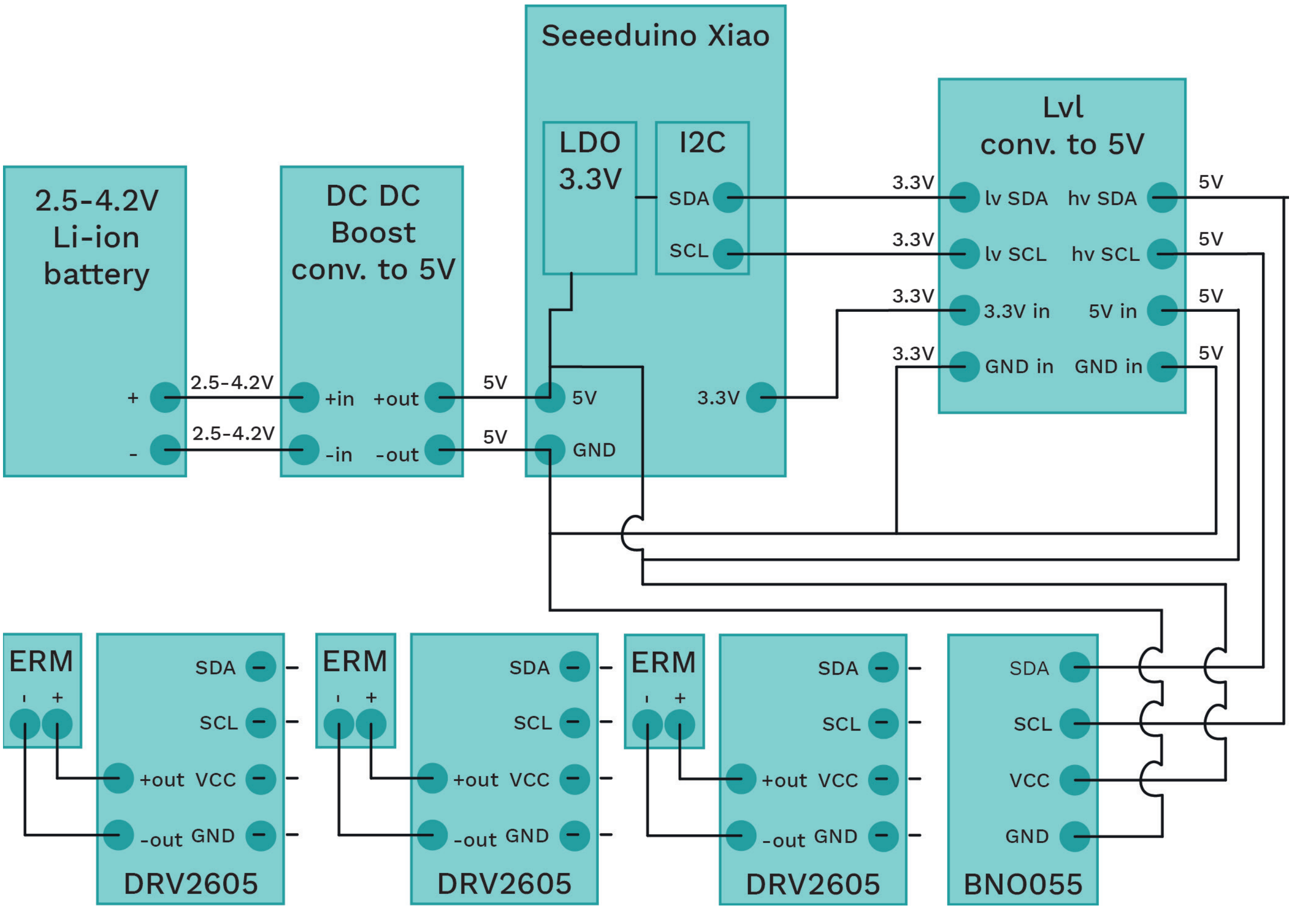


Figure 206. Hardware circuit overview final prototype

Textile carrier

The back panel of an existing cycling vest was removed and traced to create a new back panel of the desired materials. After sewing conductive yarn traces and attaching the pockets, the new back panel was sewn back into the existing cycling vest.

Materials

Pockets: Lycra/Sensitive® material & Framis® Italia as glue.
Base layer: Knitted fabric consisting of 65% Viscose, 5% Elastane and 30% PA
Yarns: Elektrisola 30004021L was used as Bobbin thread and AMANN Group Saba 80, 100% as top thread.

Production

The methodology of sewing the conductive yarn traces and connecting the PCB of the landing spot was previously elaborated in paragraphs 13.2 and 13.3 and Appendix A13. The main focus in this part lies on the production of the modules and the pockets

Main module & Landing spot

The casing of the main module was 3D printed from PLA and then spraypainted with black matt paint. The pogo pin connector and magnets were glued to the casing with superglue. The landing spot was 3D printed with different shore values ranging from A85 at the locations of the pogo pin connector and magnets to A50 at the edges of the part. Different shore values helps to increase the flexibility, allowing a better fit to the human body and implementing strain reliefs. The magnets and pogo pin connector were fixated with super glue as well. See Figure 208 for the main module of the final prototype and Figure 209 for the landing spot with different shore values.

Tactor module

The tactor modules were produced by using the overmolding technique. For this mold pieces were SLA 3D printed form High Temp V2 Resin. See Figure 210 to Figure 214 for all the production steps and the final design.

Figure 208. Main module of the final prototype

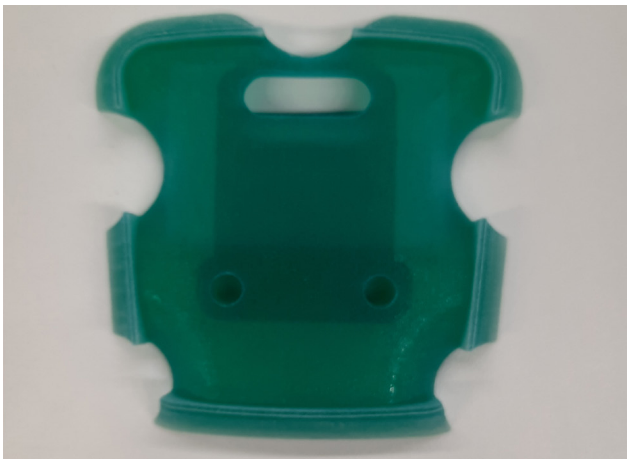


Figure 209. Landing spot of the final prototype

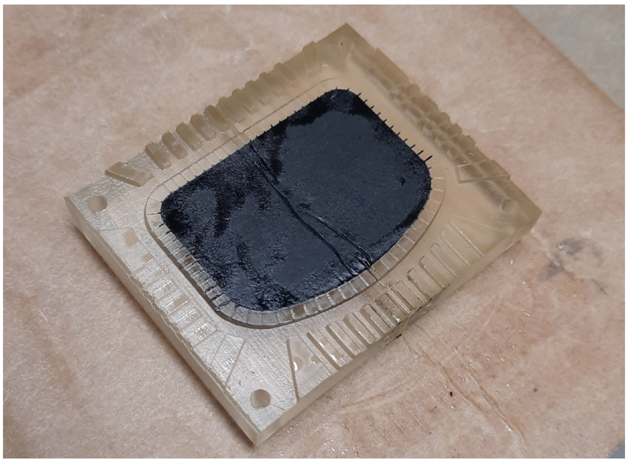


Figure 210. Overmold first flat part of tactor casing

Figure 211. Put brass strips of 2mm through markings on first overmold

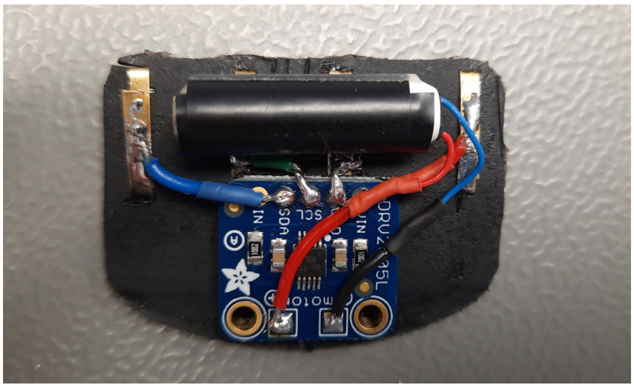


Figure 212. Solder electronics to brass strips

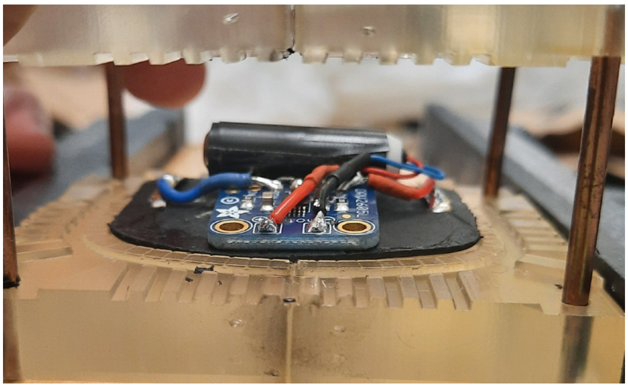


Figure 213. Overmoud first overmold and electronics with second overmold.

Figure 214. Overmoud first overmold and electronics with second overmold.

In the end the metal strips too flat and not sticking out enough to make proper contact. Additional copper tape was placed on top of the contacts to improve this.

Pocket design

For the pocket design, multiple versions were created and tested, see Figure 215. The pocket design on the right consisted of 3 layers: a base layer, Vliesofix layer and a top layer. The Vliesofix has cutouts on the locations where the pockets are located. These 3 layers merged together inhibited stretching for a comfortable fit and created

Figure 215. Multiple pocket design tested with the top left corner being the best.

a thick final textile carrier. Moreover, the Vliesofix layer was not strong enough to keep the layers merged when placing the tactor inside. The pocket on the bottom left also consisted of three layers and an additional Framis® opening in the middle, which made placing the module impossible due to the tight fit. The final iteration, on the top left corner is still stretchable due to only having local pockets at the locations where desired.

Corrosion test

To test if the gold plated contacts and conductive yarn traces of the final design are corrosion sensitive, an artificial sweat test was performed. A sodium & vinegar solution, previously made by Elitac Wearables, that matches ~1.1g/L salt and a pH between 4.5 and 7.0 just like regular sweat was used (Wikipedia 2021). A gold plated contact and a brass piece were pressed against a sewn conductive yarn trace of Elektrisola 30004021L, wrapped in a wet kitchen paper filled with fake sweat and placed in a plastic bag. The materials were left alone for 6 days. Figure 216 shows the result, which shows a ***high vulnerability to corrosion of all materials.***

Figure 216. Broken conductive yarn traces and corroded contacts after 6 days of artificial sweat

User research

Qualitative user research was performed to find out more about the ease of use and comfort of the design. In total 6 participants participated of which 3 male and 3 female. The goal of this research was to:

1. Find out if the placement of the different modules is clear for first time users.
2. How easy the placement of the electrical modules is experienced by the users.
3. If wearing of the prototype is experienced as comfortable.
4. To find points of improvements for future recommendations.

Only a brief summary of the main takeaways will be discussed here. For the full research see Appendix A22.

Placement of modules

According to all participant the placement of the main module was extremely easy (6.83/7), due to the shape and magnetic snap fit. The tactor module was rated to be placed less easy (5/7), as some of the participants found the magnetic snap fit of the main module create a large contrast with the pocket design. Some were expecting the same kind of connection for all modules. The tightness of the pockets and the size of the opening created difficulties. Most of the participants expected a horizontal placement of the pocket instead of a vertical one followed by a 90 degrees rotation inside the pocket, see Figure 217. However, the shape and size of the pockets and the modules actually made the location and final positioning clear.

Comfort & movement restriction

The overall comfort rate was a 6/7 when wearing the design. As the size of the vest was a male M, it was not a perfect fit for all participants. It was easy to put on and participants mentioned the electronics to be barely noticeable. See Figure 218 for a participant wearing the vest. All participants mentioned experiencing a small pull of the main module, but that it was not annoying and they got used to it rather quickly. The design was rated to be movement restricting free with a score of 6.83/7 points. However, some did notice the main module and some participants worried that the main module could fall off when jumping for example. Also sitting against a surface was mentioned as something that could be uncomfortable.

Improvements

The appearance and size of the main module should be improved, by making it less bulky and part of the form language of the design. Second, the ease of placing the tactor modules in the pockets should be improved. Horizontal sliding is preferred by most of the users.

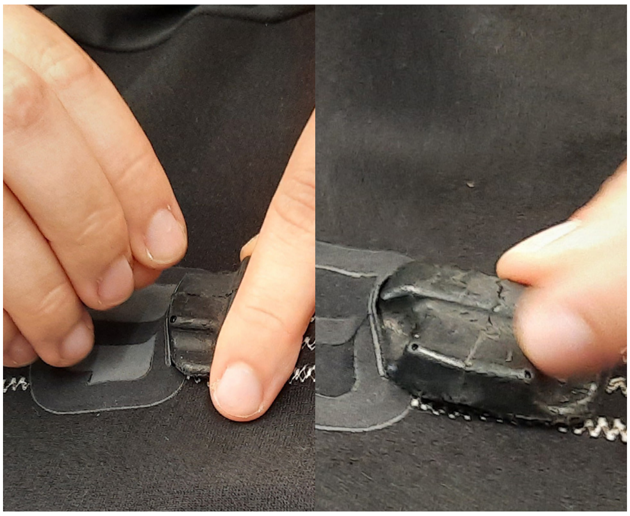


Figure 217. Preferred horizontal placement tactor (left) versus designed vertical placement (right)

Figure 218. Participant wearing the prototype to rate the comfort level of the design

Learnings & takeaways

Final prototype production

During the production of the final prototype some points of improvement were noted:

First, the ***mold design of the tactor module*** should be improved for future use, as there are still quite some ***air bubbles forming***. This can be done by ***creating more air holes*** and decrease the total volume of PA that needs to be filled. Also, only one singular ***injection point*** was used, which could be ***branched out*** to spread the fill of the mold more equally.

A ***mold for the landing spot*** was also printed and tested, but left out of the report as the mold was non-releasing enough. In a future design, a new mold that is ***self-releasing*** should be designed and the ***thickness*** of landing spot ***minimized*** to decrease the total volume of PA necessary.

A third finding was the partially ***melting of the PA overmold*** (220 degrees Celsius) ***when soldering*** (350 degrees Celsius) the electronics to the brass strips. A heat sink in the form of a copper metal plate was used to overcome this problem.

Next, the ***brass strips were too flat*** to ensure proper contact with the conductive yarns. If the vest was worn tightly to the body this problem was already partially solved. In the future, the strips need to be placed in a more ***arched shaped*** and have some springback, just ***as in prototype 1***

Moreover, the ***placement of the electronics*** should be done quite ***precise, or the overmold will not cover all components.*** In one of the three overmolds a small blue wire is still visible. Also, the ERM motor was insulated with PVC electrical tape to prevent short circuits, as the casing is made of full metal and placed against all four brass strips.

Next, even with use of Solufix a little ***tunnelling occurred during sewing***, so ***2mm additional spacing in between each conductive yarn trace was added.*** Due to this too little spacing in between the yarns to match with the tactor module contact points was prevent. Furthermore, checking the distancing with mock-up after each trace is sewn also helped a lot as shown in Figure 195 helped a lot. For each new fabric used, the level of tunnelling should be checked and adjusted for.

Finally, although not tested in practice, ***cross wire sewing*** and ***360 degrees all round sewing*** will be challenging. Cross wire sewing means different conductive yarn traces crossing each other that might create ***shot circuits.*** 360 degrees sewing, where the conductive yarn traces will rotate 360 degrees throughout sewing, as is necessary in the final design, would result in ***placing tactors modules upside*** down to still make contact with all the correct electrical lines. In the recommendations advice is given to overcome these problems.

User research

Based on the user research the following conclusions can be drawn:

Firstly, the ***pockets*** should be redesigned to improve the ease of ***placing the tactors***. Preferably this would be a ***singular swift action***, in which the tactors are already ***positioned in the final orientation.***

Next, the ***volume of the main module*** should be decreased. This can already be achieved by making a ***PCB design*** and using ***smaller electrical components***. Also, the use of thinner magnets can help decrease this size height.

The same goes for the ***landing spot*** which can be decreased in depth by using smaller magnets and creating a PCB design for the pogo pin connector. ***Additional mechanical fixation*** might be necessary to ensure the fixation of the main module on the landing spot and /or to build more trust for the users.

Finally, the prototype is ***quite robust***, as even after all these tests everything still functioned well. Only an edge of a bottom pocket became loose and some wires got fragmented at the entrance of the pockets.

20. Evaluation & Limitations

In this part of the report the final design is evaluated according to the design drivers previously stated in paragraph 7.1. The goal is to see how well the final design meets the overall assignment of Elitac Wearables The design of a modular interconnection system for smart textile applications, which is widely implementable, robust, durable cleanable, cost-effective, more integrated in the textile carrier and ergonomically to wear. Furthermore, *a critical analysis of the final design is presented to highlight important limitations. Advice on how to overcome these limitations is also given.*

Design driver evaluation

1. Robust & durable

The design should be able to withstand everyday life, cleaning processes and possible outdoor environments.
At least 6 people tried on the vest and placed all modules without previous instructions given during the user research. The system still functioned afterwards and only a little fragmenting of the conductive yarns was seen at the entrance points of the pockets. Also, a small corner of the Framis® material let go at one of the pockets. As the two other two pockets did not show similar signs, this was probably caused by incorrect heat pressing. The laundry test of chapter 14.1 showed good launderability of the Elektrisola conductive yarn. The corrosion sweat test, in which the same yarn and a gold plated contact was soaked in artificial sweat, gave a different result. The yarn traces were completely corroded and broken, and the contact point also showed signs of corrosion. All in all the design seems rather robust when it comes to mechanical forces and laundering, but it cannot be soaked in sweat for too long. Furthermore, the design should be extensively tested for outdoor environment use in the future.

2. Widely implementable

The technology design should be easily applicable in a multiple product designs of Elitac Wearables.
The final prototype shows that the design can be at least implemented in a line construction on a garment. Furthermore, the modular system in designed in such a way, that the type of garment, the number of tactors, the location of the conductive yarn traces, the tactors and the main control module, can be varied as required. Also, the electronics inside a tactor module can be varied, allowing implementation of more sensors/actuators. The design is therefore considered to be widely implementable and also more integrated in the textile carrier. Future tests should establish the maximum amount of tactors the design can implement.

3. Scalable

The materials, technology & production processes used should be scalable to a level of at least 25 pieces produced per batch. In the best case, mass production can be facilitated by potential industry partners.
The final design uses materials, technologies and production processes that are all in-house at Elitac Wearables. Therefore, at least the final prototype can be produced in batches, as Elitac Wearables already has experience with batch production. When looking at mass production, the modular design allows for separate production of electronics and the textile carrier. Avoiding the problems when trying to merge the electronics industry and textile industry as previously claimed in the problem definition in chapter 6. Therefore, the textile industry can mass produce prefabrications of the textile carrier and the electronics industry can help mass produce electrical modules. Of course the design will first need to be optimised and streamlined for batch production, before mass production can be implemented.

4. Cost effective

The new technology design should be cost effective compared to the old design, and not cost more than 2x the current production costs of the electronics design.

The final design implements the same electronics currently used by Elitac Wearables. Therefore, costs of the electrical modules will be more or less the same. The addition of conductive yarn might increase the price a bit, as these materials are rather expensive. However, this will not result in a doubling of the costs, as the final prototype only required 0.04 Euros of conductive yarn (See Appendix A21). Moreover, the modular electrical modules allow for easy replacement/reuse/possible repair. Extending the usage phase of the most expensive components significantly, compared to some original designs, where the electronics cannot be reused in a new textile carrier as they are completely embedded. Moreover, the design creates new opportunities for B2C business models.

5. Cleanable

Should be at least hand washable, but preferably also machine washable at minimally 30 degrees Celsius.

As previously stated, laundry tests performed in paragraph 14.1 showed good launderability of the Elektrisola conductive yarn.

Next to the conductive yarns, it is critical for the pockets to maintain their mechanical properties over time. Laundry tests of the Framis® material at 60 degrees Celsius were performed by Elitac Wearables, and showed perfect adhesions and no loss of material properties. The TechnoMelt PA 646 material was also tested by the company and can completely waterproof Electronics.

When summarising all these findings, it can be concluded that the final design should be cleanable at a delicate 30 degrees Celsius machine wash, when looking at the most critical points of the design.

6. Ergonomically

The design should be ergonomically to wear on the human body & to interact with.

Based on the results of the user research the design is ergonomic to wear as most participants find it comfortable to wear & movement is not restricted. The interaction does require some improvements when it comes to placement of the tactor modules inside the pockets and the size of the main module.

Limitations

Conductive yarns & metal strips

The chosen Elektrisola conductive yarns and gold plated electrical strips corrode easily when soaked in artificial sweat for longer periods of time. As the laundry tests showed non of these signs, it is advised to test vulnerable the system is when it is systematically temporarily soaked in sweat and dried again. This will be a more realistic user scenario compared to 6 full days of submersion. The PCB connector with pogo pins located in the landing spot should also be tested on corrosion sensitivity, as small amounts of fluids could seep through the fabric near the connector attached to the conductive yarns. In the end removing the thin layer of overmold on the inside of the back panel could a solution, so the moist collected near the connector can dry more easily, possibly decreasing the chances of corrosion. It is also advised to search for alternative conductive yarns that have a better resistance against corrosion, add a protective layer on top of the yarns after sewing and/or redesign the pockets in such a way, that no to little sweat can reach the contact points. Moreover, completely golden contacts could also decrease the corrosion. Another reason to search for alternative conductive yarns are the signs of wire fragmentation after replacing the tactor modules often. Using contacts with no sharp edges might already help a lot. Interesting options are other yarns of Elektrisola or the yarns of Syscom Advanced Materials.

Sewing cross wires

Some designs might require the crossing of multiple conductive yarn traces, resulting in short circuits. This could be solved by stitching conductive yarn traces on a separate piece of fabric, functioning as a bridge, see Figure 221. When optimising the settings for conductive yarn stitches, the conductive yarn will only be located on one side of the fabric, making the other side an insulator.

Sewing in all orientations

Some designs might require 360 degrees rotation of the 4 conductive yarn traces (as in the final design). This would result in upside-down placement of some of the tactors. By mirroring the gilded metal contact strips in some tactor modules, all tactors can be placed in the same orientation.

Design limits & implementing other sensors and actuators

During this research, the limits of the final design were not tested in terms of maximum conductive yarn length and the maximum number of tactors it could power. More extensive calculations and building more prototypes would help to gain more insights. Also, the use of sensor and actuators that need to be worn directly on the skin, is not possible at the moment. An opening in the base layer, a transparent part in the tactor module or direct placement at the surface of the tactor could change this.

Conclusions

In the end the design scored well on the following design drivers: ***widely implementable, scalable, cost effective and cleanable.*** The ***robustness and durability*** of the design is however ***still questionable*** when it comes to ***corrosion of conductive yarns*** caused by human sweat. The ***wire fragmenting*** is also something that will need to be prevented in future designs. Moreover, the ***ergonomics*** of the design still needs ***improvements*** when it comes to ***placing the tactors inside the pockets*** and the ***size of the main module***.

Important ***limitations*** of the design are the ***corrosion sensitivity of conductive yarns*** and gold plated contact strips. The advice is to look for alternative conductive yarns and change the design so the materials come in less contact with the human sweat. Secondly, the ***pogo pin connector PCB in the landing spot*** should also be tested for corrosion sensitivity, which could lead to more design adjustments.

Cross wiring can be enabled by using bridging pieces of fabric that are insulated from the bottom. Next, mirrored tactor modules allow for similar orientation and placement of all tactors if sewing in all directions is required.

Currently, the ***maximum length of the yarn traces*** and the ***number of tactors*** is still unknown and needs to be investigated in the future. More extensive calculations and building more prototypes would be a good starting point. Finally, to enable the ***implementation of other sensors and actuators*** that need to be directly worn on the skin, openings can be created in the base layer and transparent parts or direct placement of parts at the surface of tactors can solve this.

21. Conclusions & Recommendations

Final conclusions

This graduation project set out to design a modular interconnection system for smart textile applications for Elitac Wearables. The embodiment solution should be widely implementable, robust, durable cleanable, cost-effective, more integrated in the textile carrier and ergonomically to wear. The Double Diamond Design Process of the Design Council (2015) was adjusted to a 4 Diamond Design process to get to the final design.

In the first phase, Understanding the problem, the company Elitac Wearables and the challenges they are facing when designing smart textile wearables were analysed. Together with a market analysis and previously done literature research, a problem definition, design drivers and a program of requirements and wishes was created. In the second phase, Finding building blocks for haptic feedback systems, Technologies were collected and benchmarked on multiple properties, resulting an a selection of high potential technologies for implementation in the third phase: How to mount haptic feedback systems to garments. Multiple concepts were generated and two of them were chosen for further development: One based on conductive yarn knitted pockets and conductive Velcro and the second one based on sewn conductive yarn traces and a pogo pin connector. For the final design presented in phase 4, The embodiment design of a modular haptic feedback system for textiles, a hybrid version of these two concepts was created.

The final design was divided into four modules:

• A tactor module, containing an ERM and a driver PCB, which is connected to the system by pressing gold plated contact strips on conductive yarn traces.

• The power & data transport module, consisting of 4 sewn conductive yarn traces enabling I^2C communication.

•The main control module, containing the micro controller and power supply, which is connected through a magnetic pogo pin connector on a landing spot.

• The textile module, made of stretchable and breathable materials that makes the technology wearable.

This design was evaluated on the 6 design drivers to rate how well the goal of the graduation project was reached.

Robust & durable

The design is quite robust when it comes to everyday life and cleaning processes, as user tests showed minor damaging of the final prototype and laundry tests showed no corrosion after 8 cycles. However, the design is vulnerable to artificial sweat, as soaking the conductive yarns and gold plated contacts for 6 days broke the system completely.

Widely implementable

The modularity of the design allows it to be used as a design tool for future products, as the type of garment, the number of tactors, the location of the conductive yarn traces, the tactors and the main control module, can be varied as required per project. The design of the tactor module can be adjusted in size and materials, so other sensors and actuators can be implemented as well, making the final solution overall widely implementable. However, the maximum number of tactor modules and length of the conductive yarn traces should be tested in the future.

Scalable

The final design is scalable to at least batch production, as it uses materials, technologies and production processes that are all in-house at Elitac Wearables. The electrical modules and textile carrier can be separately produced, helping to avoid the problems when trying to merge the textile and electronics industry and opening the door the mass production.

Cost effective
As the electronics used inside the final product are based on the same electronics Elitac Wearables is currently using, the production costs will not deviate much from the original design. However, by designing removable electronics, the modules can be reused/replaced/ in multiple textile carriers over time. Resulting in the extension of the use phase and opening up new B2C business model opportunities, compared to some original designs of Elitac Wearables where the electronics are completely embedded in the textile carrier.

Cleanable
The laundry tests performed during this research showed good launderability of the Elektrisola conductive yarns, as the resistance did not change significantly after 8 washing cycles. Moreover, the overmold TechnoMelt PA 646 was tested by Elitac Wearables, resulting in waterproof casings that can be laundered as well. Also, the adhesion and material of the Framis® material remained excellent after washing cycles at 60 degrees Celsius. Therefore, the design is considered to be cleanable.

Ergonomically
Based on the results of the user research the design is ergonomically to wear, as most participants find it comfortable to wear & movement is not restricted. Though, the interaction does require some improvements when it comes to placement of the tactor modules inside the pockets, which are too tight and the rotation of the tactor modules during placement was unclear for some of the participants. Also, the size of the main module should be decreased so it looks less bulky.

When reconsidering the goal of this graduation project (the design a modular interconnection system for smart textile applications for Elitac Wearables, that is widely implementable, robust, durable cleanable, cost-effective, more integrated in the textile carrier and ergonomically to wear), the design fulfils most of the requirements. The final design scored well on the following design drivers: ***widely implementable, scalable, cost effective and cleanable.*** The ***robustness and durability*** of the design is however ***still questionable*** when it comes to ***corrosion of conductive yarns*** caused by artificial sweat. The ***wire fragmenting*** is also something that will need to be prevented in future designs. Moreover, the ***ergonomics*** of the design is overall comfortable, but can still be ***improved*** when it comes to ***placing the tactors inside the pockets*** and the ***size of the main module***.

Final Recommendations
The steps to be taken by Elitac Wearables to bring this design to the next level are elaborated.

Redesign pockets
Redesigning the pockets for ease of use is highly recommended. By creating a more tapered design as shown in Figure 219, the tactor modules can be inserted in the final orientation with a singular action. The top part will remain open and a tight fit will hold the module in place. The shape tactor is still used as usecue for correct placement.

Mirrored tactor modules
The tactor modules should be adjusted to fit the electronics used by Elitac Wearables. Also, the molds should be improved by minimizing the total volume of PA necessary, adding more air holes and a branched out injection point. Moreover, a second design of the tactor module should be created in which the golden metal strips are mirrored, see Figure 220. This will enable placement of the tactors in the same orientation at all times. Moreover, the metal strips should be more arched and sticking out, to ensure proper contact with the conductive yarns at all time, just as in the prototype presented in paragraph 13.2.

Smaller main module
By designing a PCB the volume and size of the main module can be decreased. Additional fixation with for example Velcro straps or a pocket might be necessary to

increase the trust of the users in the design and make it less vulnerable to falling of.

Thinner overmolded landing spot

The size of the landing spot is directly related to the main module. By using thinner magnets and designing a PCB for the pogo pin connector the thickness can be decreased significantly. A self-releasing mold design has to be created as well.

Figure 219. Tapered design of the pockets that would ensure more easy placement

Textile carrier

To avoid short circuits where cross wiring is necessary, pre-stitched bridging patches could be used, see Figure 221. Looking for stronger and more durable conductive yarn alternatives from Elektrisola and Syscom Advanced Materials is advised to increase the durability of the system.

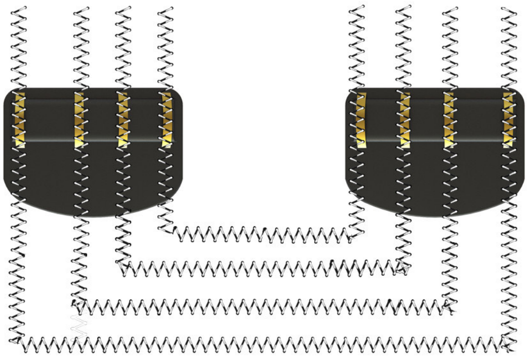


Figure 220. Mirrored tactor module to enabe the same orientation of all tactors.

Extensive testing

The design was now only tested with 3 placeholder tactor modules. In the future a prototype with at least 7 tactors of Elitac Wearables should be implemented and benchmarked against the original string of tactors. Moreover, an EMC assessment should be performed, to see where the product needs to be improved before it can be brought to the market. Also important is an extensive power & data reliability test, as only a brief test was performed during this research. Additionally, the durability of the design should be tested more extensively by performing a more sweat test and laundry test.

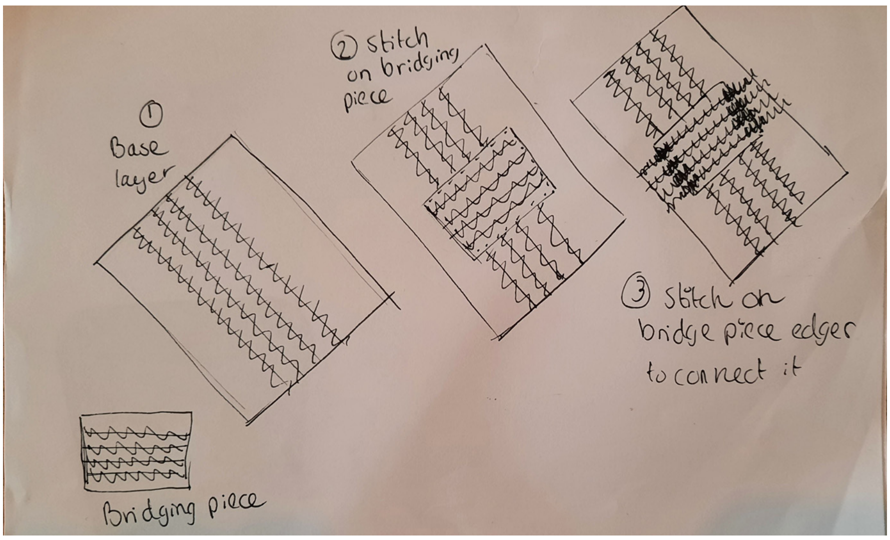


Figure 221. Bridging patches that can be used to solve cross wiring short circuits

References

Adafruit. (n.d.). *Conductive Hook & Loop Tape - 3" long.* Retrieved from https://www.adafruit.com/

Agcayazi, T., Chatterjee, K., Bozkurt, A., & Ghosh, T. K. (2018). Flexible Interconnects for Electronic Textiles. *Advanced Materials Technologies, 3*(10). https://doi.org/10.1002/admt.201700277

Ali, A., Baheti, V., Militky, J., Khan, Z., & Zhu, G. (2019). Metal Coating on Ultrafine Polyester Non-woven Fabrics and Their Ageing Properties. *Fibers and Polymers, 20*(7), 1347–1359. https://doi.org/10.1007/s12221-019-1078-z

Arduino. (2021). *PWM.* Retrieved from: https://www.arduino.cc/en/Tutorial/Foundations/PWM

Athos. (2021a). *MEN's SHIRT w/Core.* Retrieved from: https://shop.live.com/products/mens-upper-body-kit

Athos. (2021b). *Wear & Care for your Gear.* Retrieved from https://help.live.com/en/articles/459565-wear-care-for-your-gear

Bar-Cohen, Y. (2004). Electroactive Polymer (EAP) Actuators as Artificial Muscles: Reality, Potential, and Challenges, Second Edition (SPIE Press Monograph Vol. PM136) (2nd ed.). SPIE Publications. https://doi.org/10.1117/3.547465

Baxter, A. (2020, November 30). *KEYHOUSE - From Poetry to Digitalisation.* Munique - Unique Textiles Insights. https://www.munique.blog/en/keyhouse-from-poetry-to-digitalisation/

Buchilly, J.M. (July, 2018). Emerging Trends In Wearable Technology Across Several Markets. *Fischer Connectors.* https://www.fischerconnectors.com/uk/en/news/new-trend-paper-emerging-wearable-applications

Cai, Z. (2020). *Design of a modular system for textile wearables.* (Unpublished Master Thesis). Delft University of Technology, Delft

Castano, L. M., & Flatau, A. B. (2014). Smart fabric sensors and e-textile technologies: A review. *Smart Materials and Structures, 23*(5). https://doi.org/10.1088/0964-1726/23/5/053001

Chae, Y. & Buso, A. (2021). *Documentation Lecture METHOD 2.2 Measuring Product Experience.* Retrieved during participation in the FT Alliance Research MSc. elective course January-March 2021.

Chalmers. (n.d.). *Fundamental of IC assembly chapter 9.* Retrieved from http://apachepersonal.miun.se/~gorthu/goran/kurs%20nov%20dec%202013/Chapter_9%20131107%20lecture%202%20.pdf

Cherenack, K., & Van Pieterson, L. (2012). Smart textiles: Challenges and opportunities. *Journal of Applied Physics, 112*(9), 1–14. https://doi.org/10.1063/1.4742728

Cho, G., Lee, S., & Cho, J. (2009). Review and reappraisal of smart clothing. *International Journal of Human-Computer Interaction, 25*(6), 582–617. https://doi.org/10.1080/10447310902997744

Design Council. (2005). *A study of the design process.* Retrieved from https://www.designcouncil.org.uk/sites/default/files/asset/document/ElevenLessons_Design_Council%20(2).pdf

DFRobot. (n.d.). *Boson STEM Educational Kit for Kids, Coding Free - DFRobot.com.* Retrieved 26 July 2021, from https://www.dfrobot.com/boson.html

Dielectric Manufacturing. (Feb, 2019). *ABS Characteristics.* Retrieved from https://dielectricmfg.com/knowledge-base/abs/

Elitac Wearables. (2020a). *Cycling Shirt.* Retrieved from https://elitacwearables.com/projects/cyclingshirt/

Elitac Wearables. (2020b). *SmartShirt*. Retrieved from https://elitacwearables.com/projects/smarshirt/

Elitac Wearables. (2021c). *Elitac Wearables in brief.* https://elitacwearables.com/about/press/

Elitac Wearables. (2021d). *BalanceBelt.* Retrieved from https://elitacwearables.com/projects/balancebelt/

Elitac Wearables. (2021e). *Mission Navigation Belt.* Retrieved from https://elitacwearables.com/projects/mission-navigation-belt/

Elitac Wearables. (2021f). *NeuroShirt.* Retrieved from https://elitacwearables.com/projects/neuroshirt/

Fischer. (n.d.). *LP360tm.* Retrieved from https://www.fischerconnectors.com/switzerland-en/en/products/lp360tm

Freire, R. (2017). *3D printed conductive snaps.* Retrieved from https://www.flickr.com/photos/rachelfreirestudio/albums/72157682001847945/with/33348712180/

Garrod, S. (Aug, 2020). Top Wearables Trend in 2020. Retrieved from https://innotechtoday.com/top-wearable-trends-in-2020/

Hatch, K. L. (1993). *Textile science.*

Hayes, A. (May, 2020). *Wearable Technology.* Retrieved from https://www.investopedia.com/terms/w/wearable-technology.asp

Helmenstine, A.M. (2019, September 4). What is the Most Conductive Element? Retrieved from https://www.thoughtco.com/the-most-conductive-element-606683

HexoSkin. (2021a). *Hexoskin Pro Kit Men's.* Retrieved from: https://www.hexoskin.com/collections/all/products/hexoskin-pro-kit-mens

Hexoskin. (2021b). *Quick start, welcome on a new start with hexoskin.* Retrieved from https://www.hexoskin.com/pages/start

IEC. (2001). *Degrees of protection provided by enclosures (IP Code).* (CEI IEC 60529 Edition 2.1). Retrieved from https://www.wewontech.com/180619001.pdf

Innovative in Textiles. (Apr, 2014). *Smart Textiles, Ohmatex launches new washable connector.* Retrieved from https://www.innovationintextiles.com/smart-textiles-nanotechnology/ohmatex-launches-new-washable-connector/

Ismar, E., Kurşun Bahadir, S., Kalaoglu, F., & Koncar, V. (2020). Futuristic Clothes: Electronic Textiles and Wearable Technologies. *Global Challenges, 4*(7), 1900092. https://doi.org/10.1002/gch2.201900092

JAE. (2020). *Smart Textile Connector "RK01" Series Has Been Launched.* Retrieved from https://www.jae.com/en/topics/detail/id=93333

Kirstein, T. (2013). Multidisciplinary know-how for smart-textiles developers. In *Multidisciplinary Know-How for Smart-Textiles Developers.* https://doi.org/10.1533/9780857093530

Klamka, K., Dachselt, R., & Steimle, J. (2020). Demonstrating rapid iron-on user interfaces: Hands-on fabrication of interactive textile prototypes. *Conference on Human Factors in Computing Systems - Proceedings,* 1–14. https://doi.org/10.1145/3334480.3383139

Kretzer, M. (2013). Electroactive polymers. Retrieved form http://materiability.com/portfolio/electroactive-polymers/

LessEMF. (2021). *Texcare.* Retrieved from https://www.lessemf.com/fabric.html#289

Locher, I. (2006). Doctoral Thesis, Technologies for system-on-textile integration. *Eidgenössische Technische Hochschule ETH Zürich, Nr. 16467, 2006.* https://doi.org/10.3929/ethz-a-005135763

Marozau, D., Khurs, S., & Aleksandrovich, R. (2016). *U.S. Patent No. US 2016/0266645 A1.* United States: Retrieved from https://patents.google.com/patent/US20160266645A1/en

Mattmann, C. (2008). *Body posture detection using strain sensitive clothing.* (Unpublished Doctoral Thesis). ETH Zurich, Zurich

Mehmann, A., Varga, M., Gönner, K., & Troster, G. (2015). A ball-grid-array-like electronics-to-textile pocket connector for wearable electronics. ISWC 2015 - *Proceedings of the 2015 ACM International Symposium on Wearable Computers*, 57–60. https://doi.org/10.1145/2802083.2802093

Motola-Barnes, M. (2019). Haptic Actuators: Comparing Piezo to ERM and LRA. Retrieved from https://blog.piezo.com/haptic-actuators-comparing-piezo-erm-lra

Muhammad Sayem, A. S., Hon Teay, S., Shahariar, H., Fink, P. L., & Albarbar, A. (2020). Review on Smart Electro-Clothing Systems (SeCSs). *Sensors, 20*(3), 587. https://doi.org/10.20944/preprints201903.0164.v1

Myant. (2021). *Myant Empowers you to innovate.* Retrieved from https://myant.ca/innovating-together/

NEN. (2015). *Medische elektrische toestellen - Deel 1-2 Algemene eisen voor de veiligheid en essentiële prestatie* (NEN-EN-IEC 60601-1-2:2015). https://www.nen.nl/nen-en-iec-60601-1-2-2015-en-211621?gclid=Cj0KCQjw9O6HBhCrARIsADx5qCQexJ4iyDredy3bgMsLvE90kIR4ATkbO6dTNV10-1INuULRHhcByQQaApM9EALw_wcB

Nielsen, J. (2004). Usability engineering. In *Computer Science Handbook, Second Edition.* https://doi.org/10.1201/b16768-38

Öhlund, T. (2012). *Coated Surfaces for Inkjet-Printed Conductors* (Licentiate dissertation, Mid Sweden University). Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:miun:diva-16449

Overmold. (n.d.). *Technomelt PA 646*. Retrieved from https://www.overmold.com/om-materials/

Patringenaru, I. (2020, December 7). *A flexible screen-printed rechargeable battery with up to 10 times more power than state of the art.* US San Diego News Center. https://ucsdnews.ucsd.edu/pressrelease/flexiblebatteries

Post, E. R., Orth, M., Russo, P. R., & Gershenfeld, N. (2000). E-broidery: Design and fabrication of textile-based computing. *IBM Systems Journal, 39*(3.4), 840–860. https://doi.org/10.1147/sj.393.0840

Precision Microdrives. (2021). AB-028: *Vibration Motor Comparison Guide*. Retrieved from https://www.precisionmicrodrives.com/content/ab-028-vibration-motor-comparison-guide/

Pulsea. (2013). *Vibe Modules*. Retrieved from https://www.kobakant.at/DIY/?p=8293

ReTiSense. (2021). *Stridalyzer Performance Insoles.* Retrieved from https://www.retisense.com/product/stridalyzer-performance-insoles/

Roozenburg, N.F.M. & Eekels, J. (1998). *Productontwerpen, structuur en methoden* (2nd ed., Vol. 1998). Lemma BV.

Schweber, B. (2021, June 2). *Haptics Components, Pt 1 LRA, ERM, and piezo actuators.* Retrieved from https://www.powerelectronictips.com/

haptics-components-pt-1-lra-erm-and-piezo-actuators/

Sensoria. (2021). *Smart Sock V2.0 & Sensoria Core.* Retrieved from https://store.sensoriafitness.com/smart-sock-v2-0-sensoria-core/

Shull, P. B., & Damian, D. D. (2015). Haptic wearables as sensory replacement, sensory augmentation and trainer - A review. *Journal of NeuroEngineering and Rehabilitation, 12*(1), 1–13. https://doi.org/10.1186/s12984-015-0055-z

SL Power Electronics. (2019). *Design Considerations for Maximum Allowable Temperature, as per Safety Standards IED 60601-1, IEC 60950-1 and IEC 61010-1 AN-G012*. Retrieved from https://slpower.com/data/collateral/AN_Maximum_Allowable_Temperature.pdf

Somkuwar, V. U., Pragya, A., & Kumar, B. (2020). Structurally engineered textile-based triboelectric nanogenerator for energy harvesting application. *Journal of Materials Science, 55*(12), 5177–5189. https://doi.org/10.1007/s10853-020-04359-2

Sweney, M. (2021, March 21). Global shortage in computer chips 'reaches crisis point'. *The Guardian*. https://www.theguardian.com/business/2021/mar/21/global-shortage-in-computer-chips-reaches-crisis-point

TeslaSuit. (2021). *The Suit.* Retrieved from: https://teslasuit.io/the-suit/

Teyeme, Y., Malengier, B., Tesfaye, T., Ciesielska-Wrobel, I., Musa, A. B. H., & Van Langenhove, L. (2020). A Review of Contemporary Techniques for Measuring Ergonomic Wear Comfort of Protective and Sport Clothing. *Autex Research Journal, January*. https://doi.org/10.2478/aut-2019-0076

Twinlink technology. (2019). *Are there any disadvantages to pogo pin connectors?* Retrieved from https://www.twl-link.com/news_Info-11-451.html

TWI. (2021a). *What is Soldering? A Full Guide (Meaning, Definition and Types).* Retrieved 16 March 2021, from https://www.twi-global.com/technical-knowledge/faqs/what-is-soldering#:%7E:text=Soldering%20is%20a%20joiningW%20process,create%20a%20strong%20electrical%20bond

TWI. (2021b). *Pros and cons of electrically conductive adhesives (ECAS).*. Retrieved 18 March 2021, from https://www.twi-global.com/technical-knowledge/faqs/faq-what-are-the-advantages-and-if-any-the-disadvantages-of-electrically-conductive-adhesives-ecas

Ultraleap (2021a). *What is haptics?* Retrieved fromhttps://www.ultraleap.com/company/news/blog/what-is-haptics/

Ultraleap (2021b). *What is haptic feedback.* Retrieved from https://www.ultraleap.com/company/news/blog/what-is-haptic-feedback/#:~:text=Haptic%20feedback%20is%20the%20use,is%20much%20more%20than%20that.

uz Zaman, S., Tao, X., Cochrane, C., & Koncar, V. (2019). Launderability of Conductive Polymer Yarns Used for Connections of E-textile Modules: Mechanical Stresses. *Fibers and Polymers, 20*(11), 2355–2366. https://doi.org/10.1007/s12221-019-9325-x

van der Valk, D. (2020). *Knitted smart textile sensors*. (Unpublished Master Thesis). Delft University of Technology, Delft

van Langenhove, L., Hertleer, C., Westbroek, P., & Priniotakis, J. (2007). Textile sensors for healthcare. *Smart Textiles for Medicine and Healthcare Materials, Systems and Applications*, 106–122. https://doi.org/10.1533/9781845692933.1.106

von Krshiwoblozki, M., Linz, T., Neudeck, A., & Kallmayer, C. (2012). Electronics in Textiles – Adhesive Bonding Technology for Reliably Embedding Electronic Modules into Textile Circuits. *Advances in Science and Technology, 85,* 1–10. https://doi.org/10.4028/www.scientific.net/ast.85.1

Wearablex. (2021a). *30 Days free trail*. retrieved from: https://www.wearablex.com/

Wearablex. (2021b). *Inner confidence through contact Our technology*. Retrieved from https://www.wearablex.com/pages/how-it-works_v0

Wearablex. (2021c). *Nadi X User Manual*. Retrieved from https://www.wearablex.com/pages/user-manual

WEARIC. (2020, April 8). *Smart Textiles Kit*. https://www.wearic.com/product/smart-textiles-kit/

Wicaksono, I., Tucker, C. I., Sun, T., Guerrero, C. A., Liu, C., Woo, W. M., Pence, E. J., & Dagdeviren, C. (2020). A tailored, electronic textile conformable suit for large-scale spatiotemporal physiological sensing in vivo. *Npj Flexible Electronics, 4*(1). https://doi.org/10.1038/s41528-020-0068-y

Wikipedia (July 15th, 2021). *Perspiration.* Retrieved from https://en.wikipedia.org/wiki/Acetic_acid

Woop, E., Zahn, E. F., Flechtner, R., & Joost, G. (2020). Demonstrating a Modular Construction Toolkit for Interactive Textile Applications. ACM *International Conference Proceeding Series,* Figure 1, 1–4. https://doi.org/10.1145/3419249.3420075
Yazaki. (n.d.). *Connector for FPC/FFC*. Retrieved from https://connectors-catalog.sys.yzk.co.jp/english/3/033.html

Zhang, P. (2010). Advanced Industrial Control Technology [E-book]. Elsevier Inc. https://doi.org/10.1016/C2009-0-20337-0

Figures

Figure 1. Elitac Wearables (2021). ScienceSuit. Retrieved from https://elitacwearables.com/sciencesuit/

Figure 2. Elitac Wearables (2021). BalanceBelt. Retrieved from https://elitacwearables.com/about/press/

Figure 3. Elitac Wearables (2021). Logo Elitac Wearables. Retrieved from https://elitacwearables.com/about/press/

Figure 4. Market sector of Elitac Wearables:
Safety icon, made by Freepik. Retrieved from https://www.flaticon.com/free-icon/y_842518?term=helmet&page=1&position=1&page=1&position=1&related_id=842518&origin=search
Sports icon, made by Pixel perfect. Retrieved from https://www.flaticon.com/free-icon/g_1108869?term=run&page=1&position=10&page=1&position=10&related_id=1108869&origin=search
Health icon, made by Good Ware. Retrieved from https://www.flaticon.com/free-icon/l_687529?term=health&page=1&position=24&page=1&position=24&related_id=687529&origin=search
Defense icon, made by Icongeek26. Retrieved from https://www.flaticon.com/free-icon/y_102649?term=shield&page=1&position=11&page=1&position=11&related_id=102649&origin=search

Figure 5. Elitac Wearables (2020). Cycling Shirt. Retrieved from https://elitacwearables.com/projects/

Figure 6. Elitac Wearables (2021). SmartShirt. Retrieved from https://elitacwearables.com/projects/smarshirt/

Figure 7. Elitac Wearables (2021). BalanceBelt. Retrieved from https://elitacwearables.com/about/press/

Figure 9. Shull, P. B., & Damian, D. D. (2015). Haptic wearables as sensory replacement, sensory augmentation and trainer - A review. Journal of NeuroEngineering and Rehabilitation, 12(1), 1–13. https://doi.org/10.1186/s12984-015-0055-z

Figure 10. Precision Microdrives (2021a). ERM in shaft configuration. Retrieved from https://www.precisionmicrodrives.com/vibration-motors/brushless-bldc-vibration-motors/

Figure 14. Elitac Wearables (2021). Mission Navigation Belt. Retrieved from Retrieved from https://elitacwearables.com/about/press/

Figure 15. Wearablex (2021). Nadi X. Retrieved from https://www.instagram.com/p/CL45RVsHg8_/

Figure 16. Sewport, 2021). Different kind of trims. Retrieved from https://sewport.com/learn/fabrics-trims

Figure 17. Waveshare (n.d.). IMU sensor. Retrieved from https://www.waveshare.com/10-dof-imu-sensor-b.htm

Figure 18. Disrelec (n.d.). Seeeduino Xiao. Retrieved from https://www.distrelec.nl/nl/seeeduino-xiao-microcontroller-board-with-samd21-cortex-m0-seeed-studio-102010328/p/30173522

Figure 19. Alibaba (n.d.). Coin ERM motor. Retrieved from https://www.alibaba.com/product-detail/The-Worlds-Smallest-ERM-3V-DC_62437101728.html

Figure 20. AliExpress (n.d.). 3.7V 600mAh Lithium-ion battery. Retrieved from https://nl.aliexpress.com/item/825607802.html

Figure 21. Elitac Wearables (2021). Currently used cables as wiring within products. Retrieved from https://elitacwearables.com/sciencesuit/

Figure 22. Elitac Wearables (2021). 3D printed casing for controller of the ScienceSuit. Retrieved from https://elitacwearables.com/sciencesuit/

Figure 23. Leeger (2021). BalanceBelt pockets inner belt for electronics. Personal photograph Dione Leeger

Figure 26. Challenges in literature of smart textile wearables:
Usability, made by Freepik. Retrieved from https://www.flaticon.com/free-icon/y_1063396?term=usability&page=1&position=8&page=1&position=8&related_id=1063396&origin=search
Cleanability, made by Darius Dan. Retrieved from https://www.flaticon.com/free-icon/e_2890529?term=cleaning&page=1&position=3&page=1&position=3&related_id=2890529&origin=search
Durability, made by Freepik. Retrieved from https://www.flaticon.com/free-icon/k_922080?term=connection&page=1&position=14&page=1&position=14&related_id=922080&origin=search
Development, production & commercialisation, made by xnimrodx. Retrieved from https://www.flaticon.com/free-icon/e_1433114?term=factory&page=1&position=15&page=1&position=15&related_id=1433114&origin=search
Integration of electronics and textile, made by mynnamepong. Retrieved from: https://www.flaticon.com/free-icon/e_808497?term=puzzle&page=1&position=2&page=1&position=2&related_id=808497&origin=search
Comfort, made by Freepik. Retrieved from https://www.flaticon.com/free-icon/w_4145480?term=comfort&page=1&position=3&page=1&position=3&related_id=4145480&origin=search
Safety, made by Freepik. Retrieved from https://www.flaticon.com/free-icon/y_842518?term=helmet&page=1&position=1&page=1&position=1&related_id=842518&origin=search
Power supply, made by Pixel perfect. Retrieved from https://www.flaticon.com/free-icon/g_3103277?term=battery&page=1&position=2&page=1&position=2&related_id=3103277&origin=search

Figure 27. Elitac Wearables (2021). SmartShoulder. Retrieved from https://elitacwearables.com/projects/smartshoulder/

Figure 28. ANN ID (2018). Physical activity support: Heart-rate tracking of a training athlete. Retrieved from https://www.annekevanabbema.nl/portfolio/cyclingshirt/

Figure 29. Elitac Wearables (2021). BalanceBelt. Retrieved from https://elitacwearables.com/about/press/

Figure 30. Elitac Wearables (n.d.). Retrieved from https://elitacwearables.com/projects/fysiopal/

Figure 31. Challenges of smart textile wearables

for Elitac Wearables:
Integration of electronics and textile, made by mynnamepong. Retrieved from: https://www.flaticon.com/free-
Cable management, made by srip. Retrieved from https://www.flaticon.com/free-icon/e_900307?term=cabling&page=1&position=1&page=1&position=1&related_id=900307&origin=search
Robust & durable connections, made by Freepik. Retrieved from https://www.flaticon.com/free-icon/k_922080?term=connection&page=1&position=14&page=1&position=14&related_id=922080&origin=search
Development, production & commercialisation, made by xnimrodx. Retrieved from https://www.flaticon.com/free-
Waterproofing and cleanability icon, made by Darius Dan. Retrieved from:https://www.flaticon.com/free-icon/e_2890529?term=cleaning&page=1&position=2&page=1&position=2&related_id=2890529&origin=search
Mass production, made by xnimrodx. Retrieved from https://www.flaticon.com/free-icon/e_1433114?term=factory&page=1&position=15&page=1&position=15&related_id=1433114&origin=search
Design toolkit, made by Becris. Retrieved from https://www.flaticon.com/free-icon/s_3078984?term=steps&page=1&position=2&page=1&position=2&related_id=3078984&origin=search
Reliable suppliers, made by Freepik. Retrieved from https://www.flaticon.com/free-icon/s_645652?term=supply&page=1&position=2&page=1&position=2&related_id=645652&origin=search

Figure 32. Myant (2017). Skiin smart underwear. Retrieved from https://innotechtoday.com/top-wearable-trends-in-2020/
Figure 33. PatientCareSolutions (n.d.). Retrieved from https://www.patientcaresolutions.eu/products/medical-wearables.html

Figure 34. Davis, L. (2020). Smart glasses. Retrieved from https://www.newequipment.com/product-news/media-gallery/21132604/the-latest-industrial-wearables

Figure 35. UK construction online (April 18, 2017). Smart Helmet support maintenance workers. Retrieved from https://www.ukconstructionmedia.co.uk/features/augmented-reality-daqri-construction/

Figure 36. Leeger (2021). Mission Navigation Belt. Personal photograph Dione Leeger.

Figure 37. BAE Systems. (2015). BAE Broadsword power and data distribution harness. Retrieved from https://www.newequipment.com/industry-trends/article/22059087/head-first-smart-helmet-redefines-industrial-wearables

Figure 38. van Ballegoie, E. (May, 2020). Multiple smart wearable fitnes trackers.
Retrieved from https://nl.hardware.info/artikel/9949/gezond-voor-een-prikkie-spotgoedkope-fitness-trackers-afgezet-tegen-de-gevestigde-orde

Figure 39. Polar. (2017). . Polar smart wearable shirt that tracks real-timeheartrate & metrics. Retrieved from https://www.imec-int.com/en/imec-magazine/imec-magazine-july-2019/smart-cycling-outfit-prevents-back-pain-in-riders

Figure 40. ReTiSense (2021). Stridalyzed insoles for running shoes. Retrieved from https://www.retisense.com/product/stridalyzer-performance-insoles/

Figure 41. Hexoskin (2021). HexoSkin.
Retrieved from: https://www.wearables4rent.com/?product=hexoskin

Figure 42. Athos (2021). Athos shirt for men. Retrieved from: https://shop.live.com/products/mens-upper-body-kit

Figure 43. Wearablex (2021). Nadi X smart yoga pants. Retrieved from https://www.instagram.com/p/CL45RVsHg8_/

Figure 44. Sensoria (2021). Smart sock v.2.0. Retrieved from https://store.sensoriafitness.com/smart-sock-v2-0-sensoria-core/

Figyre 45. Elitac Wearables (n.d.). Smart Shirt. Retrieved from https://elitacwearables.com/projects/smarshirt/

Figure 46. TeslaSuit (2021). The TeslaSuit jacket. Retrieved from: https://teslasuit.io/the-suit/

Figure 47. Marozau, D., Khurs, S., & Aleksandrovich, R. (2016). . Example of Electrodes and sensors located on the inside of the Tesla Suit. U.S. Patent No. US 2016/0266645 A1. United States. Retrieved from https://patents.google.com/patent/US20160266645A1/en

Figure 48. FeelSpace (June 14, 2017). NaviBelt for blind people with central control module in the front. Retrieved from https://www.factorytv.de/tv/feelspace.html

Figure 49. Leeger (2021). FeelSpace. Personal photograph Dione Leeger

Figure 50. Leeger (2021). NaviBelt internal electronics connection. Personal photograph Dione Leeger

Figure 51. Wearablex (2021). Nadi X Mesh model. Retrieved from https://www.wearablex.com/products/nadi-x-mesh?variant=36902329872

Figure 63. Wearables4rent (n.d.) Hexoskin. Retrieved from https://www.wearables4rent.com/?product=hexoskin

Figure 64. Pai, A. (Nov, 2015). Athos men's shirt with module. Retrieved from https://www.mobihealthnews.com/48593/-raises-35-5m-for-health-sensing-clothing-for-athletes

Figure 65. Caddy, B. (Feb, 2018). Nadi X with visible "Pulse" and
integrated sensors/actuators. Retrieved from https://www.wareable.com/health-and-wellbeing/wearable-x-nadi-x-smart-yoga-pants-review

Figure 66. Cho, G., Lee, S., & Cho, J. (2009). Review and reappraisal of smart clothing.

International Journal of Human-Computer Interaction, 25(6), 582–617. https://doi.org/10.1080/10447310902997744

Figure 68. Science Learning Hub (2010). Standard electrical wiring made of twisted copper wires. Retrieved from https://www.sciencelearn.org.nz/images/1961-copper-wire

Figure 69. Ohmatex (n.d.) 4-wired flat cable Ohmatex. Retrieved from https://www.ohmatex.dk/products_textile-_cables_connectors/
LiTex (n.d.) Meanering flat cables. Retrieved from https://litextextile.wordpress.com/products/wired-conductive-tape/

Figure 70. Metafas. (n.d.). Screen printed electronics. Retrieved from https://www.metafas.nl/nl/innovatie/flexible-electronics/

Figure 71. MIT News (2020). Conductive polymers. Retrieved from https://news.mit.edu/2020/conductive-gels-stick-wet-0320

Figure 72. Shielday (n.d.). Metal conductive yarns. Retrieved from https://www.shielday.com/silver-fiber-conductive-yarn-thread.html

Figure 73. Taierxin (n.d.). Carbon conductive yarns. Retrieved from https://www.taierxinfiber.com/conductive-yarn/carbon-conductive-yarn.html

Figure 74. Agcayazi, M. Talha & Chatterjee, Kony & Bozkurt, Alper & Ghosh, Tushar. (2018). Flexible Interconnects for Electronic Textiles. Advanced Materials Technologies. 3. 1700277. 10.1002/admt.201700277.
Figure 75. Castano, L. M., & Flatau, A. B. (2014). Smart fabric sensors and e-textile technologies: A review. Smart Materials and Structures, 23(5). https://doi.org/10.1088/0964-1726/23/5/053001

Figure 76. Post, E. R., Orth, M., Russo, P. R., & Gershenfeld, N. (2000). E-broidery: Design and fabrication of textile-based computing. IBM Systems Journal, 39(3.4), 840–860. https://doi.org/10.1147/sj.393.0840

Figure 77. Statex (2020). Silverplated conductive yarn Shieldex. Retrieved from https://statex.de/en/shieldex-knitted-fabrics/

Figure 78. Klamka, K., Dachselt, R., & Steimle, J. (2020). Demonstrating rapid iron-on user interfaces: Hands-on fabrication of interactive textile prototypes. Conference on Human Factors in Computing Systems - Proceedings, 1–14. https://doi.org/10.1145/3334480.3383139

Figure 79. Sentry Air Systems (2010). Soldering close-up. Retrieved from https://www.sentryair.com/blog/industry-applications/electronics-technology/the-hazards-of-solder-fumes/

Figure 80. Sunstone (n.d.). Microspot welding. Retrieved from https://sunstonewelders.com/applications/specialty-metals/aluminum-micro-welding/

Figure 81. Sonobond (n.d). Ultrasonic welding. Retrieved from https://www.sonobondultrasonics.com/president-s-blog/sonobond-ultrasonic-metal-welders-generate-significant-savings-over-both-resistance-welding-and-crimp-solder-methods

Figure 82. Accelonix (n.d.). Wirebonding close-up. Retrieved from https://accelonix.co.uk/service-and-support/wirebonding-services

Figure 83.
Allekabels.nl (n.d.). Aligator grip. Retrieved from https://www.allekabels.nl/stekker/11472/1289232/krokodillenklem.XakzX1A6ko4wZTQFAiivvHMaAmo9EALw_wcB
Led montreal (n.d.). Grip & Clip. Retrieved from https://ledmontreal.com/en/led-connectors-and-accessories-led-montreal/led-connectors-and-accessories/grip-and-clip-wire-to-wire-connectors.html
Phoenix Contact (2021). screw connection & spring-cage connection. Retrieved from https://www.phoenixcontact.com/online/portal/ca?1dmy&urile=wcm:path:/caen/web/main/products/subcategory_pages/PCB_plug-in_connectors_P-11-02/42d3a3f5-0788-4f1d-854e-6f898375f068

Figure 84.
Flexfireleds (n.d.). Terminal block. Retrieved from https://www.flexfireleds.com/productimage.php?product_id=153
Grainger (n.d.). Twist on wire connector. Retrieved from https://www.grainger.com/product/BUCHANAN-Twist-On-Wire-Connector-5VYL9

Figure 85. Appli-Tec (2018). Conductive glue. Retrieved from
Figure 86. Wikipedia (2021). PVC electrical insulation tape. Retrieved from https://en.wikipedia.org/wiki/Electrical_tape

Figure 87. Amazon (n.d.). Conductive copper tape. Retrieved from

Figure 88. Sparkfun (2011). LiliPad. Retrieved from https://www.sparkfun.com/tutorials/312

Figure 89. Post, E. R., Orth, M., Russo, P. R., & Gershenfeld, N. (2000). E-broidery: Design and fabrication of textile-based computing. IBM Systems Journal, 39(3.4), 840–860. https://doi.org/10.1147/sj.393.0840

Figure 90. Audreyobscura (n.d.) Non-conductive adhesives used on textile. Retrieved from https://www.instructables.com/Fabric-Glue/

Figure 91. Locher, I. (2006). Doctoral Thesis, Technologies for system-on-textile integration. Eidgenössische Technische Hochschule ETH Zürich, Nr. 16467, 2006. https://doi.org/10.3929/ethz-a-005135763

Figure 92.
Ebay (2021). Textile TPU seam tape. Retrieved from https://www.ebay.com/itm/20m-20mm-2-Layers-Composite-Pure-TPUPU-Waterproof-Hot-Melt-Seam-Sealing-Tape-/333740709448
Framis® (2021). Framis® Italia material. Retrieved from https://www.Framis®.it/machines/taping

Figure 93. Punkin Patterns (2011). Piping. Retrieved from https://www.punkinpatterns.com/blog/2011/07/how-to-sew-in-piping.html

Figure 94. Babble (n.d.). Embroidery of cabling. Retrieved from https://nl.pinterest.com/pin/207939707765475133/

Figure 96. Wicaksono, I., Tucker, C. I., Sun, T., Guerrero, C. A., Liu, C., Woo, W. M., Pence, E. J., & Dagdeviren, C. (2020). A tailored, electronic textile conformable suit for large-scale spatiotemporal physiological sensing in vivo. Npj Flexible Electronics, 4(1). https://doi.org/10.1038/s41528-020-0068-y

Figure 97. Jtti (n.d.). Overmolded PP ring on a strap. Retrieved from https://www.jtti.com/en/produit/anneau-passant-surmoule/

Figure 98. Digikey (n.d.). Sewn LilyPad Arduino. Retrieved from https://www.digikey.be/en/maker/projects/getting-started-with-lilypad/9b8886d969e149fb82e00f212be5737e
Fischer (n.d.). Sewing pad added to LP360TM. Retrieved from https://www.fischerconnectors.com/switzerland-en/en/products/lp360tm

Figure 100. van der Valk, D. (2020). Knitted smart textile sensors. (Unpublished Master Thesis). Delft University of Technology, Delft

Figure 101. Baxter (2020). Printed electronics on textile. Retrieved from https://www.munique.blog/en/keyhouse-from-poetry-to-digitalisation/
Figure 102. Itersnew (2015). Screen printed electronic ink. Retrieved from http://itersnews.com/?p=98913

Figure 103. Cletk (n.d.). Pogo pin magnetic connection. Retrieved from https://www.cletk.com/connector/4-pin-male-and-female-magnetic-charging-cable-connector-for-smart-wear

Figure 104. Ternimed (n.d.). Snap button connection. Retrieved from https://www.ternimed.de/Snap-Button-Cable-200-cm

Figure 105. Freire (2017). 3D printed conductive snaps. Retrieved from https://www.flickr.com/photos/rachelfreirestudio/albums/72157682001847945/with/33348712180/

Figure 106. Adafruit (n.d.). Conductive Hook and Loop. Retrieved from https://www.adafruit.com/product/1324

Figure 107. Yazaki (n.d.). FFC & FFP connectors. Retrieved from https://connectors-catalog.sys.yzk.co.jp/english/3/033.html

Figure 108. JAE (2020). RK01 washable connector. Retrieved from https://www.jae.com/en/topics/detail/id=93333

Figure 109. Innovative in Textiles. (Apr, 2014). Smart Textiles, Ohmatex launches new washable connector. Retrieved from https://www.innovationintextiles.com/smart-textiles-nanotechnology/ohmatex-launches-new-washable-connector/

Figure 110. Fischer (n.d.). LP360TM connector. Retrieved from https://www.fischerconnectors.com/switzerland-en/en/products/lp360tm

Figure 111. Sports & Technology (n.d.). Hols Centre connection. Retrieved from https://sportsandtechnology.com/nieuws/smart-shirt-van-holst-centre-meet-vitale-functies-van-sporter/

Figure 112. Palmcrantz, S., Pennati, G. V., Bergling, H., & Borg, J. (2020). Feasibility and potential effects of using the electro-dress Mollii on spasticity and functioning in chronic stroke. *Journal of NeuroEngineering and Rehabilitation, 17*(1). https://doi.org/10.1186/s12984-020-00740-z

Figure 113. Mehmann, A., Varga, M., Gönner, K., & Troster, G. (2015). A ball-grid-array-like electronics-to-textile pocket connector for wearable electronics. ISWC 2015 - *Proceedings of the 2015 ACM International Symposium on Wearable Computers*, 57–60. https://doi.org/10.1145/2802083.2802093

Figure 114. Mehmann, A., Varga, M., Gönner, K., & Troster, G. (2015). A ball-grid-array-like electronics-to-textile pocket connector for wearable electronics. ISWC 2015 - *Proceedings of the 2015 ACM International Symposium on Wearable Computers,* 57–60. https://doi.org/10.1145/2802083.2802093

Figure 115. Wearic (2020). Smart textiles kit with nano controller. Retrieved from https://www.wearic.com/product/smart-textiles-kit/

Figure 116. Pulsea (2013). Vibration motor break-out module with snap fits. Retrieved from https://www.kobakant.at/DIY/?p=8293

Figure 117. DFRobot (n.d.). Modular electronics Boson. Retrieved from https://www.dfrobot.com/boson.html

Figure 118. Woop, E., Zahn, E. F., Flechtner, R., & Joost, G. (2020). Demonstrating a Modular Construction Toolkit for Interactive Textile Applications. ACM International Conference Proceeding Series, Figure 1, 1–4. https://doi.org/10.1145/3419249.3420075
Yazaki. (n.d.). Connector for FPC/FFC. Retrieved from https://connectors-catalog.sys.yzk.co.jp/english/3/033.html

Figure 119. Woop, E., Zahn, E. F., Flechtner, R., & Joost, G. (2020). Demonstrating a Modular Construction Toolkit for Interactive Textile Applications. ACM International Conference Proceeding Series, Figure 1, 1–4. https://doi.org/10.1145/3419249.3420075
Yazaki. (n.d.). Connector for FPC/FFC. Retrieved from https://connectors-catalog.sys.yzk.co.jp/english/3/033.html

Figure 125. Kooijman, A. (2021). Motor test with capacitor and
resistance chained in series. Personal photograph Adrie Kooijman

Figure 134. KinTec (n.d.). How screen printing works. Retrieved from https://www.kintec-machining.com/new/Surface-Finish-Silk-Screen-Print.html

Figure 140. Arduino (2021). Pulse-width modulation square waves example. Retrieved from https://www.arduino.cc/en/Tutorial/Foundations/PWM

Figure 182. Texas Instruments. (2018, March). DRV2604 Haptic Driver for ERM and LRA With Internal Memory and Smart-Loop Architecture. Retrieved from https://www.ti.com/lit/ds/symlink/drv2604.pdf?ts=1625229728716&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FDRV2604

Figure 183. de Hoog, G. (2021). The scope of the Gait Keeper project. Retrieved via personal communication

Figure 186. Elitac Wearables (2021). Company logo. Retrieved from https://elitacwearables.com/about/press/

Figure 187. Mood board for aesthetics inspiration:
Athos. (2021a). MEN's SHIRT w/Core. Retrieved from: https://shop.live.com/products/mens-upper-body-kit
Bo jangles (n.d.). XD Collection Fit watch. Retrieved from https://bo-jangles.co.uk/products/name/xd-collection-fit-watch/product_id/408854?size=&start=0
Cosco, A. (June 13, 2017). Canadian Apparel company myant launches skiin smart underwear. Retrieved from https://electricrunway.com/canadian-apparel-company-myant-launches-skiin-smart-underwear/
Elitac Wearables (2021). BalanceBelt. Retrieved from
Elitac Wearables (2021). NeuroShirt. Retrieved from
NightBalance (2019). Lunoa SPT. Retrieved from https://www.mylunoa.com/nl/
Owayo (n.d). Custom Cycling Jerseys C5 Pro Men. Retrieved from https://www.owayo.com/cycling-bikejerseys_pro-us.htm
Sensoria. (2021). Smart Sock V2.0 & Sensoria Core. Retrieved from https://store.sensoriafitness.com/smart-sock-v2-0-sensoria-core/
ShopStore (n.d.) Outfit para gimnasio hombre. Retrieved from https://www.en3stock.top/products.px?cname=outfit+para+gimnasio+hombre&cid=88
TeslaSuit. (2021). The Suit. Retrieved from: https://teslasuit.io/the-suit/
Wareable (June 18th, 2018). Nadi X smart yoga pants. Retrieved from https://www.wareable.com/wearable-tech/nadi-x-smart-yoga-pants-for-men-kickstarter-6217

Figure 204. PNGKit (n.d.). Perform activity. Retrieved from https://www.pngkit.com/bigpic/u2q8a9q8w7r5w7r5/

Figure 222. Precision Microdrives (2021). ERM in shaft configuration. Retrieved from https://www.precisionmicrodrives.com/content/ab-028-vibration-motor-comparison-guide/

Figure 223. Precision Microdrives (2021). ERM in coin configuration. Retrieved from https://www.precisionmicrodrives.com/content/ab-028-vibration-motor-comparison-guide/

Figure 224. Precision Microdrives (2021). LRA vibration tactor Z-axis movement. Retrieved from https://www.precisionmicrodrives.com/content/ab-028-vibration-motor-comparison-guide/

Figure 225. Precision Microdrives (2021). LRA vibration tactor Y-axis movement. Retrieved from https://www.precisionmicrodrives.com/content/ab-028-vibration-motor-comparison-guide/

Figure 226. Thorlabs (2021). Amplified Piezo vibration motor PK2F Series. Retrieved from Retrieved from https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_ID=8700

Figure 227. May (2018). Electrodes on human skin. Retrieved from https://www.clinicalpainadvisor.com/home/topics/back-spine-pain/low-back-pain/transcutaneous-electrical-nerve-stimulation-may-not-effectively-relieve-low-back-pain/

Figure 228. Linköpling University (2017). Electro active polymer knitted. Retrieved from https://liu.se/en/article/stickade-muskler-okar-kraften

Figure 229. MilitaryLeak (2020). The Mission Navigation Belt worn by Staff Officer Major van Veen. Retrieved from https://militaryleak.com/2020/07/08/first-elitac-wearables-mission-navigation-belt-delivered-to-royal-netherlands-army/

Figure 240. Wearablex (2020). Nadi X Mesh model. Retrieved from https://www.wearablex.com/collections/nadi-x-smart-yoga-pants/products/nadi-x-mesh?variant=36902329872

Figure 244. Spoor (2018). The downward facing dog position. Retrieved from https://wereldvanyoga.nl/nieuws/yoga-oefeningen/de-neerkijkende-hond-downward-facing-dog-in-yoga

Figure 290. Venere (2014). Zigzag sewn conductive yarn powering LEDs. Retrieved from https://phys.org/news/2014-06-simple-machine-high-tech-role-future.html

Figure 291. Baalman (2015). Embroidery of conductive yarn creating a touch sensitive keyboard. Retrieved from https://marijebaalman.eu/dafx/pages/Afroditi_Psarra.html

Figure 292. jmarks (2015). Weaving explained. Retrieved from https://jmarks001.wordpress.com/2015/04/25/warp-and-weft/

Figure 292. V2 (n.d.). Knitted speaker. Retrieved from https://v2.nl/lab/projects/betaknit-research

Appendix

A1. Project brief

DESIGN FOR our future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT
Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME
Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy".
Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: Leeger 4705
initials: D.M. given name: Dione
student number: 4351630
street & no.:
zipcode & city:
country:
phone:
email:

Your master programme (only select the options that apply to you):
IDE master(s): ☑ IPD ☐ DfI ☐ SPD
2nd non-IDE master:
individual programme: - - (give date of approval)
honours programme: ☐ Honours Programme Master
specialisation / annotation: ☐ Medisign ☐ Tech. in Sustainable Design ☐ Entrepeneurship

SUPERVISORY TEAM **
Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: K.M.B. Jansen dept. / section: SDE / EM
** mentor: A. Kooijman dept. / section: SDE / DE technical sup.
2nd mentor: G. de Hoog
organisation: Elitac Wearables B.V.
city: Utrecht country: The Netherlands

comments (optional)

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair K.M.B. Jansen date 11 - 02 - 2021 signature Kaspar Jansen Digitally signed by Kaspar Jansen Date: 2021.02.11 13:54:46 +01'00'

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 30 EC

Of which, taking the conditional requirements into account, can be part of the exam programme 30 EC

List of electives obtained before the third semester without approval of the BoE

★ YES all 1st year master courses passed

NO missing 1st year master courses are:

name J. J. de Bruin date 11 - 02 - 2021 signature J. J. de Bruin, SPA Digitally signed by J. J. de Bruin, SPA Date: 2021.02.11 14:40:33 +01'00'

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: ★ APPROVED / NOT APPROVED

Procedure: ★ APPROVED / NOT APPROVED

comments

name Monique von Morgen date 02 - 03 - 2021 signature

Initials & Name D.M. Leeger 4705 Student number 4351630

Title of Project A haptic feedback wearable technology: modular, scalable and cleanable

A haptic feedback wearable technology: modular, scalable and cleanable | project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 22 - 02 - 2021 | 23 - 07 - 2021 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The main stakeholder in this graduation project is Elitac Wearables, a specialist in developing haptic feedback wearables and garments for the health, safety/professional and sport sectors. They develop products made from a textile carrier on which haptic tactors and a control module is placed to provide haptic feedback to its user. The products Elitac wearables has currently designed are either for research and R&D purposes (e.g. on human motion) or to provide haptic feedback to a specific target user in a context. An example of a research product is the ScienceSuit, a unisex shirt that allows users to place a string of in series chained vibration motors (tactors) and a control module at a preferred location on the body. The BalanceBelt and the Mission Navigation Belt are two examples of products that provide haptic feedback to a target user. Whereas the BalanceBelt helps people with severe balance disorders to gain back their balance, the Mission Navigation Belt is designed for soldiers to feel waypoint navigation cues through haptic feedback (Elitac Wearables, 2021a).

Even though the current products of Elitac Wearables are designed to do their job well, the company wishes to improve and innovate the technology used and integrate the textile carrier with the electronics more in future designs. Allowing them to pioneer further in the technological trend of smart textiles and wearables for professional/commercial use, while also maintaining a competitive advantage over rivalling companies.
During this graduation assignment they ask for the embodiment design of a modular, widely implementable, cleanable & cost-effective electronics design, that is more integrated in the textile carrier and remains ergonomically to wear on the body.

Limitations of the project are mainly the washability & robustness of electronics, as electronics are currently not washable and robust by itself, which creates a challenge when integrating them in a garment that will be worn and cleaned by the end user. Furthermore, it is not common to wear a smart garment making it important to keep the psychological effects and social acceptance of wearing a smart garment in mind. Also, data collection and processing are used in smart garments, which should adhere to the privacy laws stated by government. This, however, is the responsibility of the parties developing the application for the product in the project, and not Elitac Wearables.

A great opportunity of the project is to try and apply in practice research done on robust electronical interconnections and integration of electronics with textiles. This can decrease the time it takes for these innovative new technologies to go to market so the world can hopefully profit from them faster commercially.

Recently Elitac Wearables has launched a Eurostars funded project called the Gait Keeper, in which they are to design a SMART haptic feedback wearable that improves the process of people learning to walk with a prosthetic leg. The goal of this project is to design a product that learns people how to walk with a prosthetic leg faster, easier and safer. The partners involved in this project are: TNO, GaitUp and Ottobock. Elitac Wearables is responsible for the design and embodiment of the smart garment that provides haptic feedback to the prosthetic leg user. This project will be used as a case study when designing a garment/wearable to test the new technological design. However, it is to be kept in mind that the company is looking for a solution that is not only suitable for this case study, but also implementable in other products as well. See figure 1 for the scope of the Gait Keeper project to be used as a case study in this project.

Elitac Wearables. (2021a). Our work. Retrieved from https://elitacwearables.com/projects/

space available for images / figures on next page

introduction (continued): space for images

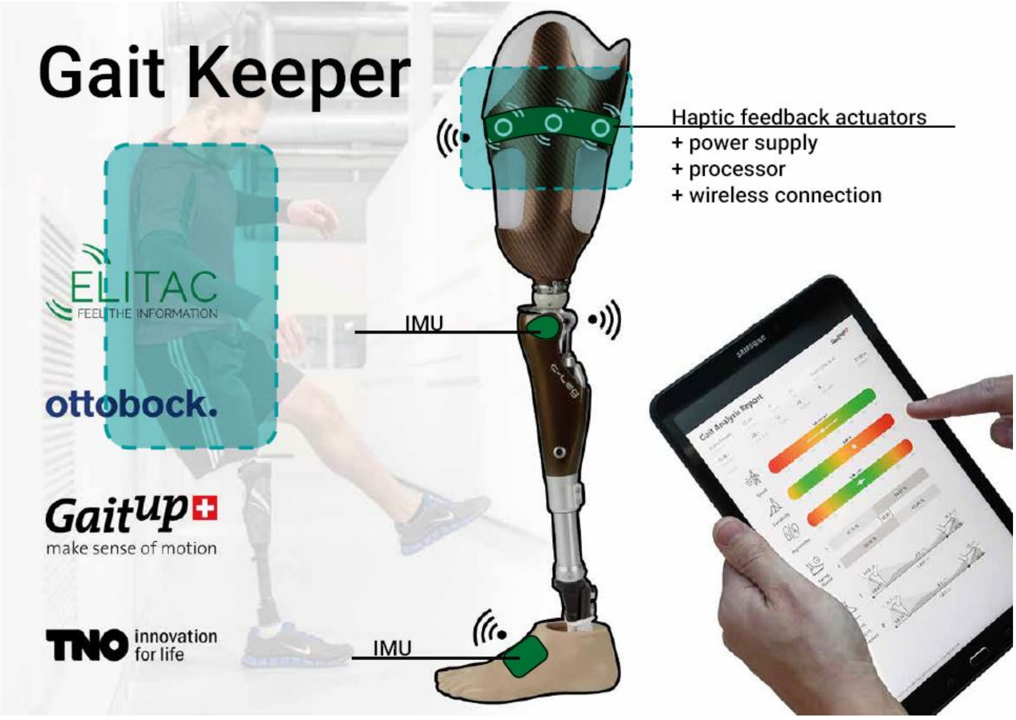


image / figure 1: The Gait Keeper project; scope present in blue (G. De Hoog, personal communication, Jan 17, 2021)

image / figure 2: A haptic feedback string with 9 tactors and a command module of Elitac Wearables (2021b).

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

In the current products designed by Elitac Wearables the haptic feedback electronics and the textile carrier are two separate entities. Furthermore, the electronics consist of a string of in series chained vibration motors (tactors) and a control module (see figure 2). As the electronics do not have the same flexible and stretchable characteristics as textile, connecting these two currently results in pulling and stretching of the textile carrier, decreasing the usability and aesthetics. Therefore, Elitac Wearables is looking for a more integrated technology that behaves as textile or can decrease the negative influences on the textile carrier. Moreover, the assembly of a tactor string is time intensive, as each tactor currently has 8 soldering points, all parts need to be connected via electrical cables and overmoulding is used to protect the tactors. Also, if the tactors are placed too close together, overmoulding is difficult as the mould will not fit in between the tactors, and interference might arise if wires overlap or are placed too close together on the textile carrier. Lastly, the current electrical cables are stiff, twist the tactors and when washing the textile carrier all electronics must be removed.

In order to optimise and improve the applicability of the electronics in future products and to keep a competitive advantage over their rivals in the haptic feedback smart textiles sector, Elitac Wearables asks for: The embodiment design of a modular, widely implementable, cleanable & cost-effective electronics design that is more integrated in the textile carrier and remains ergonomically to wear on the body.

What will be inside the scope of this assignment: The wiring, electronical modules (tactor, control module), the (inter-) connection between modules & the textile carrier and the cleanability of the system. Furthermore, the type of garment/wearable, the location, its material, the configuration and amount of tactors used. Also, the ergonomicalky design and aesthetics will be included. What will not be part of the scope: Vibration patterns, data processing & visualisation (user interface) of the IMU's, the IMU's design and its connected PCB together with firmware.

Elitac Wearables. (2021b). ScienceSuit. Retrieved from https://elitacwearables.com/sciencesuit/

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

The main focus lies on designing the embodiment of a haptic feedback wearable, of which the technology, is scalable and uses robust (inter)connections between parts. A second focus point will be the integration of the electronics with the textile carrier and thirdly the cleanability of the complete design will be analysed and tested.

The aim is to deliver a functional prototype of a complete textile wearable that includes at least 1 control module and 1 tactor. Next to this a mock-up prototype should be delivered that shows a more complete configuration (all tactors and command modules) of the design in real-life and that can be ergonomically tested. In the utmost ideal case, a complete functional prototype instead of only a mock-up will be developed.

Feasibility: The current products and electronics used by Elitac Wearables will be analysed, to get an understanding of the electrical parts that must be implemented in the design and the general product requirements.

Possible interconnection options for electrical modules and the connection possibilities for the textile carrier and the electronics will be researched in literature and existing products. A benchmarking will be used to choose the most promising options for initial testing. Furthermore, the cleanability options of the design will be analysed and tested. Resulting from this research, proof of principle prototypes will be created and tested to determine the best direction for concept development followed by the final design and prototype to be tested with humans

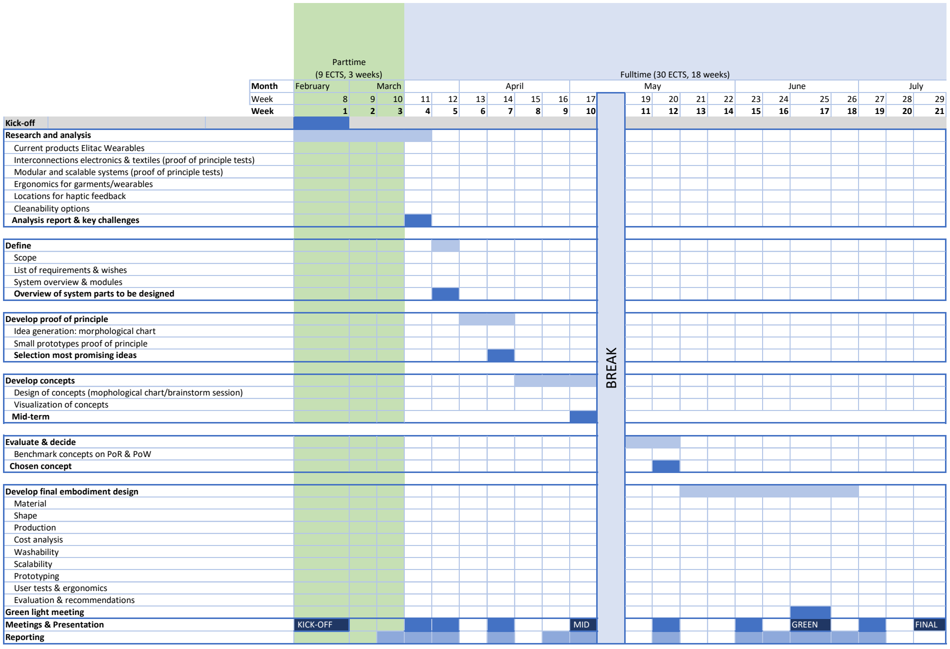
Desirability: The problems and wishes of the company will be analysed first, by interviewing Elitac Wearables and by studying their current products. The chosen type of garment/wearable, the location on the body, the materials used and the electronical configuration will be based on informed choices and ergonomically tested for comfort.

Viability: The cost-effectiveness of the design will be benchmarked against current products of Elitac and the producibility, applicability and scalability of the design will also be considered and evaluated.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 22 - 2 - 2021 23 - 7 - 2021 end date



Initials & Name D.M. Leeger 4705 Student number 4351630

Title of Project A haptic feedback wearable technology: modular, scalable and cleanable

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

Ambition 1: Gaining in-depth knowledge on what is necessary to create a wearable and usable smart garment for commercial use. What challenges do we need to overcome to bring this new technological trend to market faster?

Ambition 2: Improving my prototyping skills of smart textiles/wearables. Currently I already know how to create garments and I have some experience with prototyping electronics, but the combination is an intersection of two interests of mine. I want to learn how to combine these two interests and explore if I want to pursue a job in this direction.

Ambition 3: I want to learn more about how the company Elitac functions, tackles projects and what methodologies they use to achieve their goals. This will give me additional practical experience when working on a project besides the experience I have already gained during my bachelor and master programmes. Hopefully I can learn from them and use some of their knowledge, so I can apply this in my graduation project and help to improve the communication and final results.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

A2. Haptic feedback technology

In this paragraph different possibilities to provide haptic feedback are analysed. The positive and negative sides of each option are explained in order to explore new possible ways in future designs.

ERM vibration tactors

At present Elitac Wearables uses Eccentric Rotating Mass (ERM) for haptic feedback in their designs. This technology spins around an unbalanced mass to create vibration, which is either done in a shaft or coin configuration, see Figure 222 & 223. This technology relies on direct current (DC) voltage to operate. The shaft configuration can provide stronger haptic feedback than the coin configuration. These type of tactors are cheap and can provide strong haptic feedback that can be felt through multiple layers of fabric. Downsides are that they require a lot of power to be actuated, are heavy, bulky and vibration options are limited. Furthermore you have brushed and brush-less ERMs, of which the brush-less ERM has more durability (Precision Microdrives, 2021).

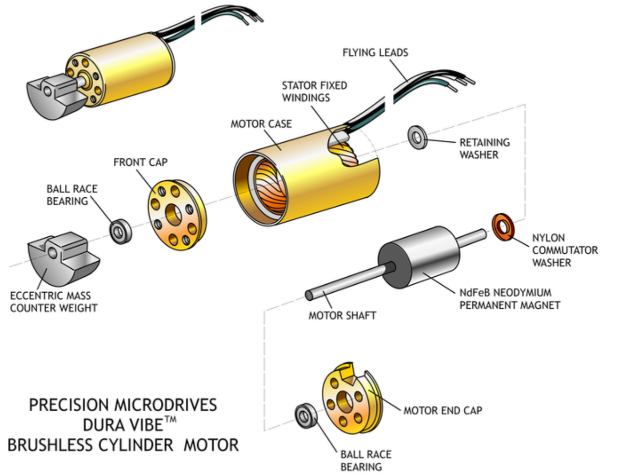


Figure 222. ERM in shaft configuration (Precision Microdrives, 2021).

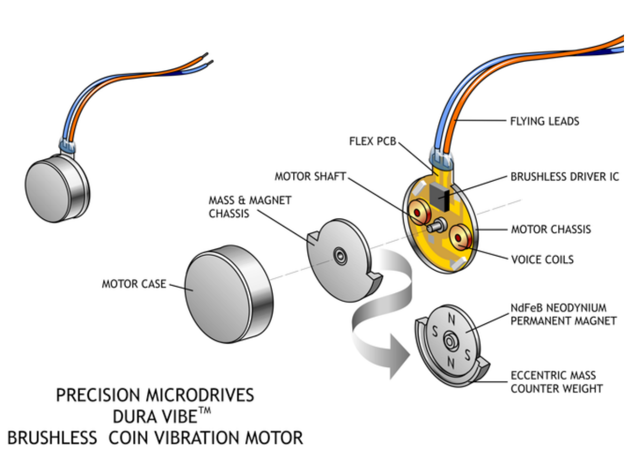


Figure 223. ERM in coin configuration (Precision Microdrives, 2021).

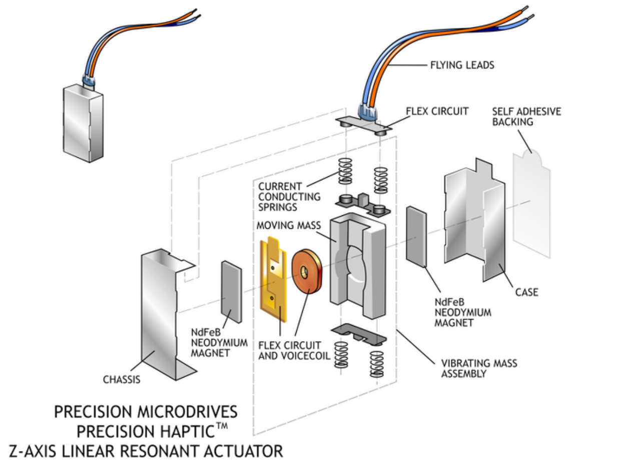


Figure 224. LRA vibration tactor Z-axis movement (Precision Microdrives, 2021).

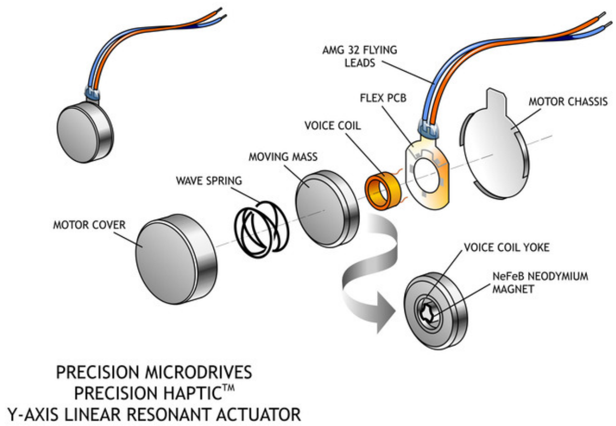


Figure 225. LRA vibration tactor Y-axis movement (Precision Microdrives, 2021).

LRA vibration tactors

Linear Resonant Actuators (LRA) use a magnetic coil and spring to push a mass up and down and relies on alternating current (AC) voltage. This movement can either be done in a coin configuration over the Y-axis or a more squared configuration in the Z-axis, see Figure 224 & 225. These vibration motors are also cheap, are less heavy, require less power and have a faster start-up time than ERMs. However, they are still bulky, difficult to integrate in textiles and less powerful than ERM vibration tactors (B. Bicknese, personal communication, Apr. 20, 2021).

Piezo electric vibration motors

A new development in the field of vibration motors are Piezo vibration motors, which produce small displacement with a high force capability when applying voltage (Zhang, 2010). These actuators are extremly costly compared to ERMs and LRAs, however they do allow for more precision actuation are much smaller en less heavy. They also require less power. Though they are quite fragile and need direct contact with a mass to transport the vibration. To solve the latter problem, amplified Piezo vibration motors can be found as shown in Figure 226. According to Kirstein (2013) Piezo electric materials have real potential for smart-textiles development and commercialization.

Electrostimulation

Electrostimulation is a method that uses small currents provided by electrodes to active muscles in human beings. This method is used in the Tesla Suit and allows for real precision haptic feedback sensation and integration of electronics. However it does need direct contact with the user's skin (Figure 227) and any bad connection can cause pain or nauseating feelings according to W. De Vos (personal communication, March 9, 2021)

Electro Active Polymers

Electro Active Polymers (EAP) can change shape, size and or volume when influenced by a strong electrical field according to Kretzer (2013). Piezo electrics fall under EAP, but also some shape memory alloys (SMA) and shape memory polymers (SMP). EAPs stand out due to their high response speed,

Figure 226. Amplified Piezo vibration motor PK2F Series (Thorlabs, 2021)

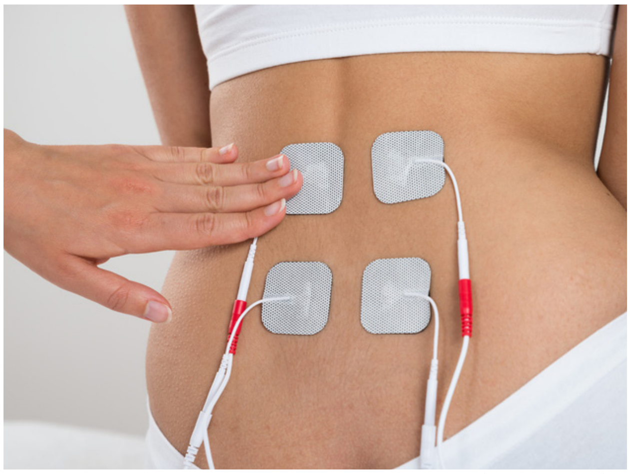


Figure 227. Electrodes on human skin (May, 2018)

Figure 228. Electro active polymer knitted (Linköpling University, 2017)

low density and large deformation potential. Moreover, they are often lightweight, fracture tolerant and inexpensive according to Bar-Cohen (2004). A downside is that they require precision engineering for each application. An example of a textile EAP can be found in Figure 228.

All pros and cons of each haptic feedback actuator were collected and summarised in Table 13.

Conclusion

For ***low duty cycles*** and ***limited haptic feedback*** the cheap ***ERM*** option is best. However if the ***duty cycle increases*** or more ***diversity in haptic feedback*** is needed ***LRA*** is the better option. Though for battery powered products, an additional DC to AC converted needs to be implemented. For ***real precision haptic feedback*** a ***piezoelectric vibration motor*** is a valid option, however they do need a mass to transport the vibration created. ***Electrostimulation*** is another option, that activates the nerves of a human being to create haptic feedback. This is a good option if the ***product is worn tightly and directly on the skin***. A final option is ***Electro Active Polymers***, that can be ***customized on material properties.*** However this does require precision engineering for each application.

Type of haptic feedback tactor	*Costs (EUR)*	*Start-up & stop time*	*Voltage / Current*	*Pros*	*Cons*
Eccentric Rotating Mass (1) (ERM)	< 1,-	50 - 100 mS & 50 - 100 mS	1.5-24V/ 120-250 mA (DC)	Cheap, powerful vibration	Bulky, heavy difficult to integrate, limited haptics motions and effects
Linear Resonant Actuators (LRA) (1&2)	< 1,-	40 - 60 mS & several 100 mS	1.2-2V/ 80mA (AC)	Cheap, less heavy than ERM	Not as powerful as ERM, bulky, difficult to integrate, bulky Requires AC
Piezo electric vibration motor (3& 4))	> 10,-	Faster reaction time than ERM & LRA	0-75 V	Precision actuation, small & light weight	Expensive, vulnerable, needs direct contact with a mass to transport vibrations
Electrosimulation	n.d.	Allows for more integration in textile	n.d.	Allows for more integration in textile	Direct contact with the skin necessary, Can cause pain/bad feeling during bad contact
Electro Active Polymer (EAP)	n.d.	Fast reaction time	n.d.	Light weight, fracture resistant, inexpensive	Still in development & material engineers needed

Table 13. Feedback actuator options and their pros and cons
(1) Schweber (2020). (2) NFP (2021). (3) Thorlabs (2021) & (4) Digikey (2020).

A3. Product portfolio Elitac Wearables

Product	*Sector*	*Type*	*Feedback type*	*Electronics*	*Battery powered*
Balance Belt	Health	Belt	Haptic	1x Accelerometer 10x Vibration motors	Yes 6h to charge 16h power
Mission Navigation Belt	Defense	Belt	Haptic	7 equally spaced vibration motors 1 compass 1 control module	No, draws from soldiers GPS system/smart phone
NeuroShirt	Health	Shirt	Haptic	14 Vibration motors on the back 1 control module + small battery?	No, draws from external computer (controll module does have small
Smart Shoulder	Safety	Vest	Light & Data	Panic button Light sensor 3 Power LEDs Battery (2x of the balance belt) (Imu inwendig?)	Yes Xh to charge Xh power
Cycling Shirt	Sports	Shirt	Haptic	Heartrate sensor Vibration motors 1 conrol module + battery	No, plug-in (phone or external control module)
Smart Shirt	Sports	Shirt	Haptic & Data	IMU? Micro processor Vibration motors	Yes?
Sentaz Tactil Navigation	Vehicle Safety	Sensors in chair	Haptic	Vibration motors	No, draws from car battery?
FysioPal	Sports	Top	Haptic	1 IMU Vibration motors	Yes? Xh to charge Xh power
ScienceSuit	Research	Top/Shirt	Haptic	Vibrations motors (9-16)	Yes? Xh to charge Xh power

Table 14. Overview of all products developed by Elitac Wearables until now and their use cases

Product overview

In Table 14 all the current products designed by Elitac Wearables are analysed to get a better overview of the different applications, technology involved and use cases. From this we can derive generally used electrical components such as the vibration motors and IMU's, the level of waterproofing necessary (minimally IP54), the demanding environment in which products are used (often dynamic and outdoor).

Product	*Use case*	*Intensity use*	*Waterproof/ Cleanable*	*Compatability*	*Remarks*
Balance Belt	Everywhere Indoor/outdoor Active/passive	Daily	No, but washable sleeve	n.a.	size XS-XL Lightweight
Mission Navigation Belt	During missions active	Daily	Yes, IP54? Washable sleeve	soldiers gps system	Robust, Perfect fit sizeable tech
NeuroShirt	During surgery inside, active	5 days a week 8h/day	No?	3rd party navigation system	Worn underneath surgery cloth
Smart Shoulder	Outdoor/indoor Remote areas Active	5 days a week 8h/day	Yes IP54? Waterproof	3rd party HQ communic- ation systems	Design can be expanded in the future
Cycling shirt	During training Active	1-5 times a week	IP54	n.a.	Byborree designed & knitted shirt
Smart Shirt	During training Active	1-5 times a week	IP54	n.a.	Data driven algorithms
Sentaz Tactil Navigation	Inside vehicles Static sitting user	Daily	n.a.	3rd party vehicle gps system	n.a.
FysioPal	Everywhere Indoor/outdoor Active/passive	Daily	unknown	n.a.	Worn underneath cloths
ScienceSuit	Everywhere Indoor/outdoor Active/passive	Unknown	Separate electronics from washable textiles	3rd party laptop and devices	Moisture-wicked mesh material 7x Velcro straps to fit

Conclusion:
Elitac Wearables has two distinctive product categories: upper body garments and belts. Almost all of their designs are based on providing the user with haptic feedback based on processed data. The products are used in physically demanding situations such as sports and need to be able to withstand outdoor conditions. The level of waterproofing which is now minimally IP54 should be taken into account in the future design of the system as well.

Mission Navigation Belt in detail

According to Elitac Wearables, if the solution developed is applicable for two of their existing products (from the different product categories), that would be a success measuring factor (G. de Hoog, personal communication, February 25th, 2021). Therefore, to understand the requirements and possible contexts of use of the solutions to be designed, two products of Elitac Wearables are analysed in depth on use case, design, electronics, production techniques and materials. The Mission Navigation Belt (MNB) is analysed from the belt product category.

General information

The MNB was designed in collaboration with the Netherlands Ministry of Defence and is designed to help navigate soldiers in an intuitive and safe way. It translates GPS direction signals to intuitive haptic feedback signals, while keeping the eyes, hands and ears of the soldier free (Elitac Wearables, 2021e).
The design consists out of two parts: The outer belt the inner sleeve with electronics. This construction was chosen due to the fact that the product should be washable at an industrial level, together with the soldiers uniform. Before washing, the inner sleeve is removed with the electronics so the outer belt can be washed.

Use-case

The lightweight belt is worn around the waste (Figure 229) by a soldier on a mission. This can be a stealth mission, but also a very dynamic one in which the user is moving a lot (e.g. a speed boat or while running). It is compatible with the armour and equipment of the soldier and can withstand harsh outdoor environments due to the use of strong material.

Design

The outer belt

This part comes directly in contact with outdoor environments and the soldiers body. It protects the inner sleeve and electronics from water as it has IP54 waterproofing.
A buckle is used to place the belt around the waist of the soldier. See figure 230 for an overview of the outer belt's design. Also, a special sizing system is implemented so it can fit each soldier perfectly without affecting the accuracy of the navigation.

The inner sleeve

The inner sleeve has all the electronics embedded. It consists of a foam like material that has cut-outs for the electronics. By embedding the electronics in the foam, they are more protected and the product is more ergonomically to wear.

Figure 229. The Mission Navigation Belt worn by Staff Officer Major Van Veen (MilitaryLeak, 2020)

Electronics

In the MNB the following electronics are implemented: 7 equally spaced vibration tactors, 1 altitude and heading reference system (AHRS) and one general control module with an individual small battery for power. A special military cable is integrated as well, to connect the system to the military GPS system of the soldiers.

Production techniques

The main production method used is sewing. Also, soldering is used to connect the electronics and overmolding to connect these to the inner sleeve foam. The cut-outs are constructed through laser-cutting.

Materials

On the inside of the MNB mesh spacing is used for comfort and the outer materials is made of Cordura. Also twill tape can be found, for sizing and attachment of the buckle. The sizing system can be fixated by the use of Velcro. The inner sleeve consists out of foam and a mesh material that helps keep the electronics in place.

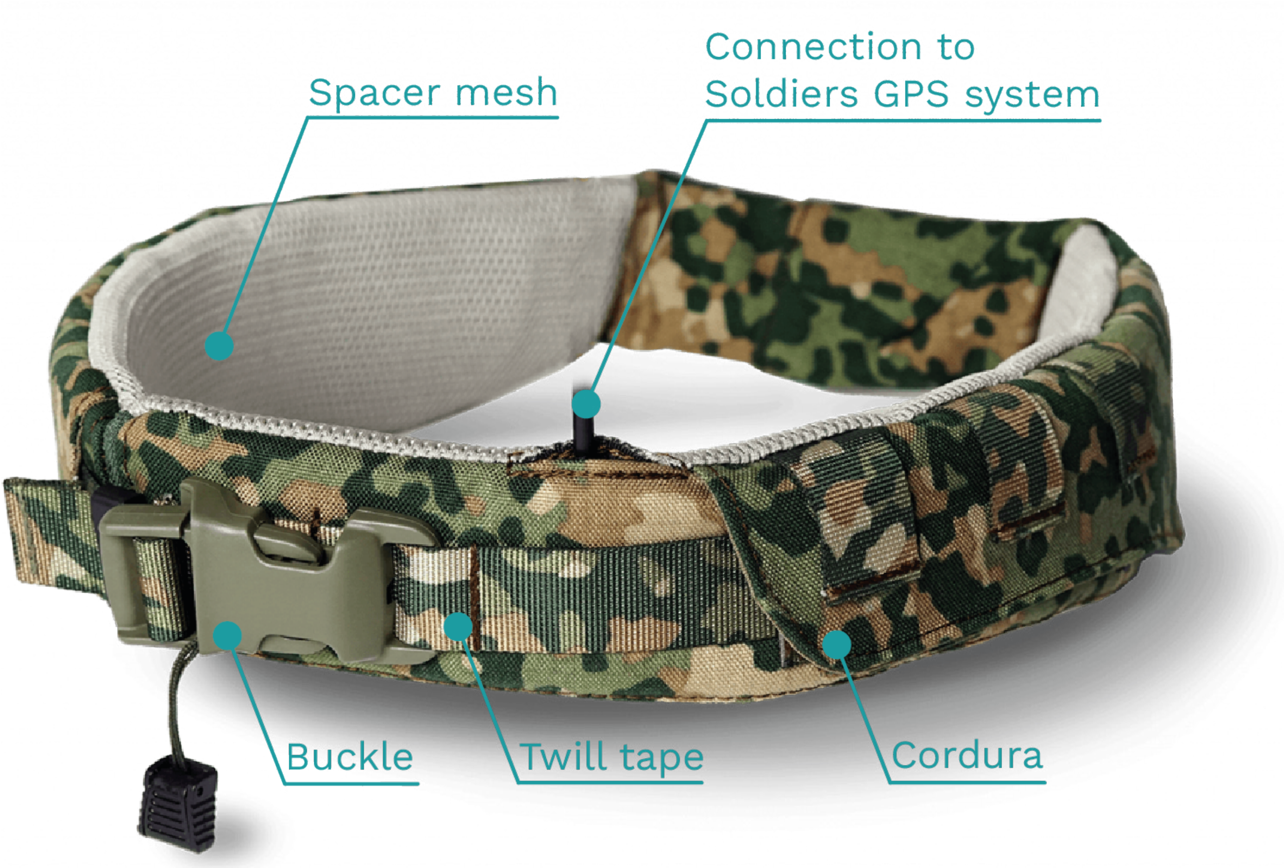


Figure 230. The Mission Navigation Belt (Elitac Wearables, 2020)

NeuroShirt in detail

The NeuroShirt is analysed, as it is one of the few products that uses that many vibration tactors in a widely spread constellation, making it a good case study for understanding design requirements of the technology used.

General information

The NeuroShirt was developed in collaboration with the UMC Utrecht. It translates data form the neuronavigation system to haptic feedback vibrations for neurosurgeons, to inform them about the proximity of critical structures such as veins and nerves. It indicates both the direction and the distance of these critical structures, while allowing the surgeon to keep their eyes on the patient in stead of watching the neuronavigation system screen (Elitac Wearables, 2021f). The NeuroShirt exists of three parts: The inner shirt, the tactor backplate and the outer shirt. See Figure 231 for the front and back view of the NeuroShirt.

Use-case

This product is used during skull based neurosurgery by a neurosurgeon. It will be worn in the surgery room underneath the surgery cloths. Focus and precision of the surgeon is key in these situations.

Design

The inner shirt

The inner shirt consists of a simple sports T-shirt with a tight fit. This shirt prevents the tactor backplate coming into direct contact with the human skin.

The tactor backplate

The tactor backplate houses all vibration tactors and can be connected to the inner shirt via Velcro. This allows for removal of the electronics before washing the rest of the shirt.

Outer shirt

The outer shirt is made of a stretchy material and allows us to cover the tactor backplate, so it is protected from direct contact with the outdoor environment and potential dirt. This construction allows for the sandwiching of the tactor backplate between the inner and outer shirt, see Figure 232. The shirt is closed by the user of a zipper on the front torso.

These three mentioned parts are layered on top of each other as presented in Figure 233.

Figure 231. NeuroShirt with tactors on the back (Elitac Wearables, 2021)

Electronics
The electronics consists of 14 vibration tactors and a control module that is compatible with the neuronavigation system of hospitals. The product draws power directly from this same system and does not require an additional battery.

Production techniques
The product is mainly produced through sewing of the textile materials. The electronics are connected via soldering, and these parts are then over-molded for waterproofing. And additional padding with cut outs is used to fixate the vibration motors again.

Materials
The shirt materials consists of a mixture between polyester and polyamide. Furthermore foam and (spacer) mesh is used to enable the fixation of vibration motors. Duotec Velcro by 3M is used to connect the tactor backplate to the inner shirt. To finish off any rough edges (stretch) bias is used.

Figure 233. Sandwich construction of materials

Figure 232. NeuroShirt front and back view (Elitac Wearables, 2020)

A4. NaviBelt research pictures

Figure 234. Packaging NaviBelt

Figure 235. Inner and outer belt construction

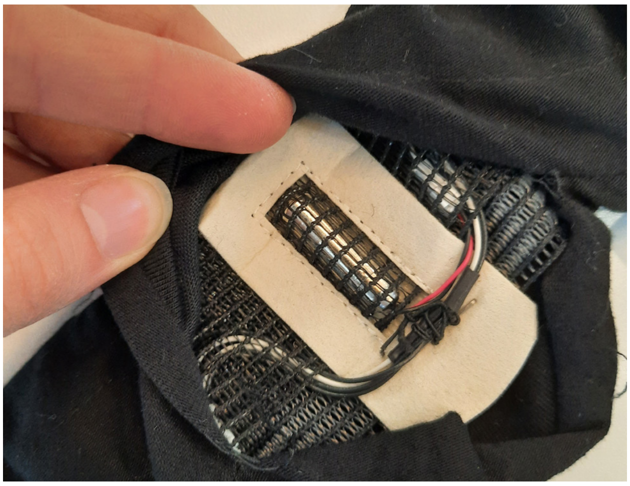


Figure 236. ERM shaft vibration motor fixation

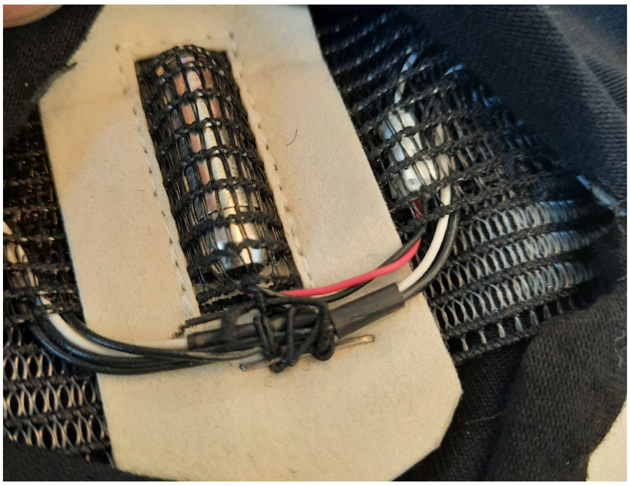


Figure 237. ERM cables close-up

Figure 238. Bottom view ERM fixation

Figure 239. Parallel circuit of ERMs

A5. Nadi X Product experience

The Nadi X Experience

As the Nadi X is an interesting product that we can learn from a lot when it comes to cleanability, one yoga pants is tested and opened up to get a better understanding of the materials used.

The model tested was the Nadi X Mesh shown in Figure 240. The size of the pants was an L, which made the fit comfortable but not tight as I am naturally a size S, see Figure 241. The idea of the yoga pants is that they are a tight fit. The large tactor modules are barely noticeable on the skin at first contact and after a few minutes I could barely feel them at all.

When trying to install the application that comes with the Nadi X, it became clear that the application was only developed for Apple devices. Which is really sad for Android users like me. In order to perform the test, I actually had to borrow an Iphone from a colleague.
After installing the application, I tried turning on "The Pulse", which is the control module and thus the brains of the pants, see figure 242. In order to active it, you had to tap the small slope side twice and white lights on the large slope would start to flicker as feedback. Then you had to click the Nadi X on the pants. This part was quit tricky, as the connection point is located on inside back of the left leg, see Figure 243. It is connected with 4 snap buttons, orientated in such a way that placement is only correct in one particular orientation. Therefore, I had to bend over all the way to get a good view on where to connect it. Apparently this took too much time, as the application told me it could not connect to the Nadi X. I tried waking it up again in the connected position, but this did not work. In order to active the Pulse properly, it has to be removed from the pants, double tapped and then placed on the pants. I would personally put it on the pants

Figure 240. Nadi X Mesh model (Wearablex, 2021)

Figure 241. Me wearing the Nadi X Mesh model size L with a comfortable fit and visible tactors.

and then tap it to activate. Not the best experience as it took me 3 times to actually get it connected properly.
After connecting, you can manually set the vibration intensity for your yoga session. I decided to put it on the strongest vibration as I had quite a loose fit of pants to what it was supposed to be. You could feel the different intensities, however the tactors did not start at all times to give feedback, and sometimes you would receive a constant vibration feedback and other times only a short pulse. Making the system feel unreliable for use.

Finally I felt confident that I could try my first yoga moves. The application provides you with a training that includes different poses. You can press play and automatically it will go from pose to pose.
The application will take you through each pose in a step by step manner with instructions in the form of text, animations and audio. The vibration motors vibrate when you need to move to a new pose and help you correct your posture during a pose. When doing the downward facing do (see Figure 244), I received a gentle vibration only at the knees and it instinctively told me that I should bend them just a little more. The vibration immediately stopped and I could move towards the next pose.

The application seems to continue on a rather slow pace and you can pause and click on the preferred pose if you missed it or want to redo it. During the session the application also gave feedback by writing “we’ve detected your pose“. For me this message felt quite unnecessary, as that is the whole reason why you would buy the Nadi X in the first place!
While practicing other poses I received haptic feedback that felt was unnecessary and at random moments. While practicing the warrior pose one of my knees started to vibrate really hard, though I had no idea what I was doing wrong. So at some points the feedback felt really natural and logic and at other moments in time I really did not understand why I was receiving vibrations at all.

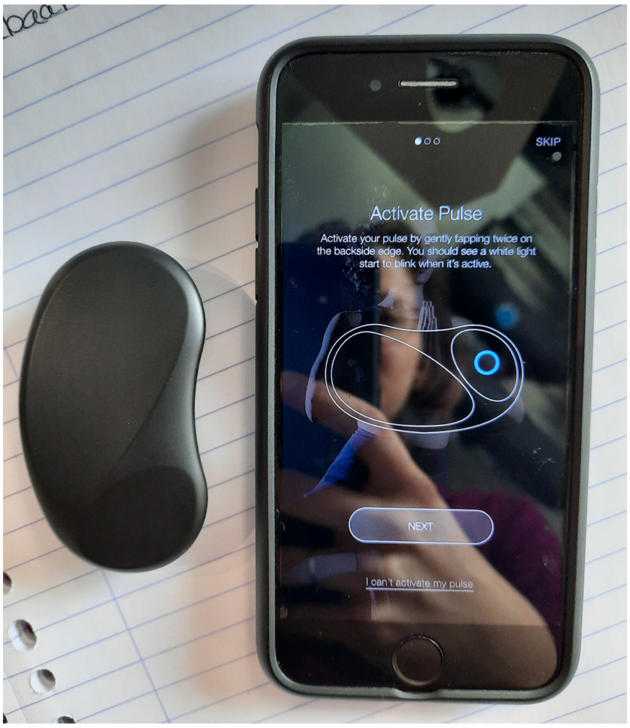


Figure 242. The Pulse and the instructions on how to active it

Figure 243. The location of the Nadi X on the inside back of by left leg

Figure 244. The downward facing dog position (Spoor, 2018).

A6. Technology benchmark Excel

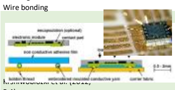
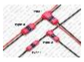
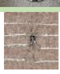
Wire connections

	General Information			Electrical properties		Processability				Mechanical properties					Market n	Additional info	Link
	Product	Image	Conductive material	Resistance (below 100 Ohm, preferrably below 6,85 Ohm)	Integration in textile carrier (1=really bad & 5=really good)	Connection possibilities	Ease of processing (1=really bad, 5=super good)	Dimensions	Tensile strength /Breaking Load/Breaking Elongation	Stretchability (If so what is the elongation)	Flexibility	Washability	Operating temperature	Lifespan	Costs		
Conductive yarn	Amberstrand 166 by Syscom Non-conductive core with conductive coating		Copper/Nickel/Silver	~3.28 Ω/m	3	Soldering, braiding (1.7 twists/inch), weaving, glueing, taping, crimping lamination & sewing (4.5 twist/inch).	2	0.246 mm (Thread diameter) 0.699mm (Flat width)	5.8 Gpa	Through design	Good	unknown	Up to 260 degrees C	Long (used in aircrafts)	Conductive	Tensile Strength 5.8 GPa Weight 0.159g/m Operating temp up to 260 degrees C Melting point 650 degrees C	https://static1.squarespace.com/static/558431b9e4b0875de16c5494/t/5d9d011bb7bacf1e9e34d93c/1570570527783/Amberstrand+166.pdf
Conductive yarn	Liberator 40 by Syscom Non-conductive core with conductive coating		Copper/Nickel/Silver	~3.3 Ω/m	3	Soldering, braiding (1.7 twists/inch), weaving, glueing, taping, crimping lamination & sewing (4.5 twist/inch)	3	0,226 mm (Thread diameter) 0.556 mm (Flat Width)	3.0 Gpa	Through design	Good	unknown	Up to 200 deg	Long	€€ 55 euro per 130 ft	Tensile Strength 3.0 GPa Weight 0.0126g/m Operating temp up to 200 degrees C Melting point 350 degrees C	http://www.metalcladfibers.com/liberator
Conductive yarn	X-steel Fiber based metal core (& coating)		Stainless Steel (AISI 316 L) & Nickel (coating)	~2.3 Ω/m	2	Soldering, braiding (1.7 twists/inch), weaving, glueing, taping, crimping lamination & sewing (4.5 twist/inch).	1		0.75 Gpa	Through design	Medium	unknown	Up to 260 deg	Long	€€ 65 euros per 130 ft	Tensile Strength 0.75 Gpa Weight 0.067g/ft Operating temp up to 260 degrees C Melting point 1,085 degrees C	http:// www.metalcladfibers.com/xsteel
Conductive yarn	Amann Silver-tech 30 Tex 96 500m X8 Non-conductive core (polyester) with conductive coating		Silver	<85 Ω/m	5	Sewing, knitting, weaving, taping, crimping, glueing, lamination	4	0,40 mm		Through design	Good	Yes on a silk washing cycle, but resistivity changes a bit over time but stays around the same level. Still a limited # of			€€	Needle size Nm 120-13	https://www.amann.com/fileadmin/user_upload/AMANN_TechX_Brochure_EN.pdf
Conductive yarn	Shieldex 235/36 dtex 2 ply HC + B by Statex		Polyamid 6.6 filament yarn metal plated with 99% Pure Silver	80 +/- 30 Ω/m	4	Sewing, knitting, weaving, taping, shrinking, glueing, lamination, crimping	4	0.75 +/- 0.15 mm diameter	Elongation until break 30% +/- 5%	Through design	Good	Yes, but resistivity increases = limited # of washes (Zaman, 2019)	Max 140 degr	Long	€€	Tenacity 50cN/tex +/-	https://statex.de/en/shieldex-tpu-yarns/
Conductive yarn	Elektrisola 31810512 Single metal core and metal coated		Copper & Silver (coating) single core CU/Ag20	2.2 Ω/m	4	Sewing, Knitting, Weaving, glueing, lamination, crimping Not solderable	3	0.1 mm diameter		Through design	Medium	Handwash up to 95 degrees		Long	€€		https://www. elektrisola.com/enamelled-wire.html
Conductive yarn	Elektrisola 31900286 Single metal core and metal coated		Copper & Silver (coating) single core CU/Ag20	2.7 Ω/m	4	Soldering, Sewing, Knitting, Weaving, glueing, lamination, crimping	3	0.09 mm diameter		Through design	Medium	Handwash up to 40 degrees		Long	€€		https://www.elektrisola.com/enamelled-wire.html
Conductive yarn	Bekinox VN 12.1.2.100Z Metal core		Steel	30.0 Ω/m	4	sewing, knitting, weaving, glueing, welding, shrink sleeve, taping, lamination	3			Through design	Good				€€		https://docs.google.com/spreadsheets/d/11QTB10Z5B_FMFsox1jg0A_kkd2u1IWOPe4Unbci7xJQ/edit#gid=806549140
Conductive yarn	Taierxin Polyester, nylon substrated carbon		Carbon	10^3~10^5 Ω/cm	3	Sewing, glueing, Lamination, gripping	2	unknown	50-70%	Through design	Good	unknown		Medium	€€		https://www.taierxinfiber.com/conductive-yarn/conductive-fiber-and-thread.html
Conductive fabric	Statex Shieldex non-woven		Silver/Copper/Nickel/Tin	Basel < 1 Ω/□ Bern < 2,5 Ω/□ Bilbao < 2,5 Ω/□ Born < 0,5 Ω/□ Kiel +30 0,02Ω/□ Average Kiel-SK-96 0,02Ω/□ Kiel wallpaper 0,02Ω/□ Köln ≤ 0.06 Ω/□ Nice 0,02Ω/□ (max 0.05) Nikko< 0.02Ω/□	4	sewing, taping, glueing.	4	Up too 100cm +/- 2 cm per 200 m roll		No	Good	Yes, some of them		Medium	€€		https://statex.de/en/shieldex-non-wovens/
Conductive fabric	Statex Shieldex knitted Knitted variants, single or double direction DS		Silver coated and some have	Balingen < 0.6 Ω/□ CombiTex <1 Ω/□ Silitex P130 <5 Ω/□ MedTex P70 unknown Ω/□ MedTex P130 unknown Ω/□ MedTex P180 unknown Ω/□ Technik-tex P130+B < 2 Ω/□ Technik-tex P180+B < 2 Ω/□ Tüll < 1,4 Ω/□	4	sewing, taping, glueing	4			Yes	Good	Unknown		Long	€€		https://statex.de/en/shieldex-knitted-fabrics/
Conductive fabric	Statex Shieldex woven		Silver & Copper	Ω/□ Berlin unknown Nora RS <0.03 Ω/□ Nora Dell Average 0.009Ω/□ Pisa unknown Porto ≤ 0.02 Ohms/□ Prag Average < 0.05 Ohm/□ The rest is unknown for now	3	sewing, taping, glueing.	4			No	Good						https://statex.de/en/shieldex-woven-fabrics/
Conductive textile	Liquid X E-textiles & Ink		Particle free ink	1.5-2.4 Ohm/square	4	Inkjet printing for the textile industry. Electronics can bedirectly mounted onto conductive trace using expoxy, solder paste, snaps, etc.	3			Yes up to 18%	Good	Yes, tested up to 100 cycles				Bendable up to 10.000 bend cycles Stretchable up to 180% Washable with stable resistance Protective coatings and dielectrics available for added protection	http://www.liquid-x.com/e-textiles/

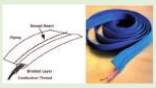
Wire connections extended

Conductive Ink	FabInks-UV-1004	Silver	~30 Ohm/square	4	Inkjet, screen printing, glueing	3		Through design	Good		€€€ 350,- /100g		http://www.fabinks.com/product/
Conductive ink	Fabinks TC-C4001	Silver	~30 Ohm/square	4	Inkjet, screen printing, glueing	3		Through design	Good		€€€ 450,- /100g		http://www.fabinks.com/product/
Conductive ink	DuPont PE873 stretchable conductor paste	Silver	<75 mΩsq/25µm	4	Inkjet, screen printing, glueing	3		Through design	Good		€€€		https://www.cci eurolam.com/de/ https://www.dupont.com/content/dam/dupont/amer/us/en/products/ei-transformation/documents/PE8
Conductive ink	Conductive ink by Sicrys	Silver	< 10 micro ohm/cm Sheet resistance is 10 micro Ohm/thickness in micro meter	4	Inkjet, screen printing, glueing	3						adhesion tested on ITC	https://www.pvnanocell.com/general-purpose.html?gclid=CjwKCAjw3pWDBhB3EiwAV1c5rMx8XPn94BQsCw6ndItnCKRrzSQkhZamQqsVgaemls5PwM
	 Bare conductive Electric paint		55 Ω/Sq/50 microns	4	screenprinting, painting, glueing	3		No	Medium	Not without protection		Works on paper/wall etc.	https://www.bareconductive.com/collections/all/products/electric-paint?variant=37766230900916
	 Yodaoke flat cable	Copper	unknown	2	Soldering, crimping, glueing, welding	2	6 mm						https://www.fswaene.com/yodaoke-10ft-6mm-flat-copper-braid-cable-bare-copper-braid-wire-ground-lead-p-652992.htm
conductive tape	LiTex conductive tape Woven copper and TPU, stretchable and non-stretchable 	Copper	362.2 Ohm/km (max 0.2 A) 213 Ohm/km (max 0.3 A) 89.4 Ohm/km (max 0.921A)		Sewing, taping, glueing, solder (after removal of insulation layer), crimping, lamination	4	0.631-0.9 mm	Yes	Good	Yes			https://litextile.files.wordpress.com/2018/02/2018-wired-conductive-tape.pdf
conductive tape	 Single-side adhesive conductive cloth tape Fabric tape one sided adhesive	unknown	unknown	2	taping	3	5-45 mm thickness				€ €9,07/20 m	Interference shielding	https://www.aliexpress.com/item/32862472443.html?spm=a2g0o.cart.0.0.13023c00Hs6qBJ&mp=1
Conductive flat cable	Ohmatex flat cables, not available on the market any longer 	Copper core 4-8 strands	0.4 Ohm/m	4	Sewing, taping, glueing, solder (after removal of insulation layer), crimping, lamination	4					100/10 m €€		
Conductive flat cable	 Dan Riley	Copper. 8 strands (customizable)		2	Taping, glueing, soldering, shrinking, crimping lamination.	3					€		
Conductive flat cable	 AMOTAPES	Copper (solver or tin coating)	0.5 Ohm/m	3		3	6-100 mm				€€		https://www.amohr.com/products/conductive-tape/?gclid=CjwKCAjw3pWDBhB3EiwAV1c5rILGU9vrjnSvtNjKPPhp6pvL6DrC2bTGilleji7gWBSTKd
Conductive flat cable	 Copper wires printed on TPU	Copper	Low enough	3		3					€€	Already extensively tested by Elitac and keeps on breaking	
Conductive polymer	 Conductive polymer Research state	Conductive polymers	Can be designed	2	Gripping, glueing, ta	2	Can be designed	No	Medium	Unknown	€€€		
conductive flat cable	 Rapid-iron on Research state		unknown	4		3					n.a.		

Electrical connections

	General Information					Mechanical information						Additional info	Link
	Product/Technique	Image	Type interconnection	Durability in active environment (1=really bad & 5=really good)	Flexibility	# of connection points (Requirement: minimal 4 connection points)	Dimensions (Wish: smallest as possible)	Washability	Ease of processing (1=really bad, 5=super good)	Lifespan	Costs	Remarks	Link
	Soldering		Mechanical & electrical	2	Bad	customizable	customizable	No	4	Good			
	Welding		Chemical and electrical	3	Bad	customizable	customizable	No	4	Good			
	Wire bonding		Mechanical & electrical	1	Bad	customizable	customizable	No	3	medium			
Lamination	[illegible] et al. (2012) P.4)		Chemical & conductive	4	Good	customizable	Customizable	unknown	4	Good	unknown	Temporary, not suitable for long-time use	https://www.researchgate.net/publication/269345303_Electronics_in_Textiles_-_Adhesive_Bonding_Technology_for_Reliably_Embedding_Electronic_Modules_into_Textile_Circuits
Grip connector	Aligator grip		Mechanical & conductive	2	Bad	1	Different sizes available 51 mm in length	No	5	Good	0.23,- per piece x 100	Temporary, not suitable for long-time use	https://www.onlinekabelshop.nl/krokodillenklem-51-mm-met-schroef?gclid=CjwKCAjwgZuDBhBTEiwAXNofRMPcLqQgovJk8Fmf7Bz_xYMb7p2sARGcYRAicorNy75iN3FPo9c_IBoCMRUQAvD_BwE
Grip connector	Grip & Clip LED Montreal		Mechanical	3	Bad	1 to 2	Different sizes available Exact dimensions unknown	No	4	Medium	1.00-1.75 dollars	Temporary, not suitable for long-time use	https://ledmontreal.com/en/led-connectors-and-accessories-led-montreal/led-connectors-and-accessories/grip-and-clip-wire-to-wire-connectors.html
Grip connector			Mechanical	2	Medium	2 to 4	2.4 x 1.5 x 0.78 cm; 20 Grams	Yes, it claims to be water proof if the cables/pcb is also waterproof	3	Medium		Temporary, not suitable for long-time use	https://www.amazon.co.uk/5050-Pin-RGB-Strip-Connectors/dp/B07XXN264X
Grip connector	Spring-cage connection Phoenix		Mechanical	4	Bad	1	Unknown	No	3	Good	unknown	Temporary, not suitable for long-time use	https://www.phoenixcontact.com/online/portal/pi?1dmy&urile=wcm:path:/pien/web/main/products/technology_pages/subcategory_pages/Connection_Technologies_Tension_spring_connection/8ff75150-0b07-4ae5-b6ae-51f829fe7127
Grip connector	Screw connection & many more Phoenix		Mechanical	4	Bad	1	Unknown	No	3	Good	unknown	Temporary, not suitable for long-time use	https://www.phoenixcontact.com/online/portal/pi?1dmy&urile=wcm%3apath%3a/pien/web/main/products/technology_pages/subcategory_pages/Screw_connection/972f9ee9-dbf8-40b8-af07-c6969417db38
Grip connector	Twist on wire connector Grainer		Mechanical	2	Medium	Max 4 wires	0.66 in height x 0.62	No	4	Medium	~0.13 dollars (12.70 dol	Temporary, not suitable for long-time use	https://www.grainger.com/product/BUCHANAN-Twist-On-Wire-Connector-6VG30
Grip connector	Terminal block		Mechanical	2	Medium	1 to X		No	3	Medium			
Conductive tape	Copper foil tape		Mechanical & conductive	2	Good	customizable	20 to 50 mm	No	3	Bad	15,09 for 20 m	Heat resistant -73 degrees Celsius tot 280 degrees Celsius	https://www.amazon.nl/Dokpav-Conductive-Poedercoating-Sublimatie-Isolerende/dp/B07ZVR8TM9/ref=asc_df_B07ZVR8TM9/?tag=nlshogostdde-21&linkCode=df0&hvadid=494635480203&hvpos=&hvnetw=g&hvrand=6039147012189796295&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9065035&hvtargid=pla-839699622176&psc=1 https://cdn.sparkfun.com/datasheets/Prototyping/Copper%20foil%20tape%20TDS-EN.pdf
Conductive glue	Elecolit conductive adhesives(ICA, TCA, ACA)		Chemical & conductive	4	Good	customizable		Could be	3	Good		Lead- and solvent-free Curing at low temperatures < 120 degrees C High flexibility at temperature shock High thermal stability No bleeding Long shelf life curing at room temperature possible, however ranges between 5 min and 2 hours.	https://www.panacol.com/panacol/brochures/elecolit-electrically-and-thermally-conductive-adhesives-and-glues.pdf
	Insulation tape		Mechanical	2	Medium	n.a.	Different sizes availal	Water resistant	3	Bad	1.15,- per 20 m	Water resistant suitable for temperatures 0°C to +70°C. Application temperature is +5°C to +40°C and storage temperature is +12°C to +25°C.	https://nl.rs-online.com/web/p/electrical-tapes/1347336/?cm_mmc=NL-PLA-DS3A-_-google-_-PLA_NL_NL_Adhesives_%26_Sealants_%26_Tapes_Whoop-_-(NL:Whoop!)+Electrical+Tapes-_-1347336&matchtype=&pla-311732438318&gclid=CjwKCAjwgZuDBhBTEiwAXNofRDaj62e1H9FlGtQYK-tKuh7mZA-V6giqvqNxVTNHLSBuGfttAemrlhoCUYsQAvD_BwE&gclsrc=aw.ds
	Sewing pads		Mechanical and conductive	4	Good	Personalisable		No, conductive yarns	4	Good			
	Threadframe joining		Mechanical and conductive	2	Medium	Personalisable	Customizable	No, conductive yarns	3	Medium			
	Stapling		Mechanical and conductive	2	Bad	Personalisable		No	4	Bad		Can break fabric and connections	
	Conductive interpose pad with conductive adhesives Research phase		Chemical & conductive	4	Medium	customizable	customizable		3	Medium			

Integration techniques for electronics and textiles

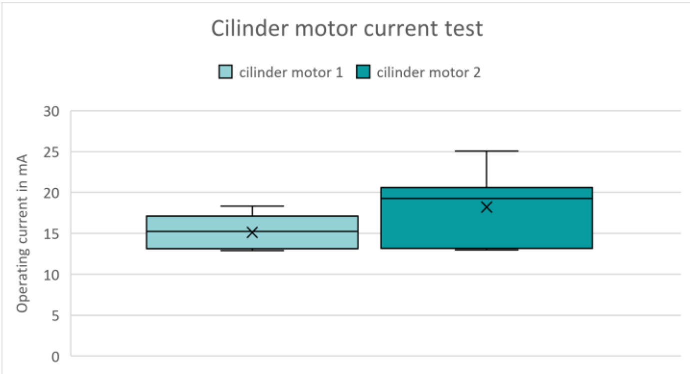
General Information											Additional info	Link
Product	**Image**	**Type interconnection**	**Integration with textile carrier (1=really bad & 5=really good)**	**Durability in active environment (1=really bad & 5=really good)**	**Dimensions (Wish: smallest as possible)**	**Washability**	**Ease of processing (1=really bad, 5=super good)**	**Validation**	**Lifespan**	**Costs**	**Remarks**	**Link**
TPU seam tape Gmarty Gore-Tex		Chemical	4	4	30m x small thickness	Good, until a certain number	4	Used by Nadi X	Medium	€ €12,99 per 30 m	Technique used by Nadi	https://www.grandado.com/products/30-meterssmelten-naaien-cordura-gore-tex-outdoor-sport-kleding-pu-tape-waterdichte-tpu-tape?variant=15387913617502&currency=EUR&gclid=Cj0KCQjwpdqDBhCSARIsAEUJ0hOM9W8z2T76oF2Sebl rh2VnBbPQJgecTLSVnw74Kz0p_XdMoT6JFHcaAs0PEALw wcB
Overmolding		Chemical		4	Customizable	Should be able to waterproof until IP54 at least	3	Tested by Elitac	Good	€€€	Time intensive, technique proven and used by Elitac Wearables	
Framis Tape		Chemical	4	4	Different sizes available, you can also cut your own sizes	Good, tested up to 60 degrees Celsius	4	Tested by Elitac	Good	€€	Technique from Framis Italia	https://www.framis.it/
Sewing pads e.g. Fischer connectors		Mechanical	4	4	Customizable	Good, like normal sewing oonnections	4	Used by Fischer	Good	€	Technique used by Fischer connectors	
Lamination		Chemical	3	4	Customizable	Should be able to waterproof until IP54 at least	3	Used by Nadi X and Eli	Medium	€-€€	Used in the Nadi X	
Stapling		Mechanical	2	1		No	4	Used by NaviBelt	Bad	€	Technique used by the NavigationBelt	
Embroidery to textile		Mechanical	4	4	maximum stitch width a	Good	3	Not yet tested	Good	€		
Knitting lamination pockets		Mechanical	4	4	Customizable	Good	3		Good	€	Proven to work with soft and hard rigid object by Daan van der Valk (2020)	
Glueing		Chemical	2	2	Customizable	Medium to Bad	2		Medium	€	Does not look aesthetically	
Textile tubes& piping for wiring		Mechanical	4	4	Customizable	Good	3	Research phase	Good	€	Well known in the textile world and can be a cool additional feature.	
3D printing of electronics on textile substrate		Mechanical	4	3		Medium to Bad	3	Done by Holst Center & TNO				

Removable connectors

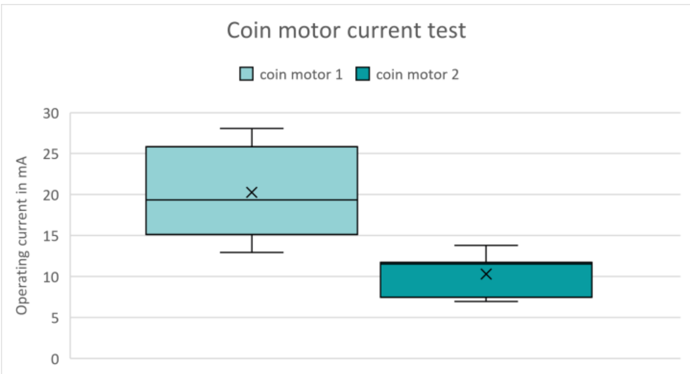
General Information		Mechanical information								Additional info	Link
Product	Type interconnection	Durability in active environment (1=really bad & 5=really good)	# of connection points (Requirement: minimal 4 connection points)	Dimensions (Wish: smallest as possible)	Washability	Ease of processing (1=really bad, 5=super good)	Lifespan	Costs	Wide availability	Remarks	Link
Pogo pins Cletk	 :al	4	1 to X. 4 is shown in the image	Different sizes available Shown in the image is 14mm (l) X18 mm (w) x5mm ((h) plugged in	IPX8	4	Good	€	Good, validated by Hexoskin socks & TU Delft proj		https ://www.cl etk.com/c onnector/ 4-pin- waterpro of- electrical- connector s
Gripper snap fist	 Mechanical and electrical	4	Customizable	8.5 mm diameter start	Yes, but corrosion appears after certain amounts of washes/sweat soacking that reduces the conductivity. Gripper snap research W. de Vos Elitac XX	4	Medium	€	Good, used by the Nadi X	Creates holes in fabric, prone to sweat. Is widely known in the textile industry	
Snap fits	 and electrical	4	Personalisable	8.5 mm diameter start	Yes, though again cor	4	Medium	€	Good	Widely available technology	
FFC & FPC	 Mechanical and electrical	3	Personalisable	Different sizes	No	3	Medium	€	Good, often used for Electrical connections in non moving parts		
Fischer's LP360TM connecto	 Mechanical and electrical	5	4 or 7	one size large	Yes	4	Good	€€€	Bad	360 degree mating freedom. Sewable silicon pad.	http s://www.f ischercon nectors.c om/global /en/prod ucts/lp36 0tm
Ohmatex washable connector not available any longer	 Mechanical and electrical	5	1 to 6	one size medium	Yes	3	Good	€€€	Bad	Not available on the market any longer	
JAE's RK01 connector	 Mechanical and electrical	5		one size large	Yes	3	Good	€€	Bad	Interesting one-way connection design, liability if product is pulled from market	https:/ /www.jae. com/en/c onnectors /series/de tail/id=93 220
Ball-grid array-like pocket cc	 Mechanical and conductive	4	Customizable	Customizable	No, removed before v	3	Good	n.a.		Research phase, data connection trustworthyness should be researched	
Holst Center shift connectio	 nductive	5	Customizable	Customizable	Module is removed b	3	Good	n.a.		Designed by Holst Center, slide and click system	
MolliiSuit	 Magnetic and conductive	5	Customizable	Customizable	Module is removed b	4	Good	n.a.		Designed by MolliSuit,	
Conductive Velcro Hook anc	 Mechanical	5	Customizable, per surface area 1	3 inch length	Yes		Good 5000 closures	€	Medium	0.8 Ohm/square when connected Can power a tacctor when connected. Velcro known by textile industry	http s://www. hookandl oop.com/ blog/elect rically- conductiv e-hook- loop/

A7. ERM motor test data

cilinder motor test #	Voltage in V (DC)	Current at which the motor start (mA)
1	3	13,33
2	3	12,9
3	3	15,22
4	3	15,88
5	3	18,32
6	3	13,18
7	3	19,26
8	3	25,05
9	3	12,98
10	3	20,6
Average motor cil 1		**15,13**
Average motor cil 2		**18,214**
General average cil		**16,672**
Resistance motor cil 1	19,2 Ohms	
Resistance motor cil 2	15,7 Ohms	



coin motor test #	Voltage in V (DC)	Current at which the motor start (mA)
1	3	19,33
2	3	23,66
3	3	17,33
4	3	12,94
5	3	28,05
6	3	11,54
7	3	11,73
8	3	7,48
9	3	6,97
10	3	13,79
Average motor coin 1		**20,262**
Average motor coin 2		**10,302**
General average coin		**15,282**
Resistance motor coin 1	29,9 Ohms	
Resistance motor coin 2	31,8 Ohms	



A8. Resistance measurements of conductive yarns

First the general method of measuring the resistance of braided yarns is explained. In the second part of the appendix all raw materials and data can be found.

Goal

1. Test conductive yarns to see if they have a low enough resistance to power an ERM tactor (the coin and cylinder model used by Elitac Wearables).

2. Verify the specifications given by the producer of the conductive yarns: The resistance, multiple dense stitches versus single straight stitch. --> The yarns consist of loose fibres and are therefore not sewable and the thickness is almost impossible to measure accurately. As a new test, braiding was performed with the yarns.

Specifications (investigated yarns)

See Table 15 for the specifications of the yarn.

Yarn	*Description*	*Thread diameter**	*Flat width***	*Resistance*	*Measured resistance*	*Measured resistance braided 3 strands*
X-steel TM 16 by Syscom	Fiber: Stainless Steel Fiber material: AISI 316L Filament count: 16	0.0075 in =0.191 mm	0.02 in =0,508 mm	~0.7 Ohm/ft (=~2.3 Ohm/m)	2.15 Ω/m	0.85 Ω/m
Liberator 40 by Syscom	Structure: Liquid Crystal Polymer (LCP) Filament count: 40	0.0089 in =0,226 mm	0.0219 in =0,556 mm	~3.3 Ohm/m	3.0 Ω/m	0.99 Ω/m
Amberstrand 166 by Syscom	Fiber: Toyobo Zylon Fiber material: PBO Filament count: 166	0.0097 in =0,246 mm	0.0275 in = 0,699 mm	~3.28 Ohm/m	4.1 Ω/m***	1.03 Ω/m

Table 15. Specifications of the conductive yarns tested based on the specifications sheet of the three yarns.
*Ideal close-packed calculated diameter
**Width of material as it lays in a braiding configuration
*** No accurate measurement was possible due to splitting of the yarn. Should be lower!

Method

Measuring the resistance non-braided:

Measure resistance without braiding with a multimeter (in total 1 m of yarn): Measure the resistance at 0.20/0.40/0.60/0.80 and 1.0 meter distance. The resistance was measured with the following setup:

1. Tape a non-conductive measuring tape to a non-conductive table and tape it to the table with painters tape each 25 cm.

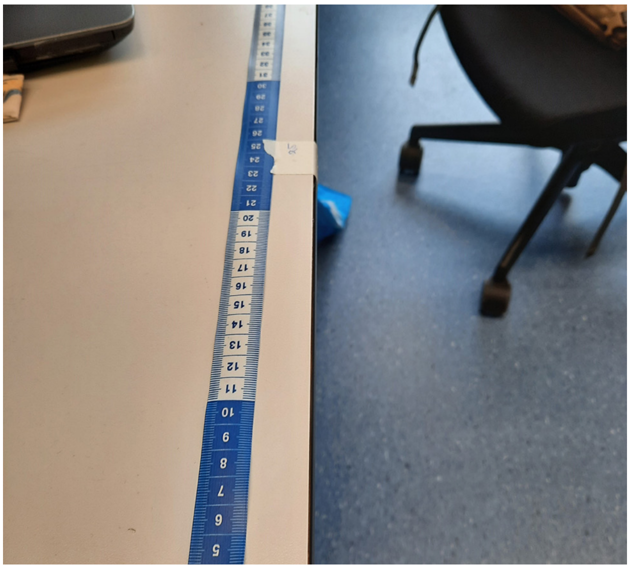


Figure 245. Measuring tape taped to table

2. Now tape 1m of a conductive yarn to the table parallel to the measuring tape. Now clamp one end of the multimeter at 0 m and the second clamp at 0.2 m, note the resistance and continue to repeat this measurement for each 0.2m up until 1 meter in total. Measuring the resistance braided:

Figure 246. The gripper clamps used

Measure resistance braided with a the (10 cm of yarn braided) with a 4 point measurement:

1. Cut off 3 strands of conductive yarn with an approximate length of 14 cm and tie them together. Tape the end to the table with painters tape and start braiding the strand by hand:

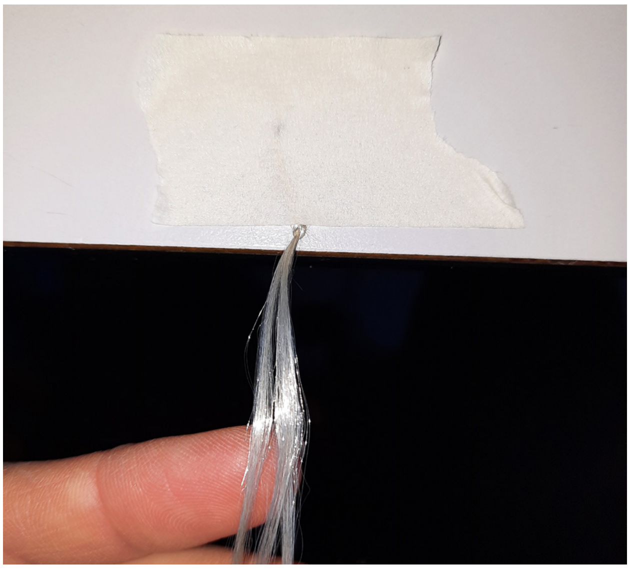


Figure 247. 3 strands of conductive yarn fixated to a table for braiding

Figure 248. 3 strands of conductive yarn braided

2. After finishing the braids setup a 4-point resistance measurement with the DC Voltage Analyser and 4 grip clamps.

The set current is 100 mA and the set voltage is 5 V. Place the clamps as shown below:

Figure 249. Clamping of conductive yarns for the 4 points measurement

The two outer clamps are placed on the + and - output of the voltage analyser and provide the current in the system. (Left clamp is + and right clamp is -). The two inner clamps are used to measure the voltage over a certain braided length of the conductive yarns. These clamps are placed on the input (sense) of the voltage analyser (left + and right -). The display of the DC voltage analyser will tell you the voltage, which can be used to draw a graph and calculate the resistance/unit length.

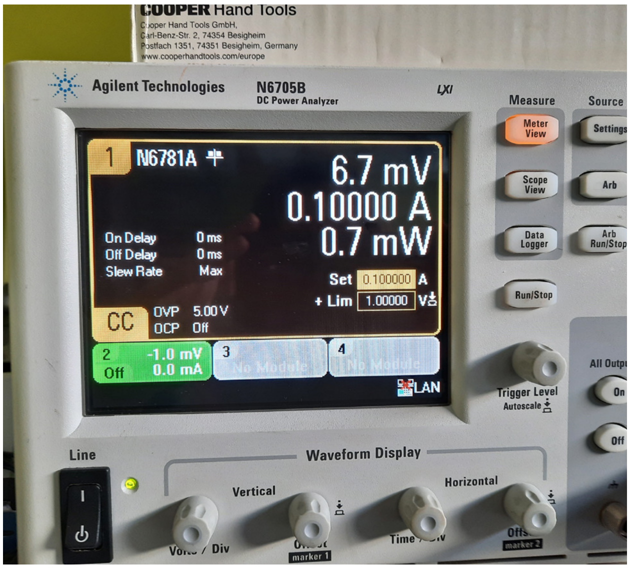


Figure 250. The DC Power Analyser measuring 6.7 mV at 100 mA and 5Volts applied (Leeger, 2021)

The parallel resistance formula makes us expect that the resistance will drop significantly (about 1/3) and will be in the order of around 1 Ohm per meter. Therefore a multimeter with a resolution of 0.1 Ohm is not sufficient enough and a DC voltage analyser with a much higher resolution is used to get more accurate measurements.

Measuring if the ERM motors can be powered through the conductive yarns:

Test if the ERM motor still starts at a distance of 1 m (when V is set to 3.00 VDC and A is set to 50 mA).

1. Keep the same setup as the non-braided resistance measurement and set the voltage output on the DC power analyser to 3V and the current to 50 mA.

2. Now connect the + of the DC power analyser to the motor and the minus to the 0m point of the conductive yarn to be tested. Wrap the - of the motor around the conductive yarn as shown in the picture below at 1m and see if the motor still starts. If it does not start, move 0.2 m down and measure again. Keep tension on the conductive yarn at all times to ensure proper contact.

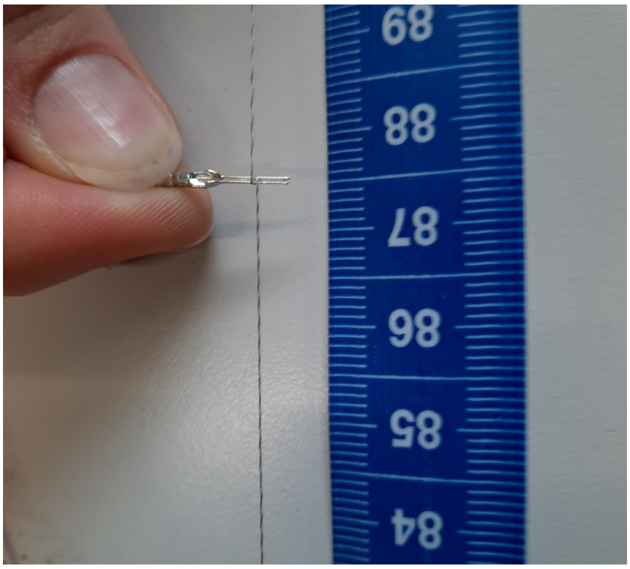


Figure 251. Conductive yarn wrapped around a header pin for electrical contact

Materials

- Conductive yarns: Liberator 40, Amberstrand 166 and X-Steel
- Type of motors: Model 306-H10 from Precision Micro Drive & C1027BE03L27
- DC Voltage Analyser
- Multimeter
- Model 199 System DMM Scanner Keithley
- 4X Measuring grip clamps

The DC Power Analyser was set to 5V and 100 mA. The zero measurement gave the values of 1mV and -0.03 mA. Therefore per each voltage measurement 1mV is subtracted and total current will be 100mA + 0.03

Results

For the detailed results, see page 235 to 237.

Conclusions

• The 3 conductive yarns are not sewable, as they all consist of loose filaments which are not twisted. Weaving or braiding are therefore the most suitable processing techniques. According to the specifications, if the yarn is professionally twisted it could be used for sewing.
• The Liberator 40 was the easiest to braid, then the Amberstrand 40 and the X-steel was difficult to braid. The X-steel needed to be kept under constant tension to avoid knots and twisting of the material (making it unbraidable).
• The measured resistance of the unbraided Amberstrand 166 was not accurate enough due to the loose filaments splitting and knotting during the measurement. This is confirmed by the non-linear graph shown in the results section. In reality the resistance should be lower and around the same as the Liberator 40 according to the specifications.
• Both ERM motor models turned on when powered with 3VDC at 50 mAh at a distance of 1 meter for all 3 conductive yarns.
• The resistances measured of the non-braided conductive yarns are: 2.15 Ohm/m (X-steel), 4.1 Ohm/m (Amberstrand 166) & 3.0 Ohm/m (Liberator 40).
• The resistance of the braided conductive yarns are: 0.85 Ohm/m (X-steel), 1.03 Ohm/m (Amberstrand 166) & 0.99 Ohm/m (Liberator 40) and therefore decreases significantly, just as expected when looking at the parallel current law (1/Rtotal= 1/R1+1/R2+1/Rn)

Recommendation

• In the future, first twist all the conductive yarns to avoid splitting and knotting of loose filaments during processing of the materials.
• Re-do the measurements of the Amberstrand 166, while keeping the strands under tension at all times, to get a more accurate resistance measurement.
• Test the resistance of the braided strands with a larger length to get a more accurate resistance in Ohm/meter.
• Test the resistance of the braided strands when braided by a professional machine so no human errors can occur.
• Test the sewability of the yarns when twisted by a professional machine in accordance with the specifications.
• Continue to test the resistance, reliability of power and data transport in the future, also after cleaning in a washing machine.
• Look for conductive yarns that have a similar resistance per unit length (unbraided) and continue testing with these yarns for processability and cleanability.

Raw data of all the conductive yarn tests

Bekaert Bekinox VN 12.2.2.175S Steel	distance in m	resistance measured in ohm	Cilinder powe	Coin powers at	Slope calculation	Y-axis cut-off
29 Ohm/m	0,2	3,8			12,71875	1,534375
	0,4	7			13,5 Ohm/m	
	0,6	9,3				
	0,9	12,4				
	1	14,6	X	X		

Bekaert Bekinox VN 14.2.9 175S Steel	distance in m	resistance measured in ohm	Cilinder powe	Coin powers at	Slope calculation	Y-axis cut off
	0,2	13,9			67,55	0,37
	0,4	28,2			67,55 Ohm/m	
	0,6	40,2				
	0,8	53,3				
	1	68,9	X	X Soft		

AmannGroup Silver-tech 50 Tex 62	distance in m	resistance measured in ohm	Cilinder powe	Coin powers at	Slope calculation	Y-axis cut off
<150 Ohm/m	0,2	31,2			142,2	3,54
0,36 mm	0,4	60,9			142,2 Ohm/m	
	0,6	89,5				
	0,8	117,7				
	1	145	X	X very soft		

AmannGroup Silver-tech 30 Tex 96	distance in m	resistance measured in ohm	Cilinder powe	Coin powers at	Slope calculation	Y-axis cut off
<85 Ohm/m	0,2	14,3			65,5	1,18
0,40 mm	0,4	27,5			65,5 Ohm/m	
	0,6	40,2				
	0,8	53,7				
	1	66,7	X	X Soft		

AmannGroup Silver-tech 120 Tex 28	distance in m	resistance measured in ohm	Cilinder powe	Coin powers at	Slope calculation	Y-axis cut off
<530 Ohm/m	0,2	101,4		X Soft	440,4	13,34
0,23 mm	0,4	189,6	X Soft		440,4 Ohm/m	
	0,6	277,7				
	0,8	365,2				
	1	454				

Elektrisola 31810512 mm copper, silverplated	distance in m	resistance measured in ohm	Cilinder powe	Coin powers at	Slope calculation	Y-axis cut off
2.178 Ohm/m	0,2	0				
0.10mm	0,4	0			0	0
single core CU/Ag20	0,6	0			Geïsoleerd!	
insulation TW-H mod. Polyester	0,8	0				
	1	0				

Elektrisola 31900286 mm copper, silverplated	distance in m	resistance measured in ohm	Cilinder powe	Coin powers at	Slope calculation	Y-axis cut off
2,178 Ohm/m	0,2	0,9			2,85	0,41
0,09mm	0,4	1,6			**2,85 Ohm/m**	
single core CU/Ag20	0,6	2,2				
insulation TW-A mod. Polyurethane	0,8	2,7				
	1	3,2	X	X		

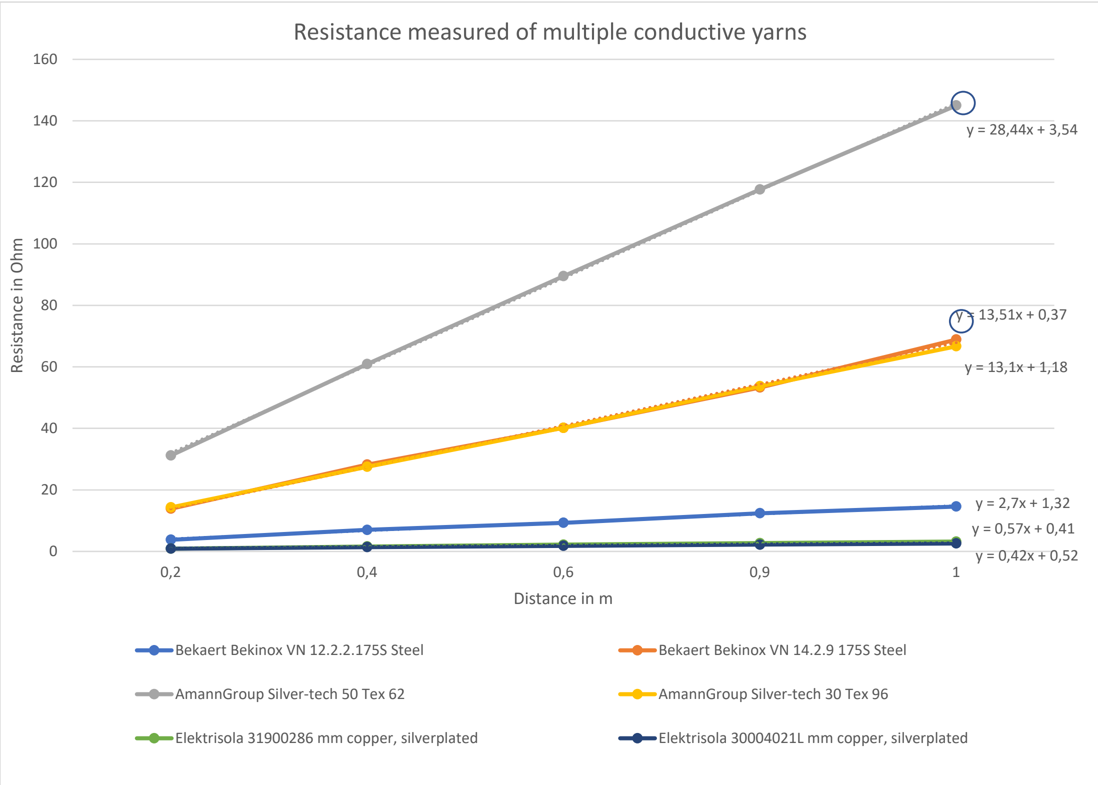
Elektrisola 30004021L mm copper, silverplated	distance in m	resistance measured in ohm	Cilinder powe	Coin powers at	Slope calculation	Y-axis cut off
2,178 Ohm/m	0,2	0,9			2,1	0,52
0,04mm	0,4	1,4			2,1 Ohm/m	
Litz wire CU/Ag50	0,6	1,8				
	0,8	2,2				
	1	2,6	X	X		

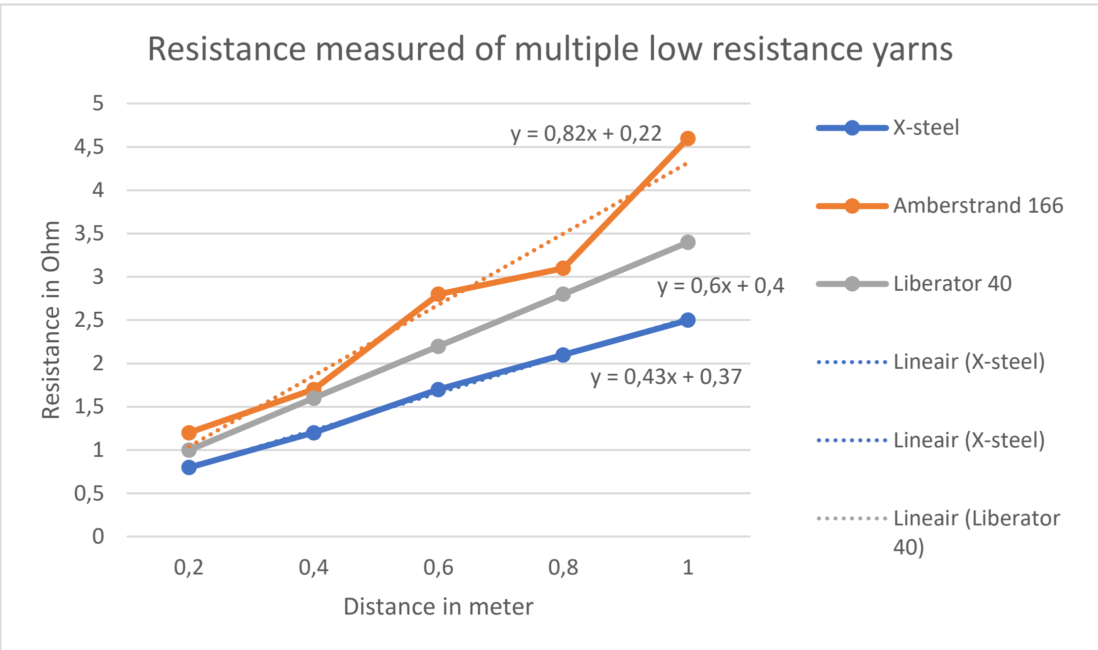
X-steel	distance in m	resistance measured in ohm	Cilinder powe	Coin powers at	Slope calculation	Y-axis cut off
~2,3 Ohm/m	0,2	0,8			2,15	0,37
	0,4	1,2				
	0,6	1,7				
	0,8	2,1				
	1	2,5	X	X		

Amberstrand 166	distance in m	resistance measured in ohm	Cilinder powe	Coin powers at	Slope calculation	Y-axis cut off
Bijna onmogelijk om goed te meten	0,2	1,2			4,1	0,22
alle fibers waaieren uit	0,4	1,7			4,1 Ohm/m	Is waarschijnlijk lager, slechte meet resultaten.
~3,28 Ohm/m	0,6	2,8				
	0,8	3,1				
	1	4,6	X	X		

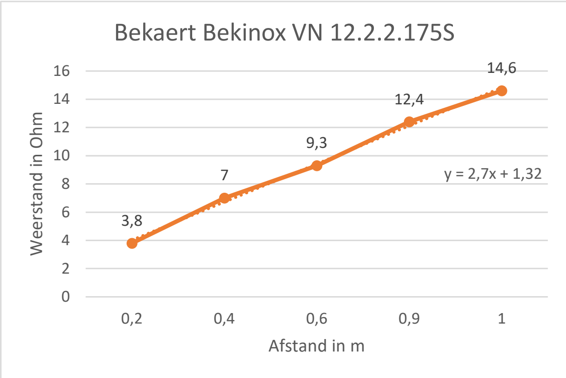
Liberator 40	distance in m	resistance measured in ohm	Cilinder powe	Coin powers at	Slope calculation	Y-axis cut off
Meest makkelijk te meten en braiden	0,2	1			3	0,4
~3,3 Ohm/m	0,4	1,6			3 Ohm/m	
	0,6	2,2				
	0,8	2,8				
	1	3,4	X	X		

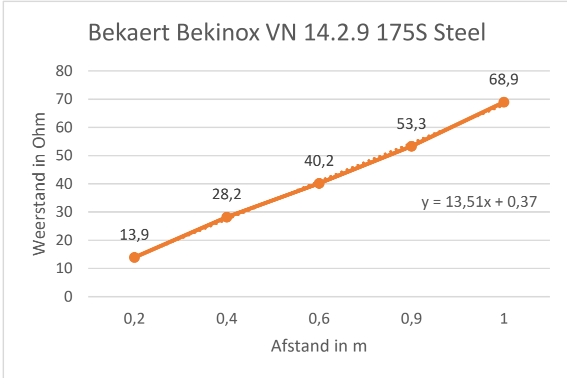
Corrected resistance in Ohm measured	Corrected resistance in Ohm using calculated slope	Cilinder moto	Coin motor vibration
13,065625	12,71875	Good	Good
68,53	67,55	Okay	Soft
141,46	142,2	Soft	Very soft
65,52	65,5	Okay	Soft
2,79	2,85	Good	Good
2,08	2,1	Good	Good
2,13	2,15	Good	Good
4,38	4,1	Good	Good
3	3	Good	Good

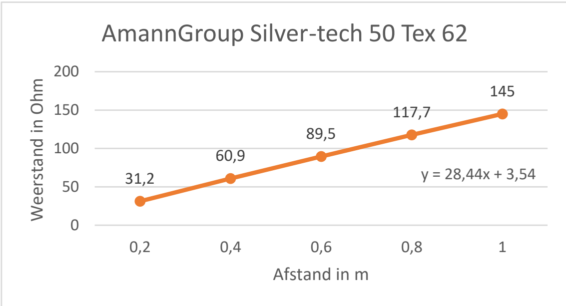


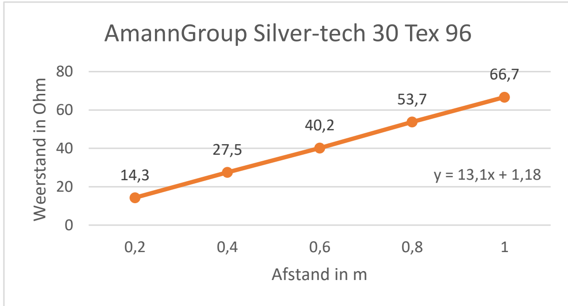


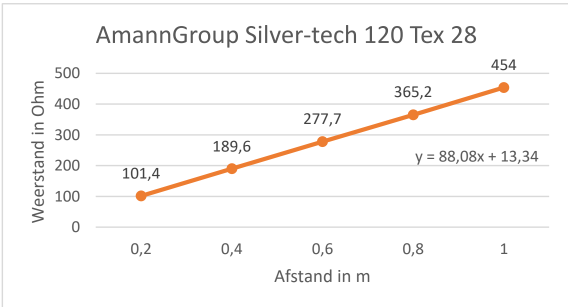
Resolution Resolution multimeter: 0.1 Ohm
Resistance Resistance circuit measured: 0.6 - 0.8 Ohm
Settings 3V Settings 3V and 50 mA in DC power analyzer

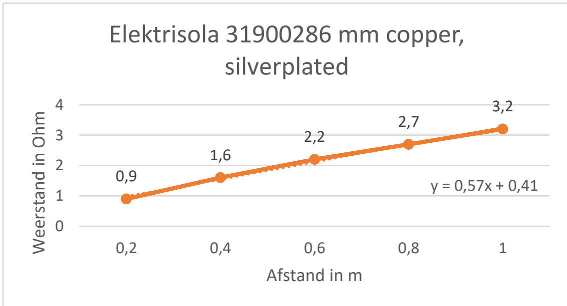


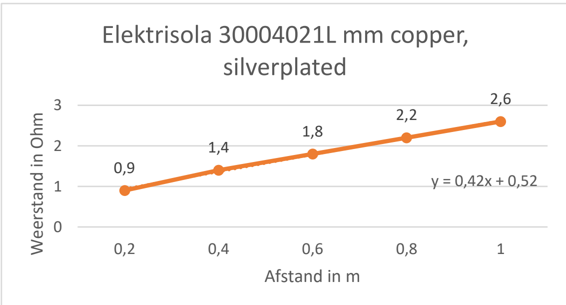


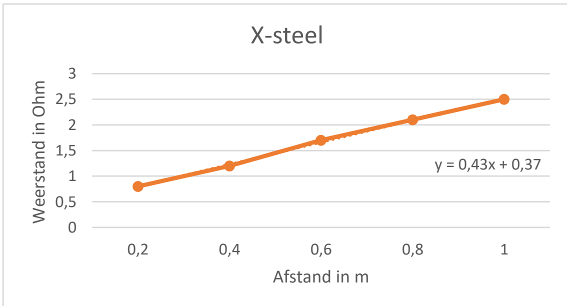


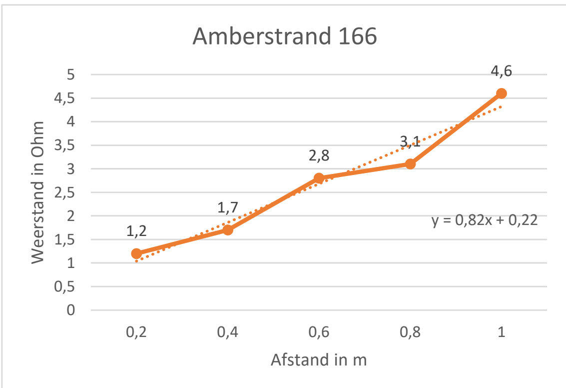


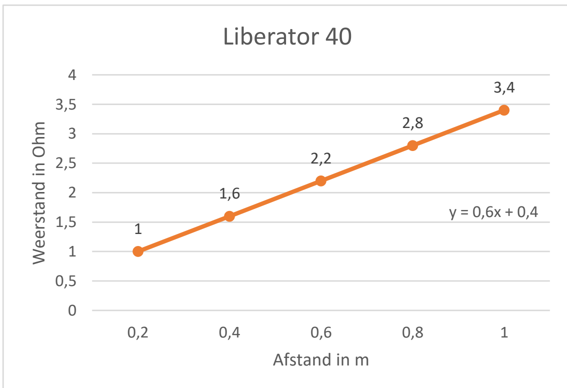






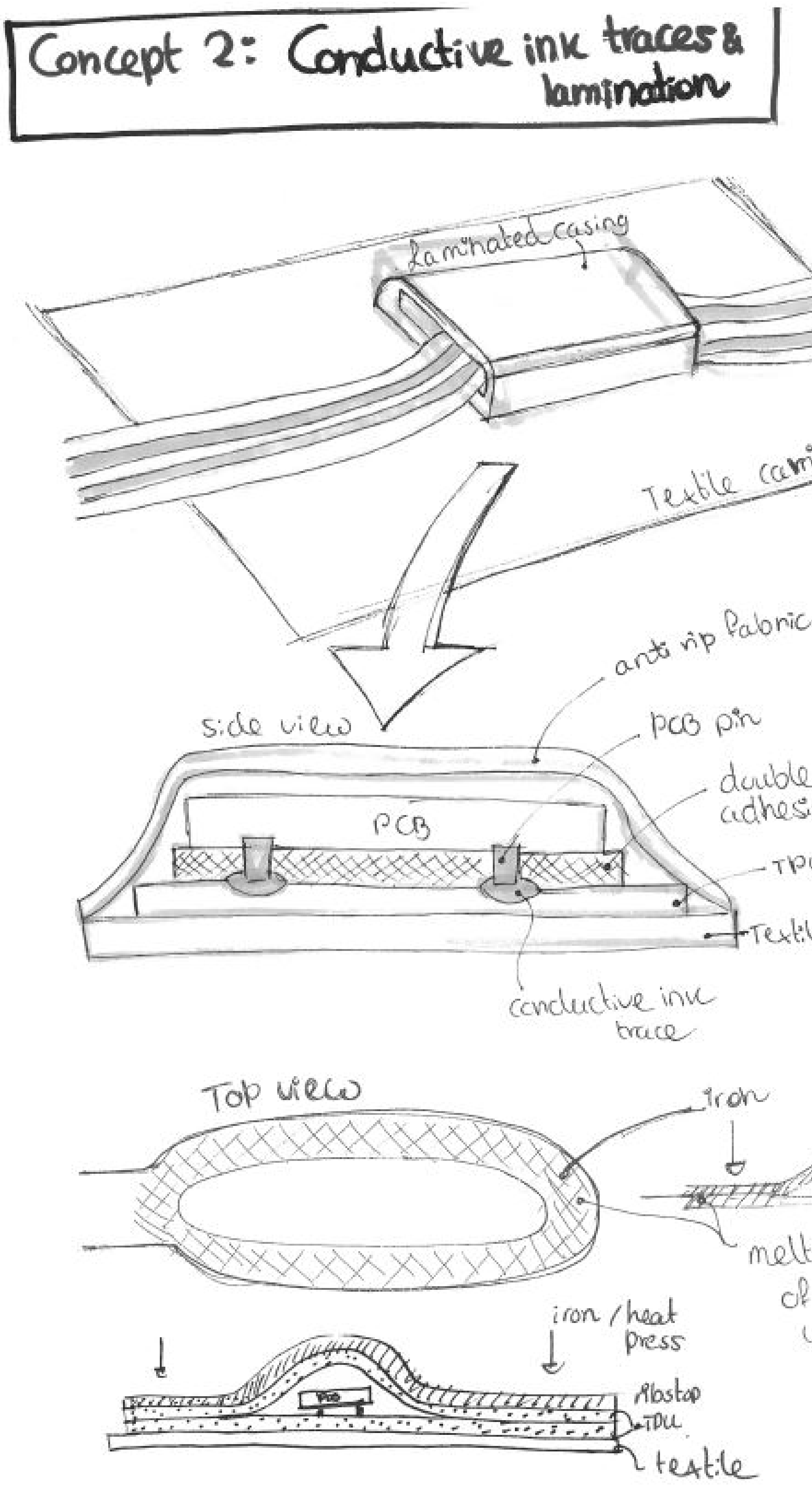






A9 Concept 3: Conductive ink traces & lamination

General design
This concepts uses conductive silver ink laminated between TPU as power and data transport systems. It is inspired by the Nadi X and uses lamination of multiple layers of materials, TPU and ripstop among others. The conductive ink can be substituted by conductive yarn or flat cables. The main control module is made detachable through snap buttons. Again this main control modules includes a battery and a USB-C connection point for charging. See Figure 252 for a visual explanation.



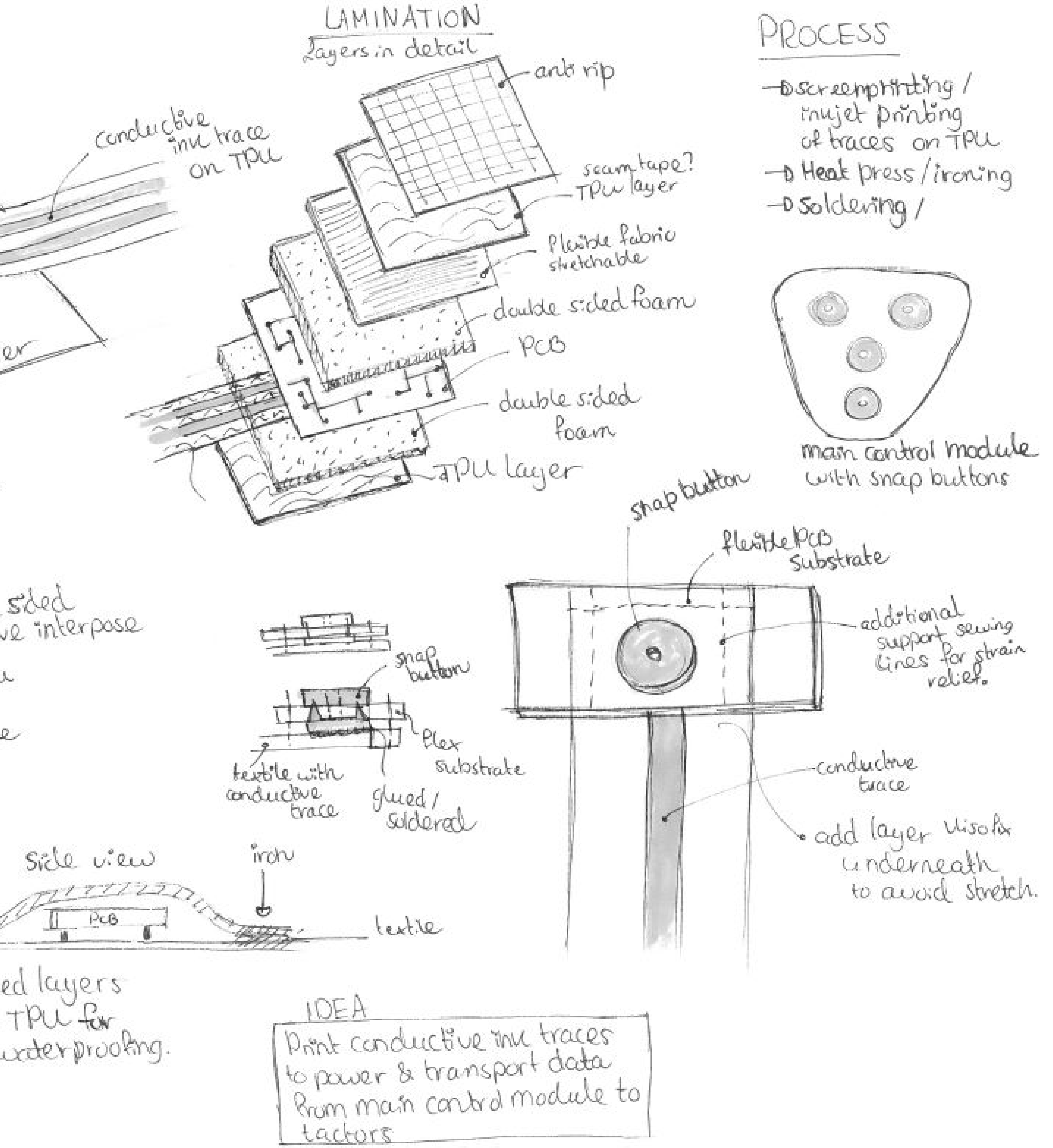


Figure 252. Concept 3 explained in a visual

	Module A: tactor	*Module B: power & data transport system*	*Module C: the main controller*
Connection of module to power & data transport	A1: Soldering of electrical components inside tactor. using adhesive interface pads and conductive glue to connect PCB pins to conductive ink traces.	B1: Conductive ***silver ink traces.*** Can be substituted by ***conductive yarn*** or ***flat cables.***	C1: Detachable main control module by the use of conductive ***snap buttons (conductive Velcro or pogo pins)*** attached to flexible PCB and then connected to conductive ink trace.
Connection of module to protective casing	A2: Lamination of different flexible materials through heat pressing, melting and glueing multiple layers.	B2: Isolation through the use of TPU seam tape on top of traces	C2: 3D printed/ Injection molded casing. closed through ***clicking/glueing.***
Connection of module to textile carrier	A3: the same as A2	B3: By melting TPU seam tape on top of the textile carrier	C3: The same as C1.

Table 16. Designed connections Concept 2, Conductive ink traces & lamination

In Table 16 an overview of the modules designed for concept 3 is given. Interchangeable components are highlighted in black.

Production processess

In order to produce this concept the following processess are involved:

• Screen printing or inkjet printing
• Overmolding (tactor module casing)
• 3D printing (main control module casing)
• Soldering (Electronics inside tactor and main control module)
• Glueing (main control module casing)
• Heat pressing (lamination of tactor module casing)
• Ironing (to enclose tactor module casing and make it waterproof)

Pros

1. Conductive traces can be precisely printed by professionals and are easy to desig with.
2. Conductive traces remove rigid cabling in earlier designs.
3. The conductive traces allow for serial or singular circuitry of tactor modules.

Cons

1.A lot of manual labor is necessary to produce all these layerings.
2. Requires new equipement or partnership for Elitac Wearables to allow inkjet or screenprinting.
3. Conductive silveriink is expensive

Discussion & concerns

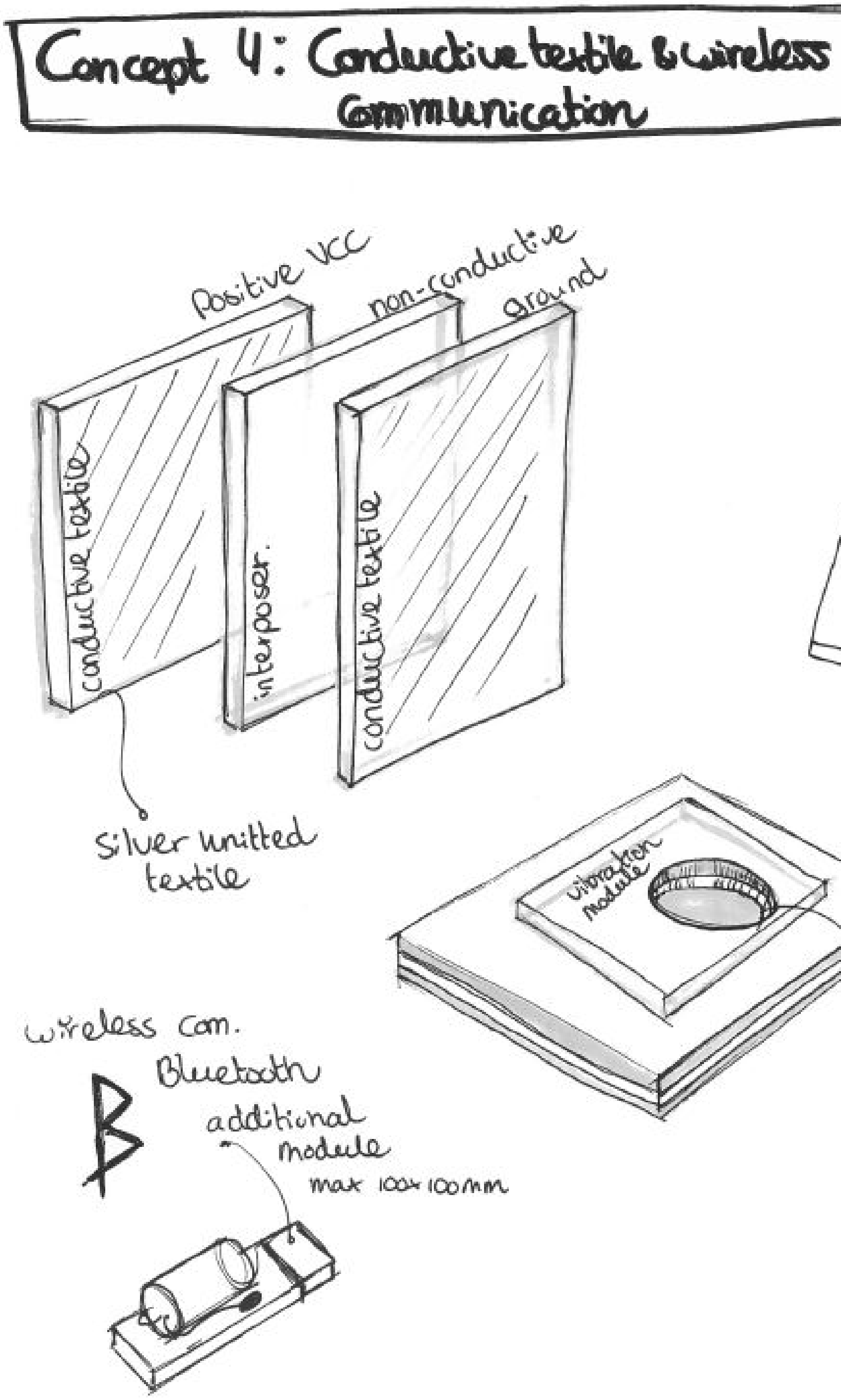
Conductive ink traces were used before by Pauline van Dongen in an earlier assignment for Elitac Wearables. However, the maximum distance due to the relatively high resistance was a limiting factor and should be researched as well if this concept is picked for further development. The durability of the TPU seamtape and lamination should also be tested, especially after multiple washing cycles. Moreover, the vibration intensity through multiple layers of materials should be investigated.
Screenprinting for small quantities is posssibe, however not that scalable for mass production. This requires inkjet printing instead.

Decision

Discontinue with this concept

A10. Concept 4: Textile pattern pieces and wireless communication

General design
This concept uses conductive textiles for power transport from the main control module to the tactor modules. The conductive textile can be either used as pattern pieces or as strokes. One side will be used as VCC and the other side as the GND, separated by a non-conductive layer. Tactor modules will be connected to the fabric through lamination or overmolding. To ensure contact with both the negative and positive side, a hole can be created through the two top layers.
The detachable main control module was inspired by the MolliiSuit, and uses magnets to ensure proper electrical connection. See Figure 253 for a more visual explanation.



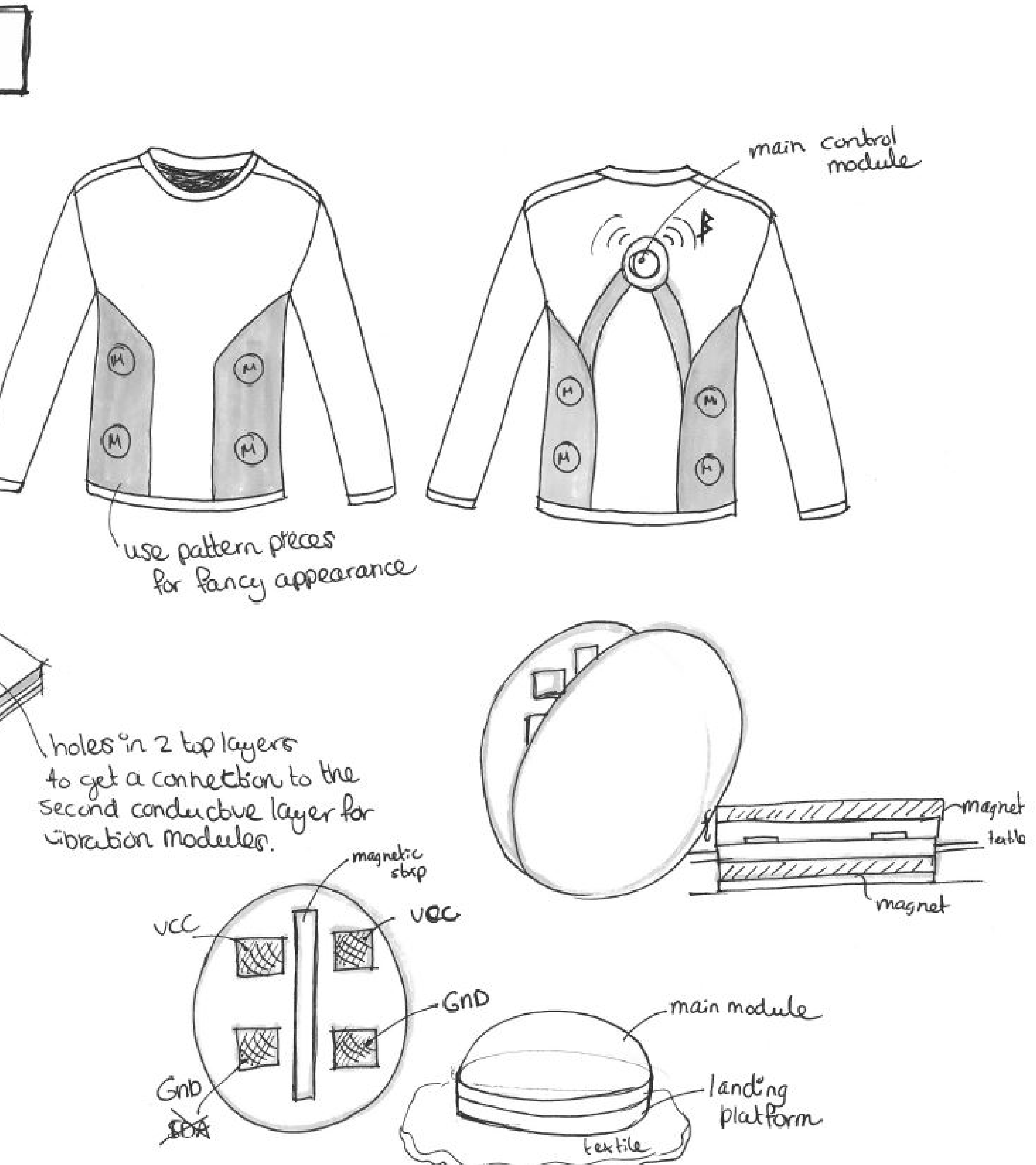


Figure 253. Concept 4 explained in a visual

	Module A: tactor	*Module B: power & data transport system*	*Module C: the main controller*
Connection of module to power & data transport	A1: Soldering of electrical components inside tactor. Using conductive glue to connect PCB pins to the conductive textile.	B1: Conductive textile pattern pieces.	C1: Detachable main control module by the use of ***magnets***. Can be substituted by ***conductive Velcro***, ***pogo pins*** or ***snap buttons.***
Connection of module to protective casing	A2: ***Overmolding*** or ***lamination*** of PCB directly over the fabric	B2: No protective casing or additional lining.	C2: 3D printed/ Injection molded casing. closed through ***clicking/glueing.***
Connection of module to textile carrier	A3:Combined by A1 & A2	B3: By sewing the conductive textile pattern pieces directly into the textile carrier	C3: The same as C1.

Table 17. Designed connections Concept 4 Textile pattern pieces and wireless communication

In Table 17 an overview of the modules designed for concept 4 is given. Interchangeable components are highlighted in black.

Production processes

In order to produce this concept the following processes are involved:

- Overmolding/Lamination (tactor module casing)
- 3D printing (main control module casing)
- Soldering (Electronics inside tactor and main control module)
- Glueing (tactor module)
- Sewing (conductive pattern pieces)

Pros

1. Conductive textile pieces can be sewn directly into the textile carrier, and can be easily prototyped and tested through available equipment at Elitac Wearables
2. This construction allows a wide variety in placement of tactor modules

Cons

1. The three layers necessary to enable the transport of power results in a thick piece of cloth, making it extra warm.
2. The durability
3. Conductive textile might need an additional protective layer to disable interference of external products or touch.

Discussion & concerns

As not all conductive textiles are durable when it comes to washing, and should therefore be tested. Moreover, the question remains if one central Bluetooth module in the main control module can connect to multiple Bluetooth receivers in each tactor. Moreover, each tactor will need an individual driver and micro controller as well. Therefore the voltage supplied to each tactor may not be less than around 3.6 Volts (Van Elteren, May 17th, 2021) or the micro controller used by Elitac will not function properly any more. The triple layers necessary to

Decision

Discontinue with this concept.

A11. Concept 5: Flat cables and sewing pads

General design
Of all concepts created, the electronics are the least integrated in this version. It allows for production of the textile carrier and electronics separately. The design uses Amohr flat cables that are placed in a tin bath and directly soldered onto the PCB of the tactor module. Next, the tactor is overmolded together with the flat cable and a strain relief is added. In the overmold, a silicon sewing ring is added, that allows for attachment of the system to the textile carrier. The flat cables can be shielded from the external touch by placing a tunnel of fabric over them. The whole system is sewn to the textile carrier, including the landing place of the main control module. This connection was inspired by Figure 111 of Holst Center and uses mechanical friction and a snap fit to ensure proper electrical connection. This casing is 3D printed or injection molded. See Figure 254 for a more visual explanation of concept 5.

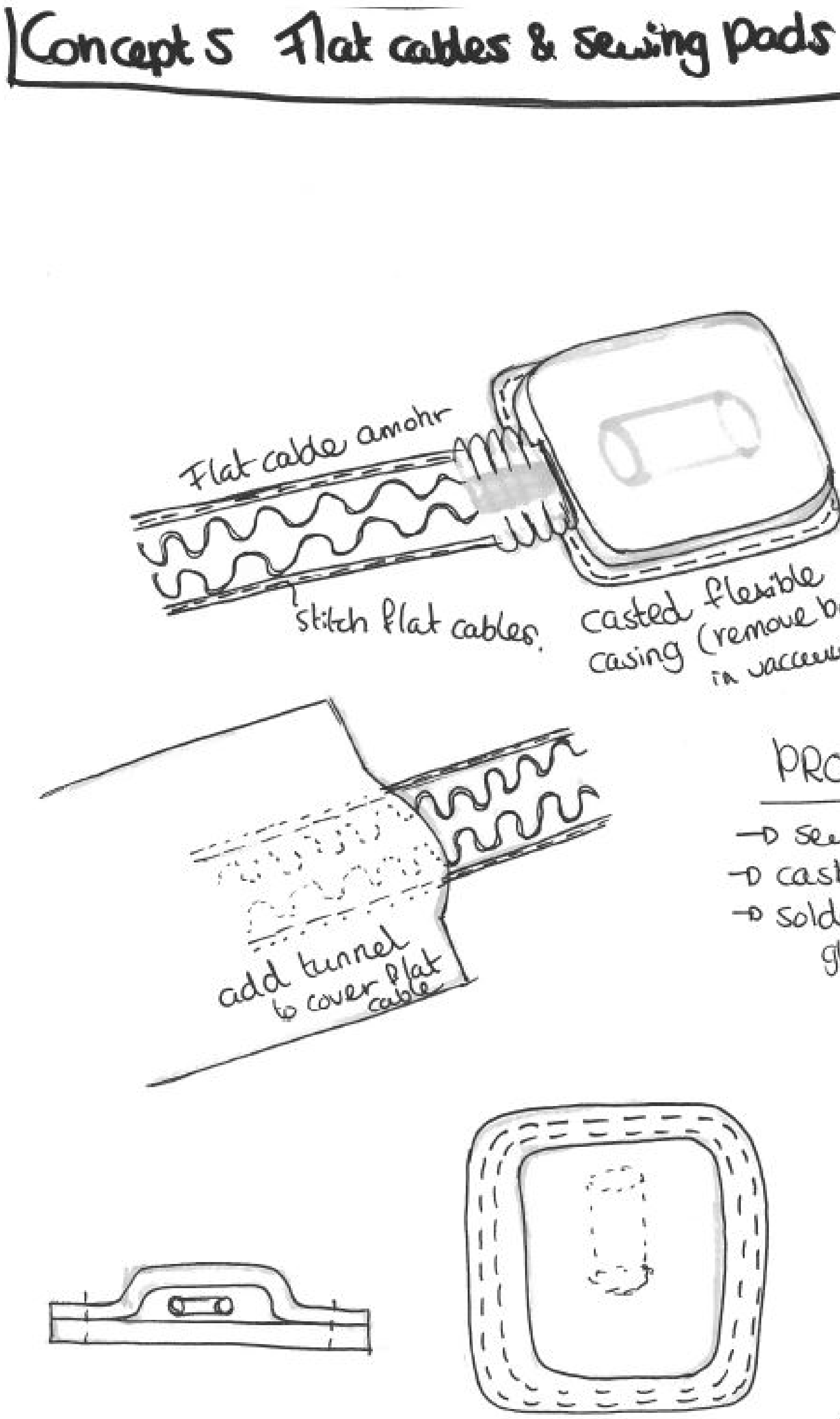


Figure 254. Concept 5 explained in a visual

	Module A: tactor	*Module B: power & data transport system*	*Module C: the main controller*
Connection of module to power & data transport	A1: Soldering of electrical components inside tactor, to connect PCB to module B.	B1: ***Amohr flat cables,*** can be substituted by ***conductive ink*** and ***yarn***.	C1: Detachable main control module by the use of ***pogo pins*** and magnets. Can be substituted by ***conductive Velcro or snap buttons.***
Connection of module to protective casing	A2: ***Overmolding*** of PCB with vibration motor. Can be substituted by ***lamination*** as well.	B2: Placing a tunnel or textile tape on top of	C2: 3D printed/ Injection molded casing. closed through ***clicking/glueing.***
Connection of module to textile carrier	A3: Sewn with non-conductive yarn onto textile carrier.	B3: By sewing conductive yarns directly on the textile carrier	C3: The same as C1.

Table 18. Designed connections Concept 5: flat cables and sewing pads

In Table 18 an overview of the modules designed for concept 5 is given. Interchangeable components are highlighted in black.

Production processes

In order to produce this concept the following processes are involved:

- Overmolding (tactor module casing)
- 3D printing (main control module casing)
- Soldering (Electronics inside tactor and main control module)
- Glueing (tactor module)
- Sewing (conductive yarn traces)

Pros

1. Conductive yarns traces sewn on textile carriers can be easily prototyped and tested through available equipment at Elitac Wearables
2. The conductive yarns allow for serial or singular circuitry of tactor modules.
3.

Cons

1. Each conductive yarn traces needs to be sewn by hand, requiring quite some time.
2. Not all conductive yarns are durable in terms of resistance when it comes to Launderability
3.

Discussion & concerns

The pogo pins used to connect the main control module might not be strong enough. Additional magnets or click finger design might be necessary. A second design of the system could allow for detachable tactors as well, making it easier to repair and more washable.
As not all conductive yarns are as durable when it comes to washing, this should be tested when low resistance yarns are selected. In previous research performed by Zaman et al. (2019) silver yarns of AMANN Group still maintained their conductivity

Decision

Discontinue for now. Flat cables are interesting to implement in other designs if necessary.

A12. Arduino test code PWM prototypes 1 & 2

Afstuderen_PWM_seeeduino_xiao

```
int motor_pin1 = 7; //declare first analog motor output pin for PWM
int motor_pin2 = 8; //declare second analog motor ouput pin for PWM
int motor_pin3 = 9; //declare 3rd analog motor output pin for PWM
void setup() {
  Serial.begin(9600); //Initialize serial monitor for error checking
  pinMode(motor_pin1, OUTPUT); //declare analog pin 7 as an output
  pinMode(motor_pin2, OUTPUT); //declare analog pin 8 as an output
  pinMode(motor_pin3, OUTPUT); //declare analoge pin 9 as an output
  delay(2000);
}

void loop() {
  analogWrite(7, 55);
  analogWrite(8, 55);
  analogWrite(9, 55);
  Serial.println("motor1: writing 20% vibration");
  Serial.println("motor2: writing 20% vibration");
  Serial.println("motor3: writing 20% vibration");
  delay(1000);


  analogWrite(7, 150);
  analogWrite(8, 150);
  analogWrite(9, 150);
  Serial.println("motor1: Writing 60% vibration");
  Serial.println("motor2: writing 60% virbation");
  Serial.println("motor3: writing 60% virbation");
  delay(1000);

  analogWrite(7, 255);
  analogWrite(8, 255);
  analogWrite(9, 255);
  Serial.println("motor1: Writing 100% vibration");
  Serial.println("motor2: Writing 100% vibration");
  Serial.println("motor3: Writing 100% vibration");
  delay(1000);

}
```

A13. Detailed production prototype 1 & 2

Production Prototype 1

Techniques

The following production methods were used to create the prototype:

• 3D printing, for the mock-up of casings.
• Sewing, of the conductive yarns & the pocket
• Knitting, to test the knitted pocket idea .
• Glueing, to fixate the ERM for soldering
• Soldering, of the ERM to springsteel contacts
• Ironing, of the Vliesofix and Vlieseline

Materials

The following materials were used to create the prototype:
• Conductive yarn Elektrisola 30004021L of 0.04 ~2.1 Ohm/meter
• AMANN Saba 80, 100% polyester grey
• 4-way stretch textile carrier 150x600mm
• Vlieseline
• Vliesofix
• Solufix
• Tailors chalk
• Sewing pins
• Baking paper
• Iron
• Super stretch needle Schmetz 75/11
• Small elastic band
• PLA for 3D prints
• 2 strips of spring steel 0.4mm thickness
• ERM cylinder motor (1x)
• Hot glue gun
• Conductive glue EXS-302: Self-Leveling EMI-RFI Conductive Silicone Sealant
• Super glue
• Soldering material
• 10x10mm conductive Velcro: Hook & Loop Adafruit (4x)
• Ultimaker 2+
• Singer Heavy Duty

Step by step approach

1. Vibration motor module

3D print the casing module & main control module with extra fine settings on the 3D printers so the fillets work out fine. Place the spring steel inside the slots and mechanically fasten them by using screws. Solder the + & - of the ERM motor to the spring steel strips. Close the casing and fixate it with a screw.

2. Marking the location of conductive yarns

Stick Solufix to the topside of the textile carrier, at the locations where the conductive yarns will be sewn. Mark the locations where the conductive yarn traces are going to come with tailors chalk or a pen, see Figure 255. Translate this to the other side of the fabric by using pins to mark the locations. The total length of the system developed is around 50 cm, allowing to cover the length of the back of a male mannequin.

2. Ironing on Vlieseline & conductive Velcro

On the other side of the fabric, iron on a piece of Vlieseline in the form of the main control module. On top of this, mark the locations of the conductive Velcro. Place a piece of Vliesofix in top, an place the conductive Velcro squares on the designated locations. Use an iron and baking paper to temporarily attach the Velcro, see Figure 256.

3. Sew conductive yarn traces

Use the AMANN Saba as top stitch yarn, and the Elektrisola in the Bobbin. To keep the stitch stretchable, a zigzag stitch was chosen See Figure 261 for a photo of the machine and detailed settings. The Solufix side should be facing upwards and the conductive Velcro downwards. Start at the bottom part where the pocket will be located and work your way up. Use multiple zigzag stitches back and forth to create the conductive traces inside the pocket, see Figure 257. Use one single zigzag stitch until you reach the conductive Velcro. There connect to the Velcro with multiple stitches as shown in Figure 258. Then switch to a straight stitch (SW=0). and sew all the way around on the edges of the Velcro.

4. Create the pocket

On top of the pocket fabric, sew a piece of elastic band. Then sew the pocket to the fabric, by stitching 3 sides with non-conductive AMANN Saba yarn. Check the tightness of the pocket and the alignment with the vibration motor module. Adjust the tightness and alignment with an additional titch if necessary, see Figure 259.

5. Attach conductive Velcro to main module

Glue the conductive velco with super glue to casing around the edges. Glue electrical wires to Velcro through the holes (see Figure 260) with conductive glue

Figure 255. Solufix with marked with pen for conductive yarn traces

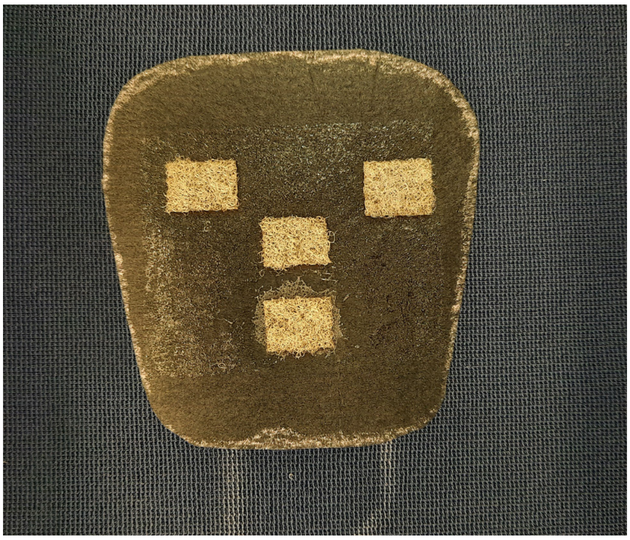


Figure 256. The conductive Velcro ironed to the textile carrier with vliesofix1

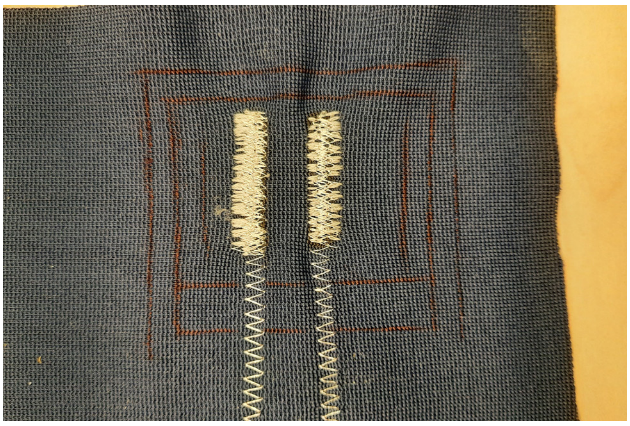


Figure 257. Pocket conductive yarn traces

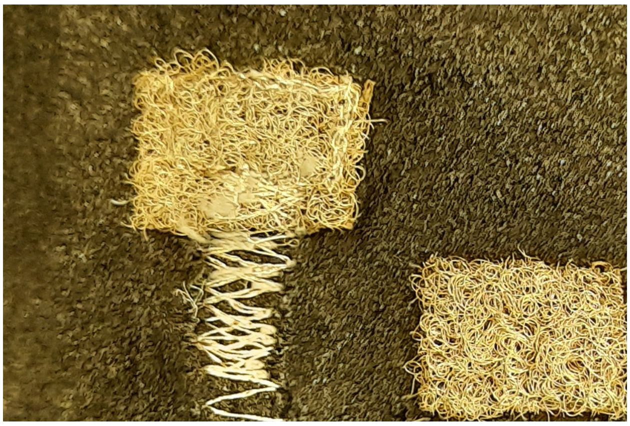


Figure 258. Pocket tightness adjustment

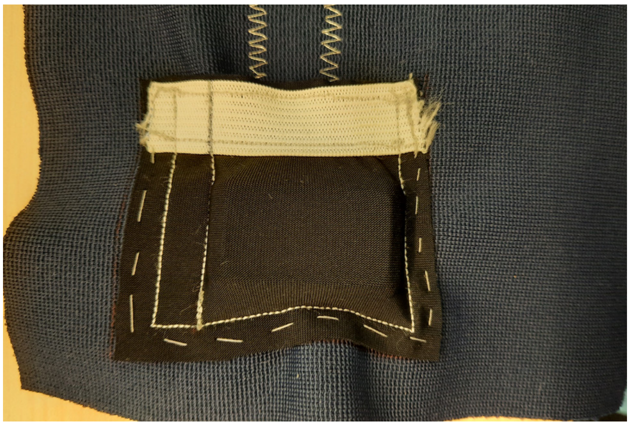


Figure 259. Sewing the conductive Velcro

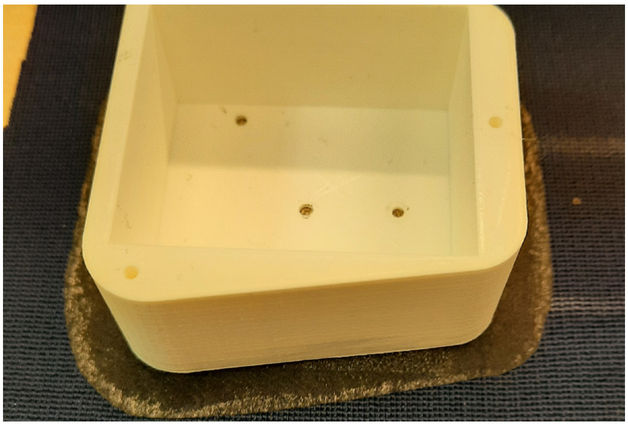


Figure 260. Main control module attachment, with holes to glue elektrical wires to conductive Velcro

Figure 261. Overview of sewing machine settings used for the Singer Heavy Duty
with the following settings: Top Tension= 8, Stitch Length= 2, Stitch Width = 6, Bobbin tension max turned to right & foot pressure lowered by 25% (turn 90 degrees anti-clockwise).

Production Prototype 2

Techniques

The following production methods were used to create the prototype:

- 3D printing, for the mock-up of casings.
- Sewing, of the conductive yarns traces.
- Glueing, to fixate the ERM for soldering
- Soldering, of the headerpins & pogo pins.
- Ironing, of the Vliesofix and Vlieseline

Materials

The following materials were used to create the prototype:

- Conductive yarn Elektrisola 30004021L of 0.04 ~2.1 Ohm/meter
- AMANN Saba 80, 100% polyester grey
- 4-way stretch textile carrier 150x600mm
- Vlieseline
- Tailors chalk
- 6 long header pins
- Prototype PCB board
- 4 Pogo-pin connector with magnets
- Baking paper
- Iron
- Super stretch needle Schmetz 75/11
- PLA for 3D prints
- ERM cylinder motor (1x)
- Conductive glue EXS-302: Self-Leveling EMI-RFI Conductive Silicone Sealant
- Soldering material
- 10x10mm conductive Velcro: Hook & Loop Adafruit (4x)
- Ultimaker 2+
- Singer Heavy Duty
- Soldering station
- Pliers
- Double sided tape Tesa
- Two small magnets
- Pattex

Step by step approach

1. 3D printing casings & hardware soldering

3D print the casing of the vibration motor and the main control module with landing spot with extra fine settings on the 3D printers so the fillets work out fine.

2. Soldering hardware

Solder the hardware of the main control module according to Figure 142 presented in

paragraph 13.1, and attach it to the first two pogo pins. Fixate the modules with Pattex inside the main control module.
Next solder the pogo pins and long header pins to a piece of prototyping PCB as shown in Figure 262. De the same for the vibration motor module as shown in Figure 263.

3. Marking the location of conductive yarns
Mark the locations where the conductive yarn traces are going to come with tailors chalk. Translate this to the other side of the fabric by using pins to mark the locations. he total length of the system developed is around 50 cm, allowing to cover the length of the back of a male mannequin. Iron Vlieseline to the textile carrier at the locations of the main control module landings pot.

4. Sew conductive yarn traces
Use the AMANN Saba as top stitch yarn, and the Elektrisola in the Bobbin. To keep the stitch stretchable, a zigzag stitch was chosen See Figure 261 for a photo of the machine and detailed settings. The side without the Vlieseline should be facing upwards. Start at the bottom part where the tactor module will be located and work your way up. Use multiple zigzag stitches back and forth to create the conductive traces for the tactor module and pogo pin module, see Figures 264, 265 and 266.
Add more zigzag stitches of the non-conductive yarn as a strain relief near the locations of the casing, see Figures 269 & 270. Moreover, add another less stretchable stitch on top of the conductive yarn as an overstretching protection, see Figure 268.

5. Connect modules
Place the headerpins of the vibration motor module and the header pins of the pogo pin module underneath the conductive zigzag stitch. Place a small piece of double sided tape between the PCB and fabric to keep it in place. Add a drop of conductive glue to ensure the electrical connection, see Figures 265 & 266.
6. Attach landing spot and tactor casing
Now place the landing spot over the pogo pin module and keep it in place with double sided tape. Fixate the magnet with Pattex. Cover and attach the tactor module casing in the same way, see Figure 269 and 270.

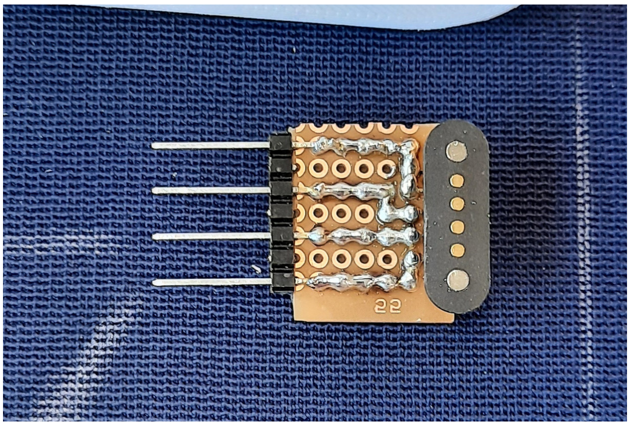


Figure 262. Pogo pin connection landingspot

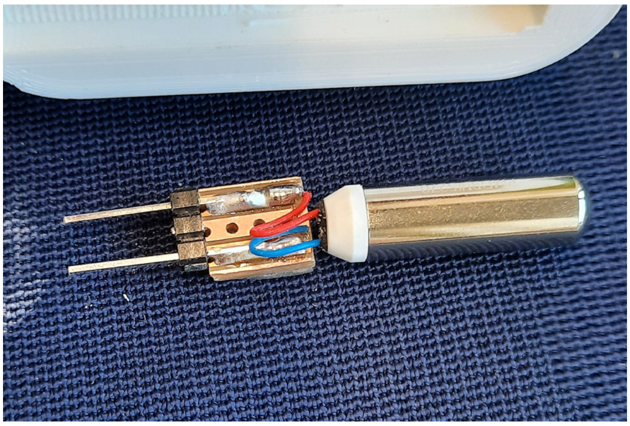


Figure 263. Tactor module soldered


Figure 264. Conductive yarn stitched

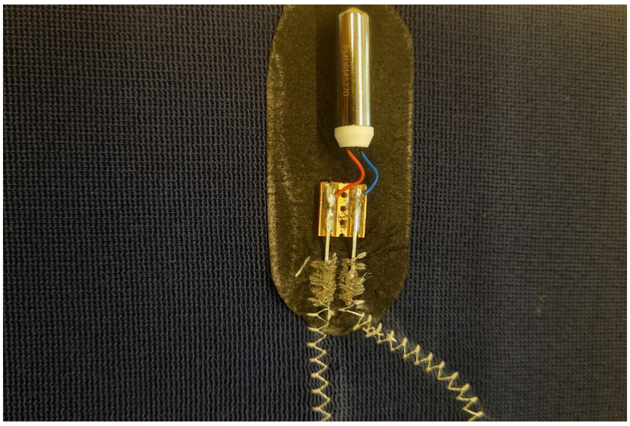


Figure 265. Tactor module attached to cond. yarn

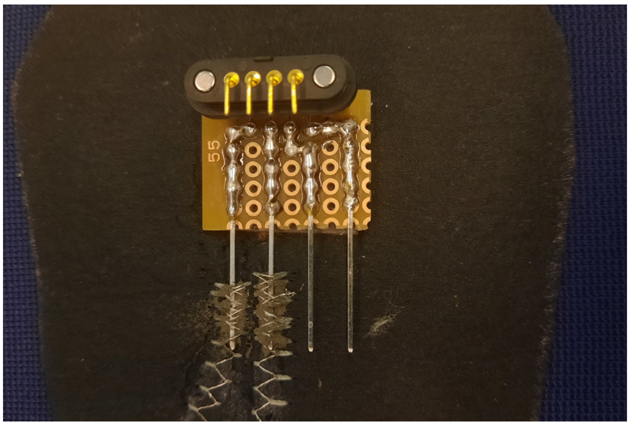


Figure 266. Pogo-pin connector attached


Figure 267. Additional zigzag as strainreliefs

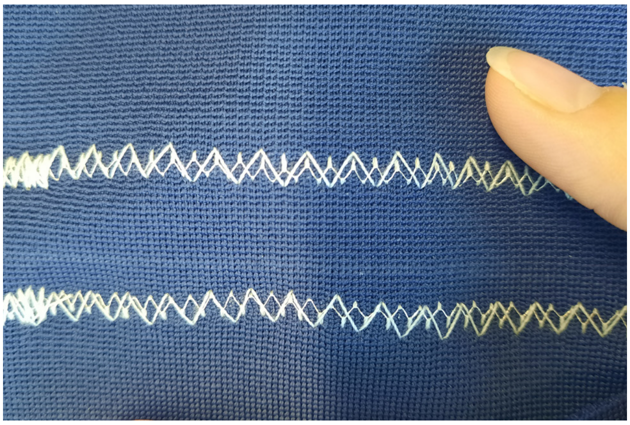


Figure 268. Overstretching protection


Figure 269. Landingspot attached

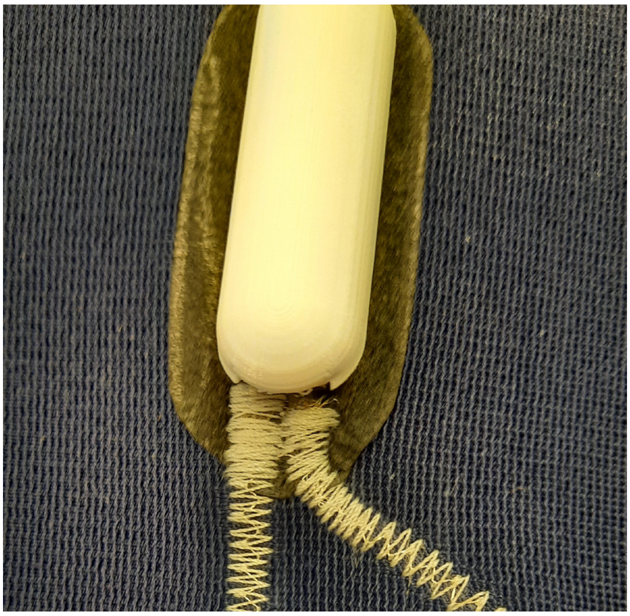


Figure 270. Tactor casing attached

A14. Silicon overmolding testst

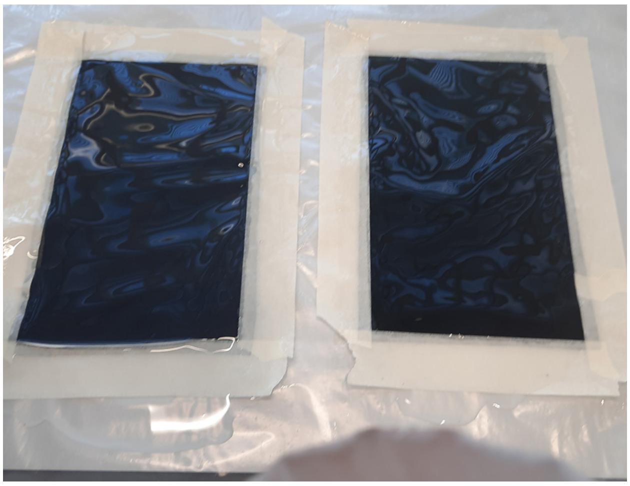


Figure 271. 1mm casting of silicon on top of fabrics

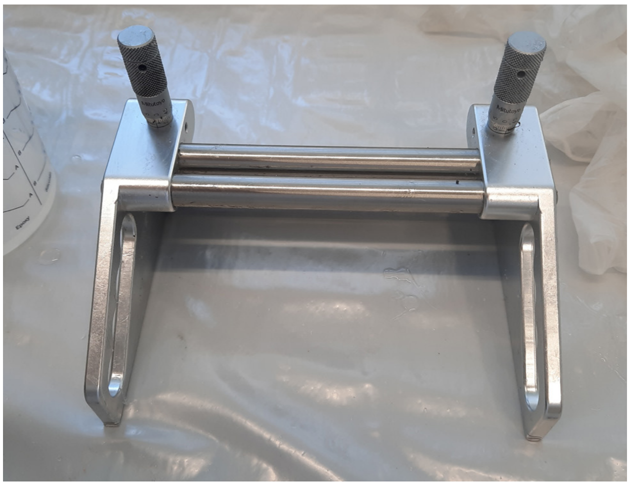


Figure 272. A micro film applicator is used for this

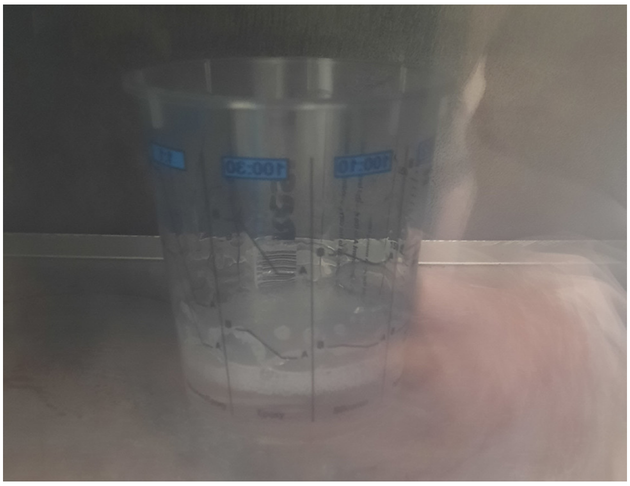


Figure 273. Mix silicon and place in vacuum oven

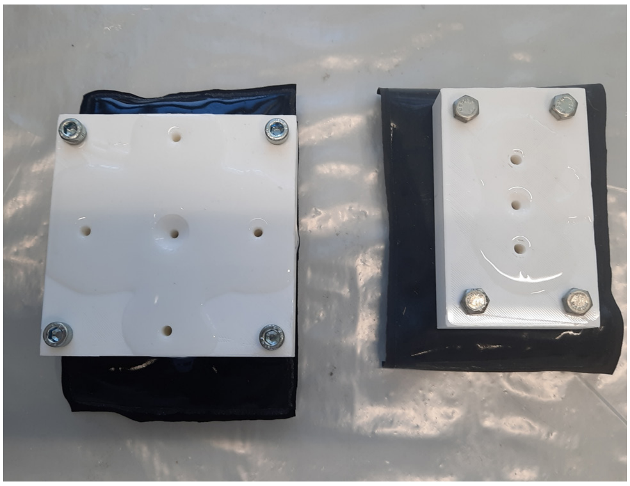


Figure 274. Inject silicon in mold with a syringe

Figure 275. Place molds in vacuum oven for removal of trapped airbubbles

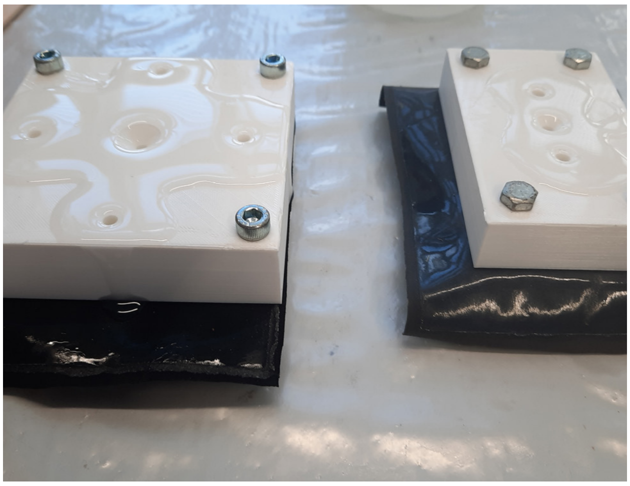


Figure 276. Let the silicon harden for 8 hours

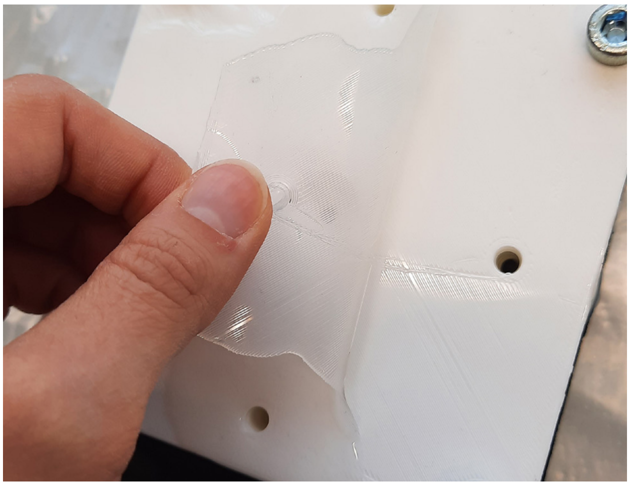


Figure 277. Remove mold and excessive silicon


Figure 280. Misplaced ERM mock-up


Figure 278. PLA mock-up motor was not fixated enough during casting and is displaced


Figure 281. Removal of airbubbles decreased the volume of silicon and left a shiny hole.


Figure 279. Casting of tactor including used mold.

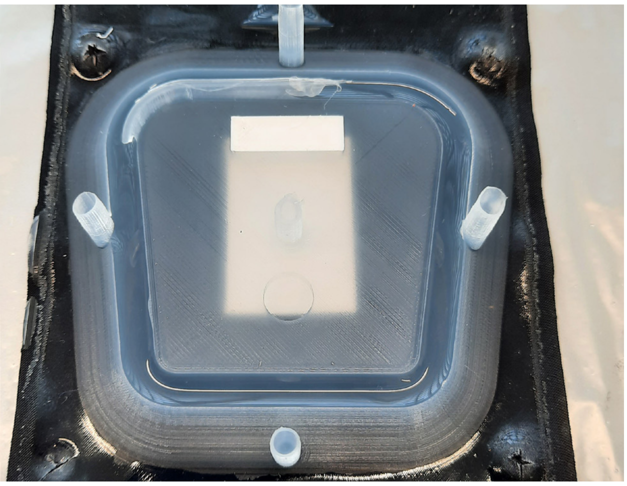


Figure 282. Landingspot overmold


Figure 283. Silicon does not attach to PLA

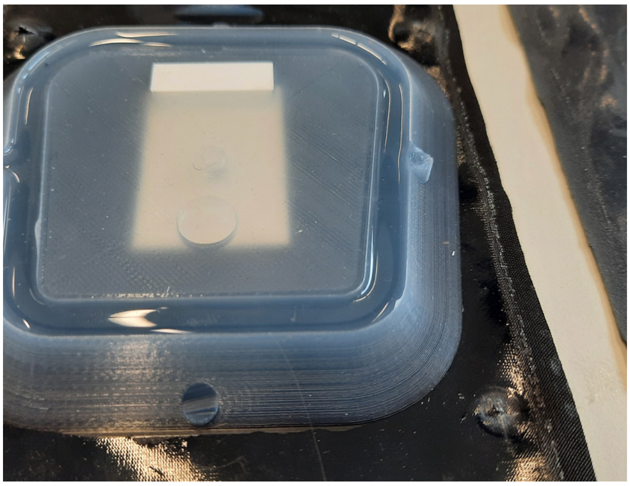


Figure 285. Landingspot overmold without injection and air vent material


Figure 286. Landing spot and main module


Figure 284. Casting landing spot including used mold

A15. Launderability test raw data

Bekaert Bekinox VN 12.2.2.175S Steel	yarns distance in meters	resistance measured in ohm before washing	Resistance washing cycle 1	Resistance washing cycle 2	Resistance washing cycle 3	Resistance washing cycle 4	Resistance washing cycle 5	Resistance washing cycle 6	Resistance washing cycle 7	Resistance washing cycle 8	Measurement	Slope calculation	Y-axis cut-off	Standard deviation S
zigzag width 3mm length 2.5mm	0,1	1,5	1,2	1,2	1,2	1	1	1	1,1	1,1	Before washing zigzag	9,2	-0,060699103	1,454991409
zigzag width 3mm length 2.5mm	0,2	2,4	2	2	2,1	1,9	2	2	2,2	2,2	straight	14,2	-0,040709895	2,245662486
zigzag width 3mm length 2.5mm	0,3	3,3	2,7	2,8	2,7	2,8	2,9	3	2,9	2,8	cycle 1 zigzag	8,3	-0,038824551	1,31415372
zigzag width 3mm length 2.5mm	0,4	4,2	3,7	3,8	3,9	3,7	3,8	3,8	3,7	3,7	cycle 1 straight	14	-0,003423131	2,221936093
zigzag width 3mm length 2.5mm	0,5	5,2	4,5	4,6	4,6	4,7	4,9	4,9	5	4,9	cycle 2 zigzag	8,6	-0,034341253	1,360882067
straight stitch length 2.5mm	0,1	2	1,6	1,6	1,7	1,6	1,7	1,7	1,7	1,6	cycle 2 straight	13,8	-0,012393073	2,189292123
straight stitch length 2.5mm	0,2	3,4	2,8	3,1	2,9	3,1	3,1	3,2	3,2	3,2	cycle 3 zigzag	8,6	-0,034316354	1,365650028
straight stitch length 2.5mm	0,3	4,9	4,3	4,2	4,3	4,2	4,3	4,3	4,2	4,3	cycle 3 straight	14	-0,012092834	2,216303228
straight stitch length 2.5mm	0,4	6,2	5,4	5,5	5,7	5,5	5,7	5,7	5,7	5,8	cycle 4 zigzag	9,2	-0,006376949	1,454991409
straight stitch length 2.5mm	0,5	7,7	7,3	7,3	7,3	7,3	7,3	7,3	7,4	7,4	cycle 4 straight	13,8	-0,012393073	2,189292123
			z0 0.2 ohm	z0 0.2 ohm	z0 0.2 ohm	z0 0.2 Ohm	z0 0.2 Ohm	z0 0.2 Ohm	z0 0.2 Ohm	z0 0.2 Ohm	cycle 5 zigzag	9,6	-0,003771131	1,518881167
											cycle 5 straight	13,8	-0,019551551	2,184490787
											cycle 6 zigzag	9,6	-0,005719237	1,519210321
											cycle 6 straight	13,7	-0,023003398	2,169792617
											cycle 7 zigzag	9,3	-0,016803841	1,478850905
											cycle 7 straight	13,9	-0,017273288	2,205221077
											cycle 8 zigzag	9,1	-0,019565217	1,446720429
											cycle 8 straight	14,2	-0,013028865	2,248999778

AmannGroup Silver-tech 30 Tex 96	distance in m	resistance before washing	Resistance washing cycle 1	Resistance washing cycle 2	Resistance washing cycle 3	Resistance washing cycle 4	Resistance washing cycle 5	Resistance washing cycle 6	Resistance washing cycle 7	Resistance washing cycle 8	Measurement	Slope calculation	Y-axis cut-off	Standard deviation S
zigzag width 3mm length 2.5mm	0,1	8,7	7,9	10,4	13,9	15,5	17,2	20,1	24,4	26,3	Before washing zigzag	68,8	-0,033896309	10,90376082
zigzag width 3mm length 2.5mm	0,2	16,7	16,6	16,8	19,9	20,3	24,9	28,8	36,9	41,9	Before washing straight	91,8	-0,025501094	14,53402904
zigzag width 3mm length 2.5mm	0,3	23,1	23,1	24,9	28,8	29,6	34,9	40,7	51,2	57,1	cycle 1 zigzag	73,8	-0,014317418	11,68473363
zigzag width 3mm length 2.5mm	0,4	30,9	31,2	35,4	38,5	40,3	47,6	51,9	64,4	72,3	cycle 1 straight	96,4	-0,013307116	15,28682439
zigzag width 3mm length 2.5mm	0,5	36	37,5	40,6	47,9	48,3	56,6	61,3	79,9	91	cycle 2 zigzag	79	-0,021262587	12,54998008
straight stitch length 2.5mm	0,1	11	10	10,3	12,1	12,8	17,5	20,9	26,6	30,2	cycle 2 straight	108,4	-0,00134751	17,19034613
straight stitch length 2.5mm	0,2	21,3	21,1	21,7	25,1	25,9	30,3	34,4	44,2	52,4	cycle 3 zigzag	86,6	-0,041757601	13,73972343
straight stitch length 2.5mm	0,3	29,9	31,6	34,7	38,7	40,6	51	58,4	72,2	79,8	cycle 3 straight	122,3	-0,00470775	19,39283373
straight stitch length 2.5mm	0,4	40,1	40,9	44,5	51,4	55,2	65,2	72,4	93,2	109,5	cycle 4 zigzag	85,6	-0,055186722	13,62240801
straight stitch length 2.5mm	0,5	47,5	48,3	53,1	60,1	63,4	78,2	89,1	108,8	131,3	cycle 4 straight	130,5	-0,000874105	20,71670823
			z0 0.2 ohm	z0 0.2 Ohm	z0 0.2 ohm	z0 0.2 ohm	z0 0.2 ohm	z0 0.2 ohm	z0 0.2 ohm	z0 0.2 ohm	cycle 5 zigzag	101,5	-0,054885518	16,09729791
											cycle 5 straight	156,3	-0,007839795	24,79643119
											cycle 6 zigzag	105,5	-0,083542833	16,7008383
											cycle 6 straight	174,4	-0,013252653	27,67802377
											cycle 7 zigzag	138,5	-0,070384873	21,91193739
											cycle 7 straight	213,4	-0,020607396	33,88480485
											cycle 8 zigzag	159,8	-0,060579639	25,28837678
											cycle 8 straight	259,3	-0,010156974	41,05402538

Elektrisola 30004021L mm copper, silverplated	distance in m	Resistance before washing	Resistance washing cycle 1	Resistance washing cycle 2	Resistance washing cycle 3	Resistance washing cycle 4	Resistance washing cycle 5	Resistance washing cycle 6	Resistance washing cycle 7	Resistance washing cycle 8	Measurement	Slope calculation	Y-axis cut-off	Standard deviation S
zigzag width 3mm length 2.5mm	0,1	0,362	0,246	0,261	0,260	0,252	0,251	0,252	0,248	0,235	Before washing zigzag	2,621310655	-0,049460171	0,416095292
zigzag width 3mm length 2.5mm	0,2	0,673	0,563	0,591	0,555	0,578	0,606	0,619	0,614	0,587	Before washing straight	3,493746873	0,010053729	0,554236684
zigzag width 3mm length 2.5mm	0,3	0,973	0,883	0,878	0,880	0,901	0,912	0,892	0,879	0,897	cycle 1 zigzag	2,818463383	0,003989689	0,44807438
zigzag width 3mm length 2.5mm	0,4	1,196	1,176	1,169	1,153	1,172	1,188	1,184	1,162	1,165	cycle 1 straight	3,412928364	0,028168033	0,541378333
zigzag width 3mm length 2.5mm	0,5	1,412	1,349	1,341	1,332	1,365	1,362	1,350	1,348	1,353	cycle 2 zigzag	2,737536217	-0,00650563	0,435149064
straight stitch length 2.5mm	0,1	0,326	0,264	0,256	0,251	0,254	0,273	0,276	0,269	0,248	cycle 2 straight	3,412928364	0,03276224	0,542318969
straight stitch length 2.5mm	0,2	0,713	0,618	0,612	0,613	0,614	0,621	0,629	0,631	0,632	cycle 3 zigzag	2,742805755	-0,001812002	0,435797324
straight stitch length 2.5mm	0,3	0,959	0,895	0,867	0,878	0,914	0,883	0,876	0,879	0,908	cycle 3 straight	3,39028777	0,029945082	0,537542363
straight stitch length 2.5mm	0,4	1,340	1,224	1,204	1,219	1,238	1,244	1,252	1,244	1,239	cycle 4 zigzag	2,821025282	0,000367774	0,448236343
straight stitch length 2.5mm	0,5	1,760	1,667	1,667	1,643	1,674	1,673	1,683	1,697	1,687	cycle 4 straight	3,464574798	0,030192809	0,548961065
											cycle 5 zigzag	2,803719628	-0,003666523	0,446502324
											cycle 5 straight	3,422657734	0,027575355	0,542991924
											cycle 6 zigzag	2,762342594	-0,006501277	0,440059709
											cycle 6 straight	3,437937238	0,027860785	0,54579952
											cycle 7 zigzag	2,74890044	-0,005585421	0,437228012
											cycle 7 straight	3,469612155	0,030557886	0,551217361
											cycle 8 zigzag	2,815592204	0,00275061	0,447953109
											cycle 8 straight	3,486256872	0,031263789	0,552942473

Elektrisola 30004021L mm copper, silverp	distance in m		Voltage measured in mV before washing	Voltage measured in mV washing cycle #1	Voltage measured in mV washing cycle #2	Voltage measured in mV washing cycle #3	Voltage measured in mV washing cycle #4	Voltage measured in mV washing cycle #5	Voltage measured in mV washing cycle #6	Voltage measured in mV washing cycle #7	Voltage measured in mV washing cycle #8
zigzag width 3mm length 2.5mm	0,1		36,5	24,9	26,4	26,5	25,7	25,5	25,7	25,3	24
zigzag width 3mm length 2.5mm	0,2		67,6	56,7	59,5	56	58,3	61	62,4	61,9	59,2
zigzag width 3mm length 2.5mm	0,3		97,6	88,7	88,2	88,6	90,7	91,6	89,8	88,4	90,2
zigzag width 3mm length 2.5mm	0,4		119,8	118	117,3	115,9	117,8	119,2	119	116,7	117,1
zigzag width 3mm length 2.5mm	0,5		141,4	135,3	134,5	133,8	137,1	136,6	135,6	135,4	135,9
straight stitch length 2.5mm	0,1		32,9	26,7	25,9	25,6	25,9	27,7	28,1	27,4	25,3
straight stitch length 2.5mm	0,2		71,6	62,2	61,6	61,8	61,9	62,5	63,4	63,6	63,7
straight stitch length 2.5mm	0,3		96,2	89,9	87,1	88,4	92	88,7	88,2	88,4	91,3
straight stitch length 2.5mm	0,4		134,2	122,8	120,8	122,5	124,4	124,8	125,8	124,9	124,5
straight stitch length 2.5mm	0,5		176,2	167,2	167,1	164,9	168	167,7	168,9	170,3	169,3
			4 punts meting: 100 mA erop. 0 meting: - 0,05 mA en 0.3 mV	4 punts meting: 100mA en 3 Volt, nul meting -0,09 & mA 0,3mV	4 outs meting: 100 mA en 3 Volts, nul meting -0.06 mA en + 0.3mV	4 outs meting: 100 mA en 3 Volts, nul meting -0.08 mA en + 0.5mV	4 outs meting: 100 mA en 3 Volts, nul meting -0.07 mA en + 0.5mV	4 outs meting: 100 mA en 3V, nul meting: - 0.01 mA en +0,4mV	4 outs meting: 100 mA en 3V, nul meting: - 0.06 mA en +0,5mV	4 outs meting: 100 mA en 3V, nul meting: - 0.04 mA en +0,5mV	4 outs meting: 100 mA en 3V, nul meting: - 0,05 mA en +0,5mV

Distance measured is a bit shorter than before as glueing ends did not work well. It protects endings well during laundering, but breaks the wire of the Elektrisola and pulls off parts of the threads of Bekinox and Amann Group. Therefor the electrodes are hooked around the sewn wires (the hooks are small enough). However they do put strain on the sewn threads, especially the Elektrisola one is sensitive to this. Straight stitch length sample 3 with a length of 300mm broke and is now 290mm long for measurements.

The lower measured resistances especially of Elektrisola can be partially explained by a small deviation in measurement distance over which the voltage was measured. Maximum distance

Notes after washing cycle 1:	this deviates lies around 10 mm
Notes after washing cycle 5	zigzag of 0,1 meter broke at the measuring point and is shortened by about 5 mm
Notes after washing cycle 6	zigzag of 0,3 meters broke at mthe measuring point and is shortened by about 5 mm zigzag of 0,1 broke and is shortened further by 5 mm
Notes after washing cycle 8	straight stitch of 0.1 meter borke and is shortened 10mm

Control test

Bekaert Bekinox VN 12.2.2.175S Steel	yarns distance in meters	resistance measured in ohm before washing	Resistance washing cycle 1	Resistance washing cycle 2	Resistance washing cycle 3	Resistance washing cycle 4	Resistance washing cycle 5	Slope calculation straight stitch	Y-axis cut-off	Slope calculation zigzag stitch	Y-axis cut-off
straight stitch length 2.5mm	0,1	1,5	1,5	1,5	1,5	1,6	1,6	14	0,1	9,5	-0,11
straight stitch length 2.5mm	0,2	2,9	2,9	2,9	2,9	2,9	3				
straight stitch length 2.5mm	0,3	4,3	4,3	4,3	4,3	4,3	4,4				
straight stitch length 2.5mm	0,4	5,7	5,8	5,7	5,7	5,8	5,8				
straight stitch length 2.5mm	0,5	7,1	7	7	7	7	7				
zigzag width 3mm length 2.5mm	0,1	0,8	0,9	0,9	0,9	0,9	0,9				
zigzag width 3mm length 2.5mm	0,2	1,8	1,9	2	1,9	2	2				
zigzag width 3mm length 2.5mm	0,3	2,8	2,8	2,9	2,8	2,8	2,8				
zigzag width 3mm length 2.5mm	0,4	3,7	3,7	3,8	3,7	3,7	3,7				
zigzag width 3mm length 2.5mm	0,5	4,6	4,5	4,6	4,5	4,5	4,6				
		z0 0.2 ohm	z0 0.2 Ohm	z0 0.2 ohm	z0 0.3 ohm	z0 0.2 Ohm	z0 0.2 Ohm				

AmannGroup Silver-tech 30 Tex 96	distance in m	resistance before washing	Resistance washing cycle 1	Resistance washing cycle 2	Resistance washing cycle 3	Resistance washing cycle 4	Resistance washing cycle 5	Slope calculation zigzag stitch	Y-axis cut-off	Slope calculation straight stitch	Y-axis cut-off
straight stitch length 2.5mm	0,1	12,6	12,5	15	18,1	31,1	24,9	125,3	0,27	93,5	-0,95
straight stitch length 2.5mm	0,2	25,3	25	29,2	36,7	44,6	52,4				
straight stitch length 2.5mm	0,3	38,1	37,9	44,5	55,9	68,1	79,9				
straight stitch length 2.5mm	0,4	50,8	50,7	59,8	74,3	89,9	104,8				
straight stitch length 2.5mm	0,5	62,5	61,9	73	85,8	105,8	125,9				
zigzag width 3mm length 2.5mm	0,1	8,4	8,9	10,3	10,2	11,3	13,9				
zigzag width 3mm length 2.5mm	0,2	17,9	19,1	22	23,7	27,3	32,2				
zigzag width 3mm length 2.5mm	0,3	27	29,1	33,1	36,7	43,4	49,6				
zigzag width 3mm length 2.5mm	0,4	36,2	39,7	45	49,9	59,3	66,8				
zigzag width 3mm length 2.5mm	0,5	46	49,6	55,8	62,9	74,3	83,4				
		zo 0.2 ohm	z0 0.2 Ohm	z0 0.2 Ohm	z0 0.3 Ohm	z0 0.2 Ohm	z0 0.2 Ohm				

Elektrisola 30004021L mm copper, silverplated	distance in m		Resistance before washing	Resistance washing cycle 1	Resistance washing cycle 2	Resistance washing cycle 3	Resistance washing cycle 4	Resistance washing cycle 5	Slope calculation zigzag stitch	Y-axis cut-off	Slope calculation straight stitch	Y-axis cut-off
straight stitch length 2.5mm	0,1		0,223	0,197	0,202	0,192	0,202	0,193	2,144934258	0,015516408	###########	############
straight stitch length 2.5mm	0,2		0,451	0,407	0,410	0,405	0,414	0,405				
straight stitch length 2.5mm	0,3		0,661	0,624	0,623	0,622	0,631	0,622				
straight stitch length 2.5mm	0,4		0,876	0,839	0,844	0,839	0,849	0,841				
straight stitch length 2.5mm	0,49		1,062	1,018	1,023	1,023	1,025	1,039				
zigzag width 3mm length 2.5mm	0,1		0,118	0,109	0,129	0,113	0,105	0,120				
zigzag width 3mm length 2.5mm	0,2		0,281	0,276	0,294	0,278	0,272	0,285				
zigzag width 3mm length 2.5mm	0,3		0,448	0,443	0,462	0,449	0,442	0,454				
zigzag width 3mm length 2.5mm	0,4		0,610	0,603	0,620	0,609	0,604	0,618				
zigzag width 3mm length 2.5mm	0,5		0,773	0,744	0,758	0,745	0,739	0,758				

R=U/I

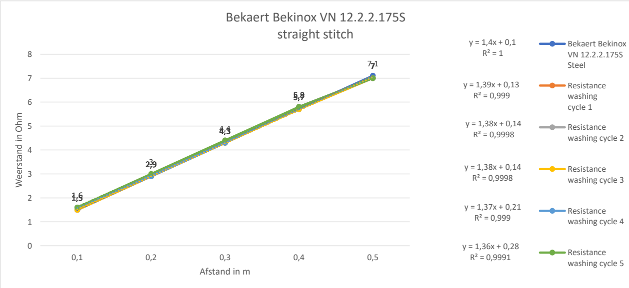
Elektrisola 30004021L mm copper, silverplated	distance in m		Voltage measured in mV before washing	Amperage put over in mA before washing	Voltage measured in mV washing cycle #1	Amperage put over in mA washing cycle #1	Voltage measured in mV washing cycle #2	Amperage put over in mA washing cycle #2	Voltage measured in mV washing cycle #3	Amperage put over in mA washing cycle #3	Voltage measured in mV washing cycle #4	Amperage put over in mA washing cycle #4	Voltage measured in mV washing cycle #5	Amperage put over in mA washing cycle #5
straight stitch length 2.5mm	0,1		22,3	99,92	19,7	99,92	20,16	99,86	19,2	99,83	20,2	99,91	19,3	99,91
straight stitch length 2.5mm	0,2		45,1	99,92	40,7	99,92	40,92	99,85	40,4	99,83	41,4	99,9	40,5	99,9
straight stitch length 2.5mm	0,3		66,1	99,93	62,4	99,93	62,2	99,86	62,1	99,84	63	99,91	62,1	99,91
straight stitch length 2.5mm	0,4		87,5	99,91	83,8	99,92	84,26	99,85	83,8	99,83	84,8	99,9	84	99,9
straight stitch length 2.5mm	0,49		106,1	99,93	101,7	99,92	102,1	99,85	102,1	99,83	102,4	99,91	103,8	99,91
zigzag width 3mm length 2.5mm	0,1		11,8	99,93	10,9	99,92	12,9	99,94	11,3	99,83	10,5	99,91	12	99,91
zigzag width 3mm length 2.5mm	0,2		28,1	99,93	27,6	99,92	29,4	99,85	27,8	99,83	27,2	99,9	28,5	99,91
zigzag width 3mm length 2.5mm	0,3		44,8	99,92	44,3	99,91	46,1	99,84	44,8	99,83	44,2	99,9	45,4	99,91
zigzag width 3mm length 2.5mm	0,4		61	99,92	60,3	99,92	61,9	99,85	60,8	99,84	60,3	99,91	61,7	99,91
zigzag width 3mm length 2.5mm	0,5		77,2	99,93	74,3	99,92	75,7	99,84	74,4	99,84	73,8	99,9	75,7	99,9
			4 punts meting: 100 mA max erop. 0 meting: -0,07 mA en 0.5 mV		4 punts meting: 100 mA max erop. 0 meting: -0,07 mA en 0.5 mV		4 punts meting: 100 mA max erop. 0 meting: -0.01 mA en 0.4 mV		4 outs meting: 100 mA en 3V, nul meting: +0.01 mA en +0,4mV		4 outs meting: 100 mA en 3V, nul meting: -0.07 mA en +0,5mV		4 outs meting: 100 mA en 3V, nul meting: -0.05mA en 0.5mV	

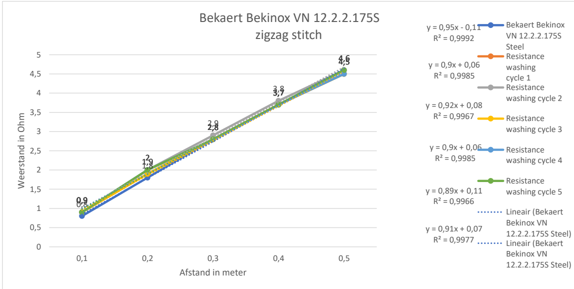
Resolution multimeter: 0.1 Ohm
Zero measurement system 0.2 Ohm

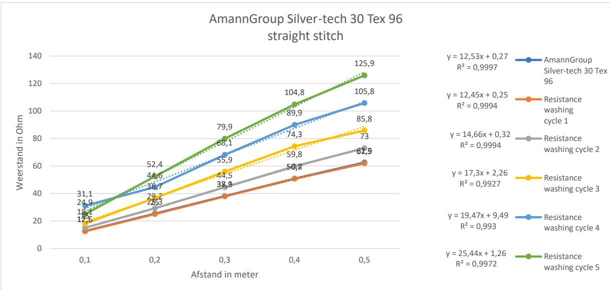
Bovenspanning 2,5
Standard needle used

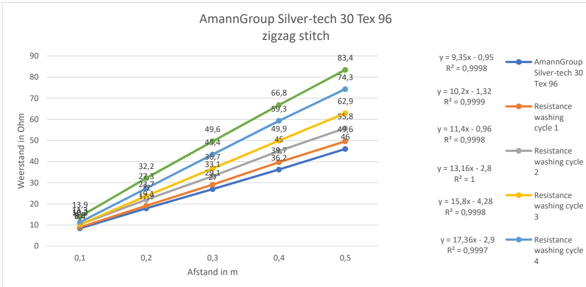
Settings 3V and 50 mA in DC power analyzer

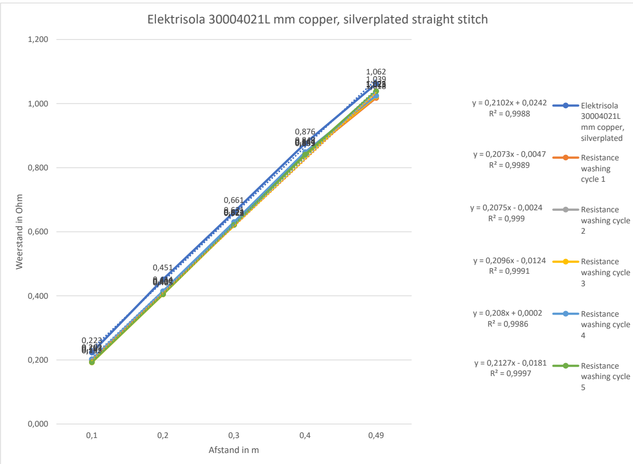
Wastest
zijde was 30 graden Celsius
centriguferen 400 rpm
Formil Lidl huismerk wasmiddel 25 mL
hang to dry

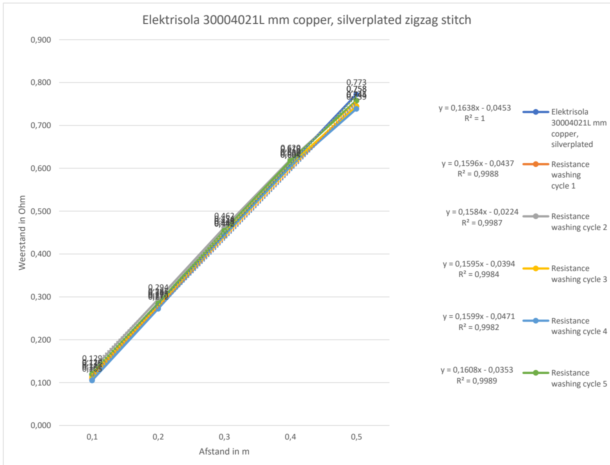












A16. Current vs. heat test raw data

Yarn tested AmannGroup Silver-tech 30 Tex 96 0.5m

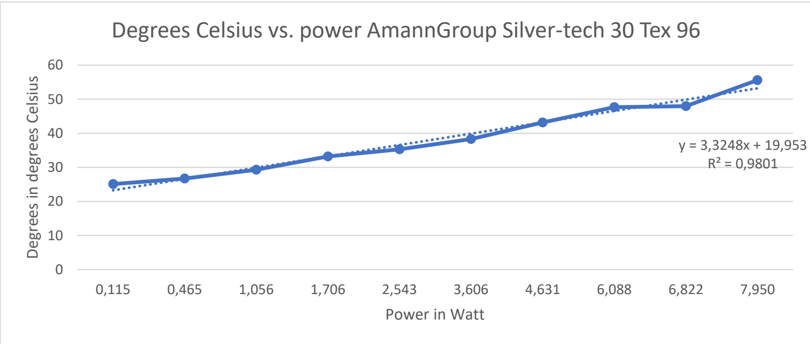
Current in mA	Time applied in S	Maximum measured temperature in degrees Celsius	Voltage in V	Notes	Power in Watt
50	10	25,1	2,29	3882	0,115
100	10	26,7	4,65	3883	0,465
150	10	29,3	7,04	3884	1,056
200	10	33,2	8,53	3885	1,706
250	10	35,3	10,17	3886	2,543
300	10	38,3	12,02	3887	3,606
350	10	43,2	13,23	3888	4,631
400	10	47,7	15,22	3889	6,088
450	10	48	15,16	3891	6,822
500	10	55,6	15,9	3892	7,950
150	60	28,5	3,37	3894	0,506
300	60	40,5	7,35	3895	2,205

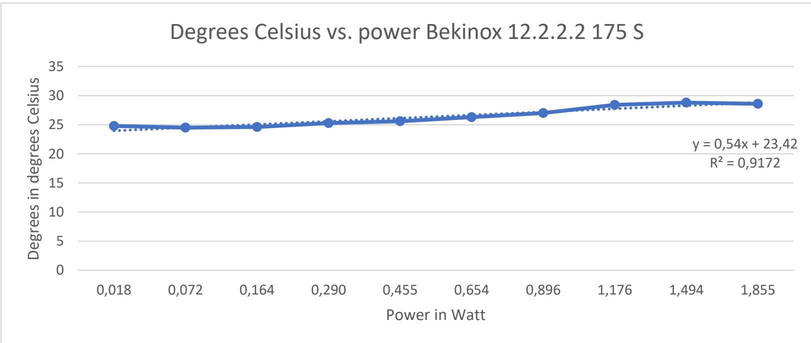
Yarn tested Bekinox 12.2.2.2 175S 0.5m

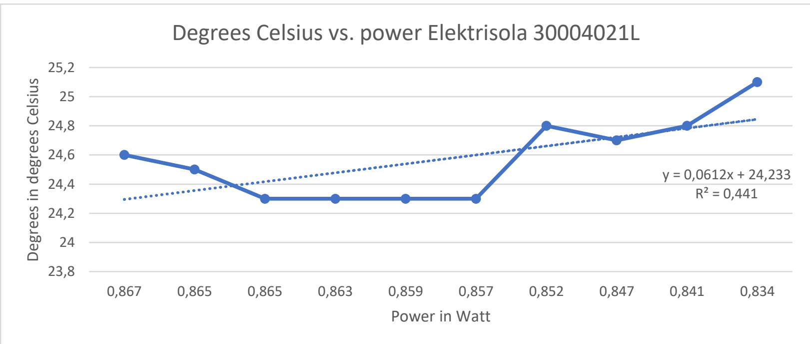
Current in mA	Time applied in S	Maximum measured temperature in degrees Celsius	Voltage in V	Notes	Power in Watt
50	10	24,8	0,36	3898	0,018
100	10	24,5	0,72	3899	0,072
150	10	24,6	1,09	3900	0,164
200	10	25,3	1,45	3901	0,290
250	10	25,6	1,82	3902	0,455
300	10	26,3	2,18	3903	0,654
350	10	27	2,56	3904	0,896
400	10	28,4	2,94	3905	1,176
450	10	28,8	3,32	3906	1,494
500	10	28,6	3,71	3907	1,855
150	60	25,1	1,08	3908	0,162
300	60	28,3	2,2	3909	0,660

Yarn tested Elektrisola Cu/Ag50 0,04 mm 300042021L 0.5m

Current in mA	Time applied in S	Maximum measured temperature in degrees Celsius	Voltage in mV	Notes	Power in Watt
50	10	24,6	57,7	3910	0,867
100	10	24,5	115,6	3911	0,865
150	10	24,3	173,5	3912	0,865
200	10	24,3	231,8	3913	0,863
250	10	24,3	290,9	3914	0,859
300	10	24,3	350,2	3915	0,857
350	10	24,8	410,6	3916	0,852
400	10	24,7	472,4	3917	0,847
450	10	24,8	535,1	3918	0,841
500	10	25,1	599,3	3919	0,834
150	60	24,4	173,6	3920	0,864
300	60	24,6	350,9	3921	0,855


Degrees Celsius vs. power AmannGroup Silver-tech 30 Tex 96
Degrees in degrees Celsius
60
50
40
30
20
10
0
0,115
0,465
1,056
1,706
2,543
3,606
4,631
6,088
6,822
7,950
Power in Watt
y = 3,3248x + 19,953
R² = 0,9801


Degrees Celsius vs. power Bekinox 12.2.2.2 175 S
Degrees in degrees Celsius
35
30
25
20
15
10
5
0
0,018
0,072
0,164
0,290
0,455
0,654
0,896
1,176
1,494
1,855
Power in Watt
y = 0,54x + 23,42
R² = 0,9172


Degrees Celsius vs. power Elektrisola 30004021L
Degrees in degrees Celsius
25,2
25
24,8
24,6
24,4
24,2
24
23,8
0,867
0,865
0,865
0,863
0,859
0,857
0,852
0,847
0,841
0,834
Power in Watt
y = 0,0612x + 24,233
R² = 0,441

A17. Data reliability test arduino scripts & data

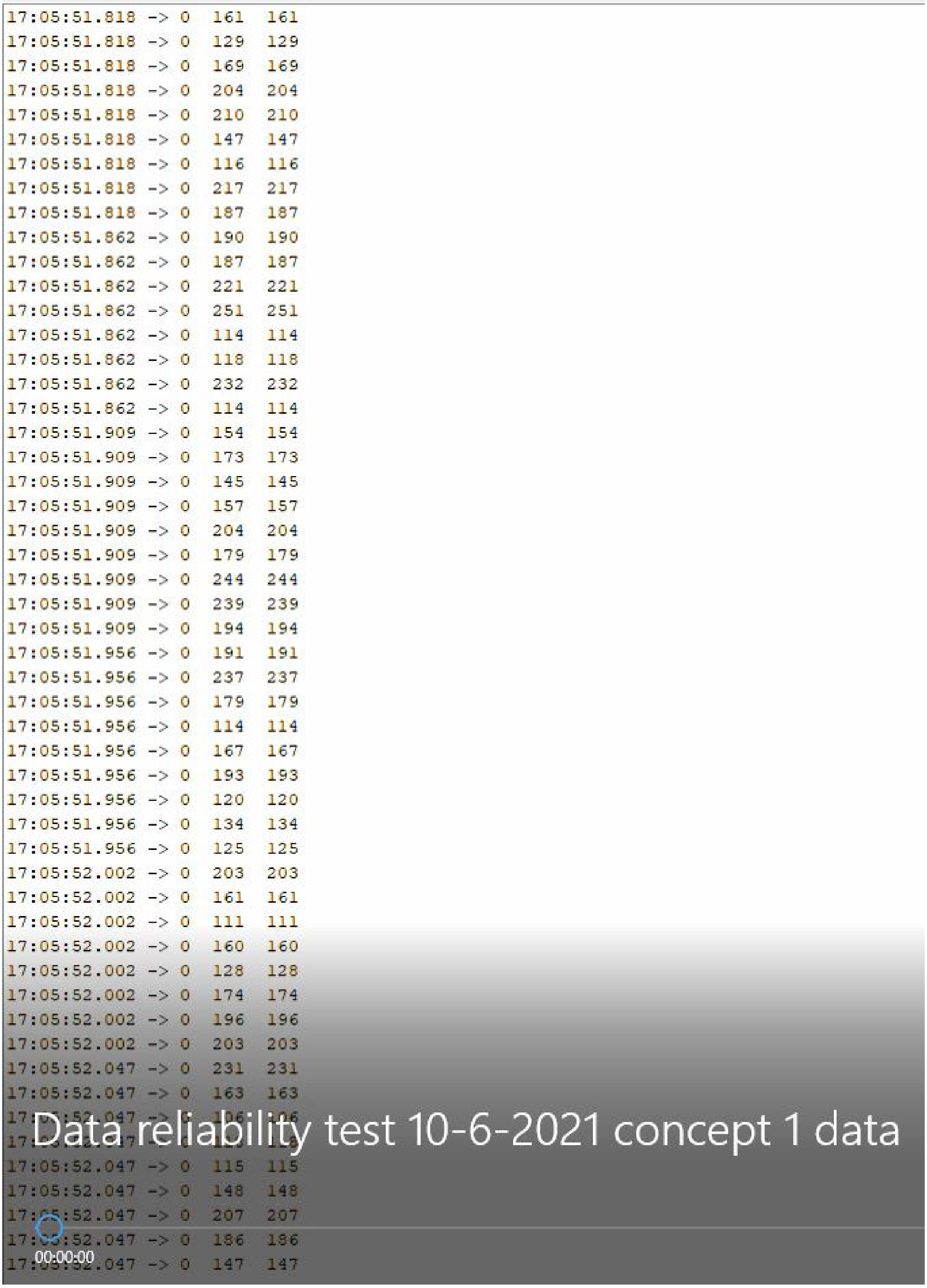
receiveSoftwareSerial

```
#include <SoftwareSerial.h>
SoftwareSerial mySerial(10, 11); // RX, TX

int ledPin = 13;

void setup()
{
  // Open serial communications and wait for port to open:
  Serial.begin(115200);
  while (!Serial) {
    ; // wait for serial port to connect. Needed for Leonardo only
  }

  Serial.println("Goodnight moon!");

  // set the data rate for the SoftwareSerial port
  mySerial.begin(4800); // don't overspeed softwareserial ...
  mySerial.println("Hello, world?");
  delay(100);
  pinMode(13, OUTPUT);
  randomSeed(1);
  Serial.println(random(256));
  Serial.println(random(256));
  Serial.println(random(256));
  Serial.println(random(256));
  Serial.println(random(256));
  randomSeed(1);
}

byte i, control;
unsigned int errors;

void loop() {
  if (mySerial.available()) {
    byte received = mySerial.read();
    if (received == 255) {
      randomSeed(1);
      errors = 0;
      control = 255;
    } else {
      control = random(100,255);
    }
    //byte received = mySerial.read();
   Serial.print(received);
   Serial.print(' ');
   Serial.print(control);
   if (received != control) {
     Serial.print(" ******** ");
     errors++;
   }
   Serial.print(' ');
   Serial.println(errors);
   digitalWrite(ledPin, !digitalRead(ledPin));
  }
}
```

sendSoftwareSerial_read_echo_as_well

```
// ReceiveSerial
// A quick and dirty test for SoftwareSerial
// Connect this to the PC usb and open the serial monitor.
// Crosslink pin 10 and 11 with the Arduino that is 'SendSerial'
// I will copy everything that is received on the software serial pin 10/11 to the serial monitor.
// See also SendSerial....
//
// Adrie Kooijman, Oktober 2014
// Edited: June 2021 by Adrie Kooijman & Dione Leeger

#include <SoftwareSerial.h>

SoftwareSerial mySerial(10, 11); // RX, TX
unsigned int error;


void setup()
{
  // Open serial communications and wait for port to open:
  Serial.begin(115200);
  while (!Serial) {
    ; // wait for serial port to connect. Needed for Leonardo only
  }

  Serial.println("Goodnight moon!");

  // set the data rate for the SoftwareSerial port
  mySerial.begin(4800);
  delay(1000);
  mySerial.println("Hello, world?");
  delay(1000);
  pinMode(13, OUTPUT);
  randomSeed(1);
  Serial.println(random(256));
  Serial.println(random(256));
  Serial.println(random(256));
  Serial.println(random(256));
  Serial.println(random(256));
  randomSeed(1);
  mySerial.write(255);
  Serial.println(255);
}

byte i;
void loop() {
  //mySerial.write(i++);
  i = random(100, 255);
  mySerial.write(i);

  if (mySerial.available()) {
    byte received = mySerial.read();
    if (received != i) {
      error++;
    }
    Serial.print(error);
    Serial.print("  ");
    Serial.print(i);
    Serial.print("  ");
    Serial.println(received);
  }
  digitalWrite(13, !digitalRead(13));
  delay(1);
}
```

Raw data screenshots

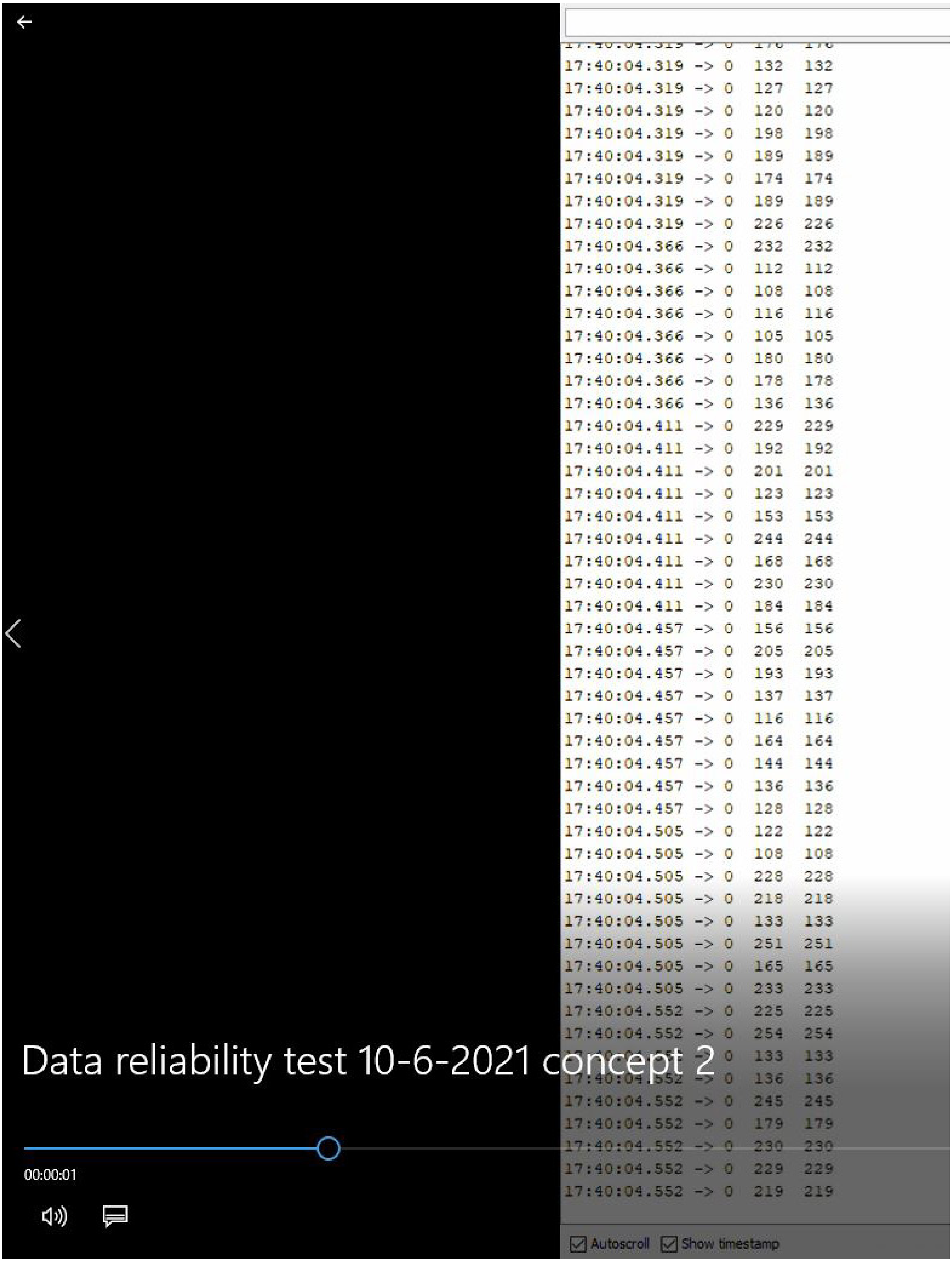



```
17:05:51.818 -> 0  161  161
17:05:51.818 -> 0  129  129
17:05:51.818 -> 0  169  169
17:05:51.818 -> 0  204  204
17:05:51.818 -> 0  210  210
17:05:51.818 -> 0  147  147
17:05:51.818 -> 0  116  116
17:05:51.818 -> 0  217  217
17:05:51.818 -> 0  187  187
17:05:51.862 -> 0  190  190
17:05:51.862 -> 0  187  187
17:05:51.862 -> 0  221  221
17:05:51.862 -> 0  251  251
17:05:51.862 -> 0  114  114
17:05:51.862 -> 0  118  118
17:05:51.862 -> 0  232  232
17:05:51.862 -> 0  114  114
17:05:51.909 -> 0  154  154
17:05:51.909 -> 0  173  173
17:05:51.909 -> 0  145  145
17:05:51.909 -> 0  157  157
17:05:51.909 -> 0  204  204
17:05:51.909 -> 0  179  179
17:05:51.909 -> 0  244  244
17:05:51.909 -> 0  239  239
17:05:51.909 -> 0  194  194
17:05:51.956 -> 0  191  191
17:05:51.956 -> 0  237  237
17:05:51.956 -> 0  179  179
17:05:51.956 -> 0  114  114
17:05:51.956 -> 0  167  167
17:05:51.956 -> 0  193  193
17:05:51.956 -> 0  120  120
17:05:51.956 -> 0  134  134
17:05:51.956 -> 0  125  125
17:05:52.002 -> 0  203  203
17:05:52.002 -> 0  161  161
17:05:52.002 -> 0  111  111
17:05:52.002 -> 0  160  160
17:05:52.002 -> 0  128  128
17:05:52.002 -> 0  174  174
17:05:52.002 -> 0  196  196
17:05:52.002 -> 0  203  203
17:05:52.047 -> 0  231  231
17:05:52.047 -> 0  163  163
17[illegible]
17[illegible]
17:05:52.047 -> 0  115  115
17:05:52.047 -> 0  148  148
17[illegible]52.047 -> 0  207  207
17[illegible]52.047 -> 0  186  186
17[illegible].047 -> 0  147  147
```

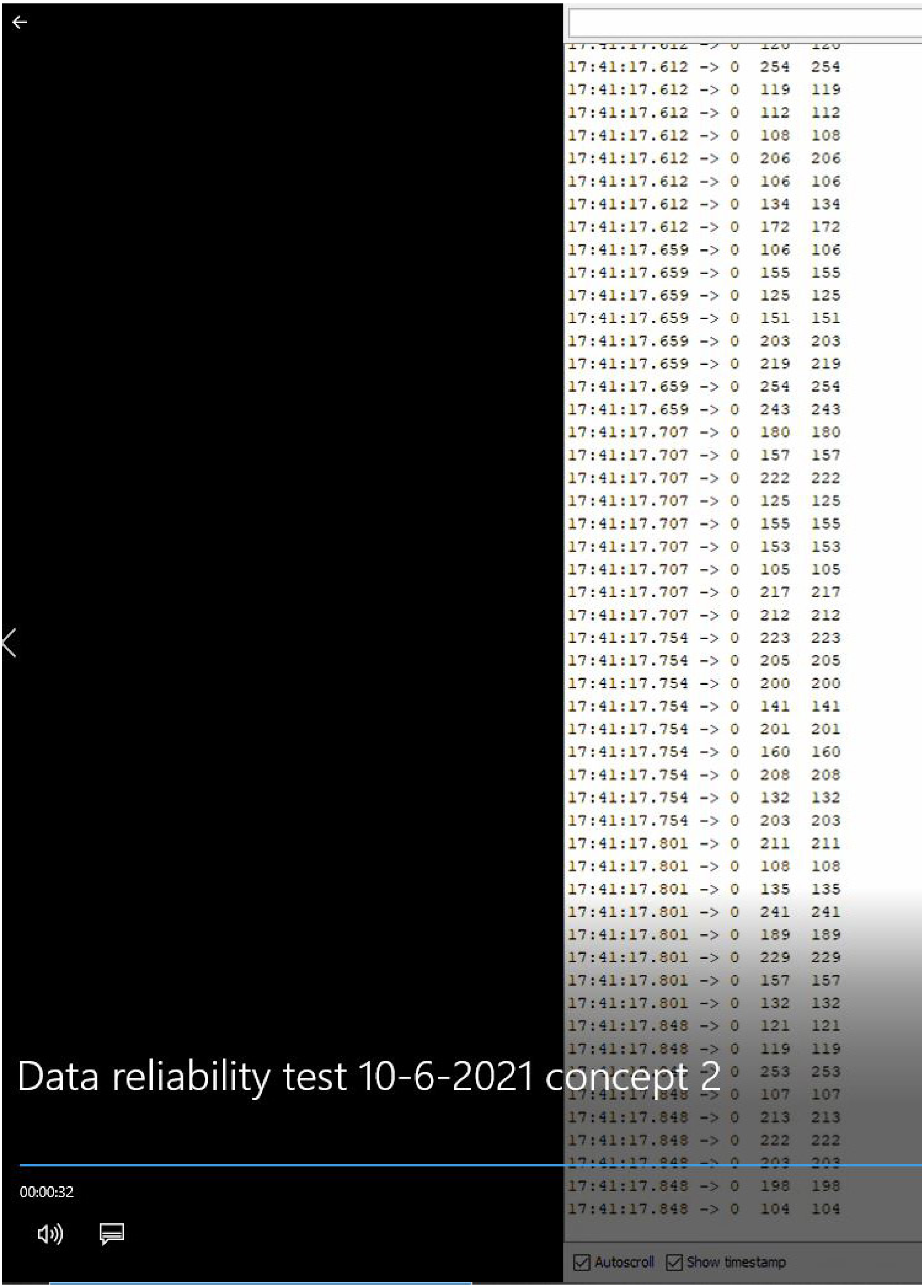
```
17:06:58.701 -> 0  119  119
17:06:58.701 -> 0  112  112
17:06:58.701 -> 0  108  108
17:06:58.701 -> 0  206  206
17:06:58.748 -> 0  106  106
17:06:58.748 -> 0  134  134
17:06:58.748 -> 0  172  172
17:06:58.748 -> 0  106  106
17:06:58.748 -> 0  155  155
17:06:58.748 -> 0  125  125
17:06:58.748 -> 0  151  151
17:06:58.748 -> 0  203  203
17:06:58.795 -> 0  219  219
17:06:58.795 -> 0  254  254
17:06:58.795 -> 0  243  243
17:06:58.795 -> 0  180  180
17:06:58.795 -> 0  157  157
17:06:58.795 -> 0  222  222
17:06:58.795 -> 0  125  125
17:06:58.795 -> 0  155  155
17:06:58.795 -> 0  153  153
17:06:58.842 -> 0  105  105
17:06:58.842 -> 0  217  217
17:06:58.842 -> 0  212  212
17:06:58.842 -> 0  223  223
17:06:58.842 -> 0  205  205
17:06:58.842 -> 0  200  200
17:06:58.842 -> 0  141  141
17:06:58.842 -> 0  201  201
17:06:58.889 -> 0  160  160
17:06:58.889 -> 0  208  208
17:06:58.889 -> 0  132  132
17:06:58.889 -> 0  203  203
17:06:58.889 -> 0  211  211
17:06:58.889 -> 0  108  108
17:06:58.934 -> 0  135  135
17:06:58.934 -> 0  241  241
17:06:58.934 -> 0  189  189
17:06:58.934 -> 0  229  229
17:06:58.934 -> 0  157  157
17:06:58.934 -> 0  132  132
17:06:58.934 -> 0  121  121
17:06:58.934 -> 0  119  119
17:06:58.934 -> 0  253  253
17:06:58.981 -> 0  107  107
17:[illegible]:58.981 -> 0  213  213
17:[illegible].981 -> 0  [illegible]  [illegible]
17:06:58.981 -> 0  203  203
17:06:58.981 -> 0  198  198
17:06:58.981 -> 0  104  104
17:06:58.981 -> 0  150  150
17:[illegible].981 -> 0  223  223
```

Data reliability test 10-6-2021 concept 1 data

00:00:00



17:40:04.319 -> 0 132 132
17:40:04.319 -> 0 127 127
17:40:04.319 -> 0 120 120
17:40:04.319 -> 0 198 198
17:40:04.319 -> 0 189 189
17:40:04.319 -> 0 174 174
17:40:04.319 -> 0 189 189
17:40:04.319 -> 0 226 226
17:40:04.366 -> 0 232 232
17:40:04.366 -> 0 112 112
17:40:04.366 -> 0 108 108
17:40:04.366 -> 0 116 116
17:40:04.366 -> 0 105 105
17:40:04.366 -> 0 180 180
17:40:04.366 -> 0 178 178
17:40:04.366 -> 0 136 136
17:40:04.411 -> 0 229 229
17:40:04.411 -> 0 192 192
17:40:04.411 -> 0 201 201
17:40:04.411 -> 0 123 123
17:40:04.411 -> 0 153 153
17:40:04.411 -> 0 244 244
17:40:04.411 -> 0 168 168
17:40:04.411 -> 0 230 230
17:40:04.411 -> 0 184 184
17:40:04.457 -> 0 156 156
17:40:04.457 -> 0 205 205
17:40:04.457 -> 0 193 193
17:40:04.457 -> 0 137 137
17:40:04.457 -> 0 116 116
17:40:04.457 -> 0 164 164
17:40:04.457 -> 0 144 144
17:40:04.457 -> 0 136 136
17:40:04.457 -> 0 128 128
17:40:04.505 -> 0 122 122
17:40:04.505 -> 0 108 108
17:40:04.505 -> 0 228 228
17:40:04.505 -> 0 218 218
17:40:04.505 -> 0 133 133
17:40:04.505 -> 0 251 251
17:40:04.505 -> 0 165 165
17:40:04.505 -> 0 233 233
17:40:04.552 -> 0 225 225
17:40:04.552 -> 0 254 254
0 133 133
0 136 136
17:40:04.552 -> 0 245 245
17:40:04.552 -> 0 179 179
17:40:04.552 -> 0 230 230
17:40:04.552 -> 0 229 229
17:40:04.552 -> 0 219 219
Data reliability test 10-6-2021 concept 2
00:00:01
Autoscroll
Show timestamp


17:41:17.612 -> 0 254 254
17:41:17.612 -> 0 119 119
17:41:17.612 -> 0 112 112
17:41:17.612 -> 0 108 108
17:41:17.612 -> 0 206 206
17:41:17.612 -> 0 106 106
17:41:17.612 -> 0 134 134
17:41:17.612 -> 0 172 172
17:41:17.659 -> 0 106 106
17:41:17.659 -> 0 155 155
17:41:17.659 -> 0 125 125
17:41:17.659 -> 0 151 151
17:41:17.659 -> 0 203 203
17:41:17.659 -> 0 219 219
17:41:17.659 -> 0 254 254
17:41:17.659 -> 0 243 243
17:41:17.707 -> 0 180 180
17:41:17.707 -> 0 157 157
17:41:17.707 -> 0 222 222
17:41:17.707 -> 0 125 125
17:41:17.707 -> 0 155 155
17:41:17.707 -> 0 153 153
17:41:17.707 -> 0 105 105
17:41:17.707 -> 0 217 217
17:41:17.707 -> 0 212 212
17:41:17.754 -> 0 223 223
17:41:17.754 -> 0 205 205
17:41:17.754 -> 0 200 200
17:41:17.754 -> 0 141 141
17:41:17.754 -> 0 201 201
17:41:17.754 -> 0 160 160
17:41:17.754 -> 0 208 208
17:41:17.754 -> 0 132 132
17:41:17.754 -> 0 203 203
17:41:17.801 -> 0 211 211
17:41:17.801 -> 0 108 108
17:41:17.801 -> 0 135 135
17:41:17.801 -> 0 241 241
17:41:17.801 -> 0 189 189
17:41:17.801 -> 0 229 229
17:41:17.801 -> 0 157 157
17:41:17.801 -> 0 132 132
17:41:17.848 -> 0 121 121
17:41:17.848 -> 0 119 119
Data reliability test 10-6-2021 concept 2
17:41:17.848 -> 0 213 213
17:41:17.848 -> 0 222 222
00:00:32
17:41:17.848 -> 0 198 198
17:41:17.848 -> 0 104 104
Autoscroll
Show timestamp

A18. Detailed Weighted Objectives

	Objective	Weight (1-5)	Concept 1 all about pockets Score	Total	Reasoning
Performance & implementation	R.1.1 Connect 7 vibration motors, of which 3 max at the same time.	4	6	24	PWM: Individual rather large velcro contact per motor necessary, development of knitted design with motors. I^2C: 4 Velcro contacts in total necessary.
	R.1.2 Vibration motor strength	4	7	28	Normal design would be knit, and require more conductive yarn then sewn, thus a higher resistance. However, width of traces could help compensate for this.
	R.1.3 Implementation of other sensors	2	8	16	Design of main control module can be adjusted, or a special additional module can be designed per project
	R1.4 Robustness mechanical stressess	4	8	32	The Conductive Velcro is highly conductive, however does lose a lot of fibers per hook&loop cylce. The pocket however stabelizes the vibration motor module well. The stretch stich allows for bending and stretching of the fabric.
	R.1.5 Stretching of textile carrier	3	9	27	Knit can stretch and pockets can also move
	R.1.7 Max. Resistance of 6.85 to 9.09 Ohms	4	8	32	The sewn concept fulfils the requirement now, however the knitting resistance might be higher
	R.1.8 Max voltage of 20V	4	8	32	Operating voltage of 5V has shown to be sufficient during the testing of the concepts.However, due to the expected higher resistance, a higher operating voltage might be necessary
Production & processing	R2.1 Suited for batch production of 100	4	4	16	Knitting concept costs more money and is more suited for mass production.
	R2.2. Uses widely available technology	3	7	21	Knitting machines & patterns would be used. Conductive yarns with low resistance, which are available from a couple of suppliers.
Cost	R.3.1 Less than 2x expensive current design	3	5	15	A knitting pattern is expensive to create and will only be profitable during mass production.
Cleanability	R4.1 IP54	4	2	8	The current design is not yet IP54
	R4.2 25 delicated washes	3	8	24	Based on the results of the washing test of conductive yarns, this should be possible.
Ergonomics	R5.1 Not restrict users in movement	4	9	36	The stretchable character of the knit will be comfortable and stretch where necessary.
	R5.2 Technology integrated	4	7	28	The technology is integrated well through the use of the pockets. The conductive Velcro allows for a thin landingplace for the main control module. However, the current design makes it feel as if the main control module is a bit seperate from the textile carrier.
	R.5.3 Aesthetics	3	7	21	The integrated pocket idea is clean and It can almost be made invisible for the user. However, the landingspot of the Velcro looks a bit cheap.
	R. 5.4 Comfortable to wear	3	6	18	The vibration modules prototyped create pressure points on the human body.
	R. 5.5 Not too hot to wear	2	7	14	Knitting the fabrics might results in thicker and warmer fabrics than stretchable fabrics made from PA&EA
	R.5.6 Ease of use	4	7	28	The placement of the module inside the pocket does require some attention. Placement of the main control module is easy.
	R.5.7 <43 degrees Celsius	4	8	32	
			Total	452	

			Concept 3 sewing with pogo pins		
	Objective	**Weight (1-5)**	**Score**	**Total**	**Reasoning**
Performance & implementation	R.1.1 Connect 7 vibration motors, of which 3 max at the same time.	4	8	32	PWM: Individual small pogo pin contact per motor necessary. I^2C: 4 small pogo pins contacts necessary.
	R.1.2 Vibration motor strength	4	8	32	Resistance can be kept below the required amount of ~7 and ~9 Ohm in total, by stitching multiple lines on top of each other.
	R.1.3 Implementation of other sensors	2	8	16	Design of main control module can be adjusted, or a special additional module can be designed per project
	R1.4 Robustness mechanical stressess	4	6	24	A single stitch is vulnerable and breaks easily. This can be improved by adding multiple stitches for redundancy, cover the stitches for protection and adding a protection against overstretching.
	R.1.5 Stretching of textile carrier	3	7	21	Some stitches can stretch, but you will need stretch security so it does not stretch too much
	R.1.7 Max. Resistance of 6.85 to 9.09 Ohms	4	9	36	Sewn conductive yarns are very low in resistance and the rest of the connections used, based on the resistance measurements of the concepts
	R.1.8 Max voltage of 20V	4	9	36	Operating voltage of 5V has shown to be sufficient during the testing of the concepts.
Production & processing	R2.1 Suited for batch production of 100	4	7	28	Sewing can be done well, might be a bit time consuming, but can be done in phases/production belt idea
	R2.2. Uses widely available technology	3	8	24	Conductive yarns with low resistance are available from a couple of suppliers. Sewing machines and textilse are widely available.
Cost	R.3.1 Less than 2x expensive current design	3	7	21	The use of conductive yarns is quite expensive and will increase the price.
Cleanability	R4.1 IP54	4	4	2	The current prototype is not yet IP54
	R4.2 25 delicated washes	3	8	24	Based on the results of the washing test of conductive yarns, this should be possible.
Ergonomics	R5.1 Not restrict users in movement	4	7	28	The stretchable character of the fabric and the stretchable sewn traces will help. However, additional protection against overstretching might limit the stretchability. Also the places where modules will be placed will decrease the stretchability.
	R5.2 Technology integrated	4	8	32	The technology is integrated in the textile through overmolding/casting. The main control module has a clear landingspot on the textile carrier and feels complete.
	R.5.3 Aesthetics	3	8	24	The prototype developed looks clean and complete. Does need a redesign to decrease the sizes.
	R. 5.4 Comfortable to wear	3	7	21	The hard prototyped casings now are not comfortable. However create less pressure points on the body.
	R. 5.5 Not too hot to wear	2	9	18	The use of stretchable thin sports fabrics made of PA & EA can be used.
	R.5.6 Ease of use	4	9	36	Placement of the main control module is eay and automatically alligns.
	R.5.7 <43 degrees Celsius	4	8	32	
			Total	487	

A19. Pattern pieces back panel final design

A20. Conductive yarns processing methods

Conductive yarns

One can create conductive yarns by coating yarns with conductive polymers and fibres according to Ismar et al. (2020). However, conductive polymers do offer low processability due to being insoluble, having non-melting characteristics. Moreover they have poor mechanical properties, though by combining them with more commonly used textiles this can be overcome (Ismar et al., 2020). Conductive yarns can also have a metal base, resulting in superior electrical conductivity over conductive polymer yarns, though the sensation on the skin is less comfortable according to Ismar et al. (2020). Examples of conductive yarns can be seen in Figure 287 & 288. Currently, graphene is known to bring about high performance conductive textiles due to its thermal and electrical conductivity, flexibility and chemical stability (Ismar et al., 2020). Well-known producers of conductive yarns are Statex, Elektrisola, Bekaert Fiber Technologies, Bekintex, Taierxinfiber and Aracon. Conductive yarns can have a small resistance of even ~0.0001 Ohm/cm, such as the Aracon MCAF yarns known for their Kevlar base. In Figure 289 an overview of the different types of yarns and their electrical conductivity is given in S/cm. The higher this numberer the higher the electrical

Figure 287. Metal conductive yarns by Shielday (n.d.)

Figure 288. Carbon conductive yarn by Taierxin (n.d.)

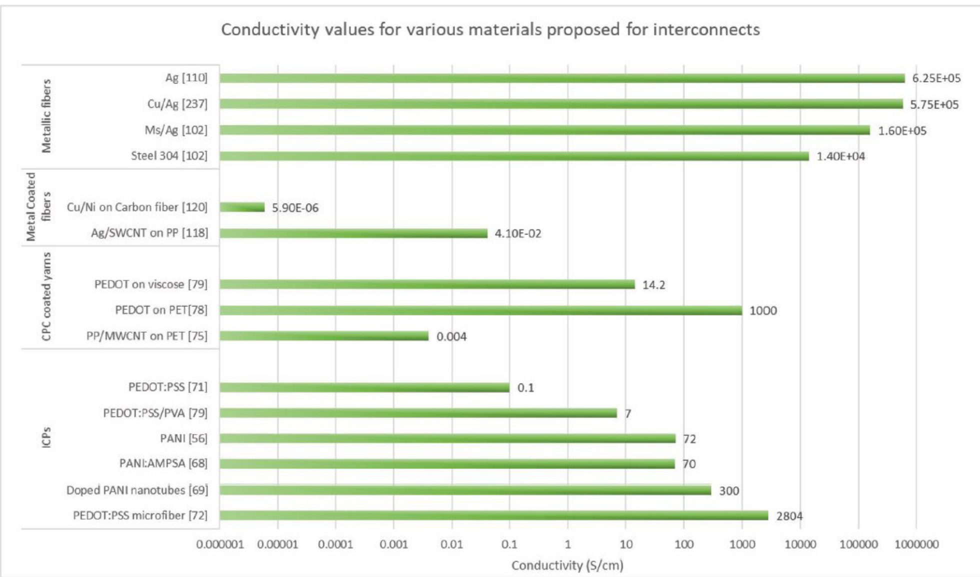


Figure 289. Overview of the electrical conductivity of conductive yarns (Agcayazi et al., 2018, p. 12)

conductivity. This graph shows us that conductive yarns made from metal fibres have the highest conductivity (up to 6.25 E+05 S/cm for silver fibres) and metal coated carbon fibres the lowest (5.90 E-06 S/cm).

Processing methods

Sewing

Processing conductive fabric and yarn can both be done via sewing. However, creating short-circuits should be avoided. An example of sewn conductive yarn can be seen in Figure 290, in which a LED is connected and powered via conductive yarn.
Conductive yarns can become rather thick and stiff due to the metal integrated. Therefore most yarns might not be suitable for the sewing machine, but are more easily woven or knitted.

Embroidery

Embroidery is also a method just like sewing where yarns are sewn on top of a carrier. Figure 291 shows an example application where the embroidery of conductive yarn and a LilyPad Arduino create a touch sensitive keypad. Conductive yarn changes its resistance upon touch, and can therefore act as pressure sensor in this case. Again not all conductive yarns are suitable for embroidery just like sewing.

Weaving

A commonly used process method for conductive yarns and to create conductive fabrics is weaving. With weaving you have a weft and warp direction in which threads can be woven, see Figure 293. The pattern of this weft and warp can be adjusted (e.g. 2 warp strings woven together instead of one) to obtain different material properties. Woven fabrics are a good choice when rigidity is required (Ismar et al., 2020).

Knitting

Knitted fabrics are more flexible and stretchable than woven ones, according to Ismar et al. (2020). As knitting also can be done in a wide variety of patterns, different material properties can be implemented, such as making it more stretchable in one direction than the other. In Figure 292 an example of a knitted speaker can be seen.

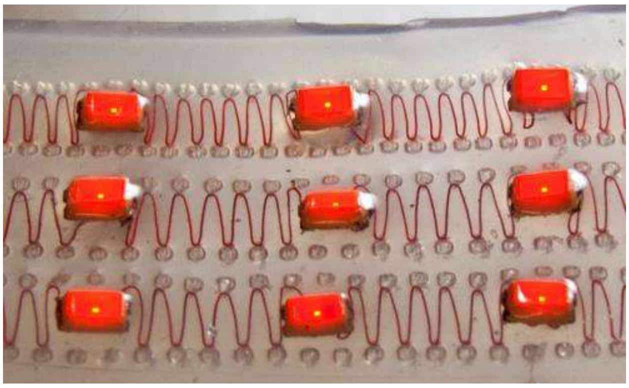


Figure 290. Zigzag sewn conductive yarn powering LEDs (Venere, 2014)

Figure 291. Embroidery of conductive yarn creating a touch sensitive keyboard (Baalman, 2015)

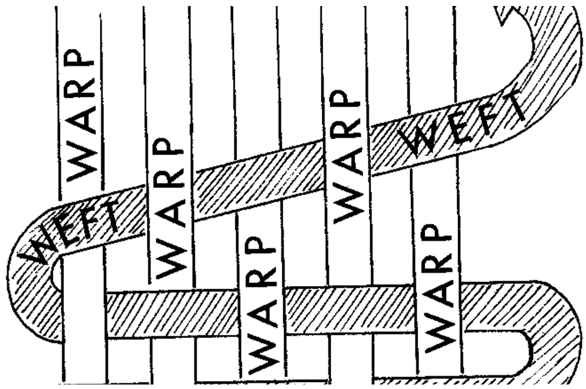


Figure 293. Weaving explained (jmarks, 2015)

Figure 292. Knitted speaker (V2, n.d.)

A21. Cost analysis final prototype

Module	Part	Amount	Price per part	Explanation factor	Costs in €	Website
Main module	PLA Casing	35g	1,54	PLA filament ultimaker €33.00 euros 2.855mm 750g	1,54	https://www.cards3dprinting.com/ultim
	Accelerometer/ versnellingsmeter/gyroscoop/kompas - BNO055	1	36,32231405	Price €43,95 incl. vat	36,32231405	https://www.bitsandparts.nl/Accelerome
	MT3608 2A Max DC-DC Step Up Power Module Booster Power Module	1	1,231404959	€1,49 incl. vat	1,231404959	https://www.otronic.nl/a-65057024/spa
	3.7 V==B 600 mAh Li-ion battery	1	4,45	€4,45 excl. Vat	4,45	https://nl.aliexpress.com/item/8256078
	I2C Logic Level Converter Bi-Directionele Board Module 5V 3.3V	1	0,129	€1,29/ 10 pieces excl. Vat	0,129	https://nl.aliexpress.com/item/3221684
	Magnetische Pogo Pin Connector 4 Pole Pitch	1	2,712	€13,56/5 pieces excl. Vat	2,712	https://nl.aliexpress.com/item/4001222
	Seeeduino XIAO - Arduino Microcontroller - SAMD21 Cortex M0+	1	5,743801653	€6,95 incl. vat	5,743801653	https://www.kiwi-electronics.nl/seeedui
	Roest Vrij Stalen Schroef met bolle cilinderkop M1,6 x 3mm	1	0,09	€0,90/10 incl. vat	0,09	https://www.microschroeven.nl/nl/kruis
	Roest Vrij Stalen Schroef met bolle cilinderkop M2 x 8mm	3	0,085	€0,85/10 incl. vat	0,255	https://www.microschroeven.nl/nl/kruis
	Schijfmagneet Ø 5 mm, hoogte 5 mm, houdt ca. 940 gr	2	0,289256198	€0,35/piece incl. vat	0,578512397	https://www.supermagnete.nl/schijfmag
	COMPONENTS SU527629 Printplaat Hardpapier	0,05	1,148760331	1,39/piece incl. vat	0,057438017	https://www.conrad.nl/p/tru-componen
Landing spot	stratasys J735 3D print different shore values made of: Vero Vivid Cyan, Magenta, Yellow & Agilus30 clear	1	20,73553719	25,09 incl. vat	20,73553719	
	Pin header; pin strips; male; PIN:20; s	4	0,009	0,18/20 pieces incl. vat	0,036	http://www.elektronica-componenten.n
	Schijfmagneet Ø 5 mm, hoogte 5 mm, houdt ca. 940 gr	2	0,289256198	€0,35/piece incl. vat	0,578512397	https://www.supermagnete.nl/schijfmag
	COMPONENTS SU527629 Printplaat Hardpapier	0,05	1,148760331	1,39/piece incl. vat	0,057438017	https://www.conrad.nl/p/tru-componen
Texile carrier	Textile incl. trims	1	8,26446281	€60/piece incl. vat selling pric	8,26446281	https://www.bol.com/nl/nl/p/agu-core-f
	Amann 100% Polyester CoreSpun Sewing Thread Saba 80 1000M Color 331 Winter Gray, 12 meter	15	0,002404959	2,91 incl. vat selling price per	0,03607438	https://www.ebay.com/itm/1317181980
	Elektrisola 30004021L, 12 meter	15	0,00231405	€353,11 incl, vat selling price	0,034710744	
Tactor module	PA 646 Technomelt 3x4g	12	0,00822314	€199 incl. vat per 20 kg	0,098677686	
	Brass 0,1mm thickness	0,001	17,63636364	€21,34 incl. vat 150mm x 100	0,017636364	https://www.romijn.nl/plaat-folie-en-ga
	Adafruit 2305 Controller Board for DRV2605L for Haptic Motor	3	6,991735537	€8,46 incl. vat	20,97520661	https://nl.rs-online.com/web/p/power-n
	ERM motor	3	1,809917355	€2,19 incl. vat per piece	5,429752066	https://www.reichelt.nl/nl/nl/vibratiem
	FormLabs High Temp V2 Resin mold 67mL total, with 1 mold you can 100x overmold	3	0,19	€190 excl. vat per L	0,3819	https://www.makerpoint.nl/nl-nl/consu
Total costs complete prototype incl. complete main module, 3 tactors and 3D printed landing spot					**109,7553793**	
Tactor module					**9,024545455**	
Textile carrier					**8,335247934**	
Main module incl. BNO055					**53,10947107**	
Main module without BNO055					**16,78715702**	
Costs landing spot 3D printed					**21,4074876**	
BN055					**36,32231405**	
Total costs without IMU and with landingspot overmould instead of 3D print					**54,6975281**	2 euros materials costs Technomelt PA 646

A22. Arduino script final prototype

9-axis_orientation_IMU_test___driving_one_vibration_motor_2.0

```
#include <Wire.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_BNO055.h>
#include <utility/imumaths.h>
#include <Adafruit_DRV2605.h>

Adafruit_BNO055 bno = Adafruit_BNO055(55); //declare IMU sensor
Adafruit_DRV2605 drv; //declare motor driver

void setup() {

  Serial.begin(9600);
  Serial.println("Orientation Sensor Test"); Serial.println(" ");
  Serial.println("DRV test");
  drv.begin(); //start driver

  drv.selectLibrary(1);//select driver library

  //I2C trigger by sending 'go' command
  // default, internal trigger when sending GO command
  drv.setMode(DRV2605_MODE_INTTRIG);

  /*initialise the sensor */
  if (!bno.begin())
  {
    /*There was a problem detecting the BNO55... check your connections */
    Serial.print("Ooops, no BNO055 detected ... Check your wiring or I2C address!");
    while (1);
  }
  delay(1000);

  bno.setExtCrystalUse(true);
}

uint8_t effect = 0;

void loop() {
  drv.begin(); //start driver
  drv.selectLibrary(1);//select driver library
  drv.setMode(DRV2605_MODE_INTTRIG);

  /*Get new sensor event */

  sensors_event_t event;
  bno.getEvent(&event);

  /*Display the floating point data */
  Serial.print("\tX: ");
  Serial.println(event.orientation.x, 4);
  // Serial.print("\tY: ");
  // Serial.println(event.orientation.y, 4);
  //  Serial.print("\tZ: ");
  //  Serial.println(event.orientation.z, 4);
  // Serial.println(" ");
  if (event.orientation.x >= 100)
  {
    Serial.println(F("52 - Pulsing Strong 1 - 100%"));
    effect = 52;
  }
  else {
    Serial.println(F("120 - Smooth Hum 2 (No kick or brake pulse)- 30%"));
    effect = 120;
  }

  drv.setWaveform(0, effect); //play effect 52
  drv.setWaveform(1, 0); //end waveform

  //play the effect!
  drv.go();
```

A22. User research

Participant folder to be filled in per participant

Thank you for taking the time participate in this research. During the test we will be looking at the ease of use and ergonomics of a new smart textile wearable. I kindly ask you to think out loud and explain why you are doing what you are doing. If you have any questions during the test, also feel free to ask them. The research will take about 15 minutes of your time. By signing this document, you agree to photo's being taken during the research. The results will be used anonymously and for research purposes only.

Participant: ……………………………… Date: …………………… Location: ………………………. Signature: ………………………..

Step 1: Placement of modular electronics

In front of you lies a vest that can provide a user with haptic feedback (vibrations as a reaction to certain behaviour). This vest comes with multiple modular electrical parts: One main control module with the brains of the system and multiple small vibration motor modules. ***Your assignment is to place them on the vest in the way you think is correct. Please say out loud why you think they should be placed at a particular spot.***

Step 2: After placement of the modules

Based on your previous experience, please answer the following questions:

Question 1: On a scale from 1-7, in which 1 = extremely difficult and 7=extremely easy, how easy was it to attach the main control module to the vest?

Extremely Difficult						Extremely easy
1	2	3	4	5	6	7

Please elaborate your answer:

………
………
………

Question 2: On a Likert Scale from 1-7, in which 1 = extremely difficult and 7=extremely easy, how easy was it to attach the vibration motor module to the vest?

Extremely Difficult						Extremely easy
1	2	3	4	5	6	7

Please elaborate your answer:

………
………
………

Question 3: Was there anything unclear on how or where to place the different modules? If yes, what was unclear? If no, what made the placement clear for you?

………
………
………

Step 3: Putting on the garment

Now please put on the garment and say out loud what you are thinking along the way.

Step 4: Wearing the garment

Now that you are wearing the garment, please answer the following questions:

Question 4: On a Likert Scale from 1-7, in which 1 = not comfortable at all and 7=extremely comfortable, how comfortable do you find the vest to wear?

Not comfortable at all						Extremely comfortable
1	2	3	4	5	6	7

Please elaborate your answer:
………
………
………

Question 5: On a Likert Scale from 1-7, in which 1 = very restricting and 7= not restricting at all, how restricting do you find the vest to be in terms of body movement?

Very restricting						Not restricting at all
1	2	3	4	5	6	7

Please elaborate your answer:
………
………
………

Step 5: Taking off the garment

Now please take off the garment and answer the following questions:

Question 6: On a Likert Scale from 1-7, in which 1 = unaesthetically and 7 = very aesthetically, how aesthetically do you find the vest to be?

Unaesthetically						Very aesthetically
1	2	3	4	5	6	7

Please elaborate your answer:

……
……
……

Question 7: If you could improve anything, what would it be and why?

……
……
……

Question 8: Do you have any final remarks you would want to share?

……
……
……

Thank you for participating in this user research!

Raw anonymous data of 6 participants in total.

Question #	Question / Reasoning / Quotes	Participant 1 F	Participant 2 M	Participant 3 M	Participant 4 F	Participant 5 F	Participant 6 M	Average grade
1	On a scale from 1-7, in which 1 = extremely difficult and 7=extremely easy, how easy was it to attach the main control module to the vest?	7	7	6	7	7	7	6,833333333
	Reasoning participant	The connectors were visible, the shape was obvious and the fit was a quick snap	The pins are a sigal and enable for a magnetic snapfit	Recognizable shape and the magnets holds the module nicely in place	The shape was super logical, it fits like a puzzle piece	It clicked very easy with the magnets, this you cannot palce it wrong	The shape is quite distinctive, and the magnets are self-explanatory	
	Observations & quotes	"I am guessing by the size and shape the main module goes here... Oeh.. Snap, nice!" "The shape of the tactor tells me how to place it" "Tight pockets, but that is how it is supossed to be I think" "I do not intend to break it.'' I wonder why the last pocket is blue, might be a specific order you want me to but things in." "The black pocket is most robust and tight" "Do I need to connect anything to the port is that a charging port?"	'There are 3 components and a large one, three of them look the same size wise.'' ''I guess it doesn't matter where you put the tactor modules right?'' Main module is placed correctly from the first try.	'The shape of the main module and the colour of the landing spot, logic that these two belong together'' ''You take the main module first, because this one is most clear and is the biggest. The same usecue I also expected for the rest.''	Main module clearly has to go on the landing spot, shape makes it clear Clicks with magnets.	The main module clicks and connects to the landing spot, it is clear it belongs there	'The main module is the largest and it is logic that it goes first''	
2	On a Likert Scale from 1-7, in which 1 = extremely difficult and 7=extremely easy, how easy was it to attach the vibration motor module to the vest?	6	5	5	6	2	6	5
	Reasoning	Easy enough and you get a sense that it needs to be tight, but the ease with which I could cokket the contorl module created a higher contrast	Much easier when I noticed/was told I had to put it in from the side and rotate. However before that I had no clue. Thought it should also be magnetic.	Needed some fiddeling, but it has a good fit. Pocket was not immediatly apparent though, and the colours gave me misdirection	I thought it was magnetic too, but I noticed it wasn't. Then I saw the pockets and again the shape was logical. Also fitting like a puzzle piece	You cannot slide them in easily in the pocket. The opening was a bit too small. Inserting them sideways and rotating them = many steps needed.	A bit of stretching the pockets	
	Observations & quotes		User places them on the outside of the pocket, expects them to stick just as the main module. ''You see the shape of the tactor modules and the pockets, they show me a direction and they don't fit in in that way, that's why I did not place them inside the pockets'' ''The main module snaps right in place, I would want to snap the tactors too.'' ''I would just need an instruction on how to put the tactors in, maybe an arrow on the module showing how to put it in.'' Maybe making it like a pocket used in cycling shirts on the back.'' ''I hate to take things out, if I put it there I want it to stay.'' User struggles with tightness of the pockets, however manages to place them correctly rather quick when having figured it out''	"Contacts are in line with the conductive sewn traces'' "Tactors belong in the pockets, I don't know what the colours mean, as all 3 modules look identical" "First I would place the modules horizontally in the pocket, but this did not fit so I rotated them 90 degrees, placed them in and rotated them back to horizontal position" "Fit is suer tight, but also very flexible" "I find it difficult to estimate how flexible the fabric is, if it can break and if I placed the tactors correctly." Lowest pocket becomes loose at an edge	First placed tactors on top of pockets, immediatey realised it were pockets and placed all 3 modules within a minute correctly without explanation	I would expect the tactor modules to be placed horizontally inside the pockets. Now I have to place them in vertically and rotate them 90 degrees inside the pocket hwich is difficult. I though that they did not belong inside the pockets, as they do not fit in horizontally. I would expect I could easily slide them in the pockets.	'The shape of the tactor modules match the locations on where to put them.''	
3	Was there anything unclear on how or where to place the different modules? If yes, what was unclear? If no, what made the placement clear for you?	The shape maks it very easy to understand what goes where. The vib, modules looked identical, but their sleeves were coloured differently. So I wondered if there was a sequence or particular pairing.	The shape fit in pocket is misleading as it prompts the use to insert the vibration motor modules in a horizontal orientation.	Regarding position of the modules it was clear. I was a bit confused if the modules should be placed the same as the main module. The shape of the pocket has the same shape as the tactor module, that really helped as it was clear that they needed to be positioned there.	Unclear: Difference between magnetic and not Clear: Super clear shapes	Yes, I thought the vibration modules were placed wrong, because the pocket opening is smaller in width than the motor.	Not really, the shape of the modules matches the slots	
4	On a Likert Scale from 1-7, in which 1 = not comfortable at all and 7=extremely comfortable, how comfortable do you find the vest to wear?	7	7	4	6	6	6	6
	Reasoning	Easy to put on. I feel weight on the back but only a bit and it doesn't bother me	I do not feel any difference from wearing my everyday cycling shirt	The vest is a bit too small, but a perfect fit when road cycling! But no clash/interference with the modules	Less comfy than sweates, but not uncomfortable	I do no feel the electronics	I felt a slight weight of the main module and it is a bit in the way of the scapula	
	Observations & quotes	"I am putting it on over the tbale in case the main module falls off, since it is a prototype'' "A little bit of weight on the back." "It feels comfortable, though I can feel something hanging on the back" "It feels like a regular jacket now, it takes a little getting used to the weight" When putting on and off the user was scared the main module would fall off.	"I don't feel it though, the electronics on the back. I don't feel a difference with wearing my normal sweat T-shirt" "Cool design for the pockets, symmetry and patterns. Also the black and the multiple colour use is awesome" "Can you implement a light in the main module that blinks at night?" "Can the main module be smaller? As small as the tactors?"	'The shirt is extremely tight, but I do not feel the main control module'' ''If you move you do feel something located on the back, but that seems normal and does not restrict me in my movements.'' ''Everything is fixated properly and the fit is tight, funny that you do not feel the electronics'' "This would work well if you were to sport in a tight outfit and do not have to sit against a surface"	It does not restrict my movements. Maybe I should not go jumping with this product, as the main module might fall off. Taking of the main module while wearing the product was really easy. The location is good and I had it at the first try.	I do not feel that there is something of electronics on my back. I do feel a little bit of weight near my shoulders.	"Whenever I move I can feel the main module move slightly against my scapula"	
5	On a Likert Scale from 1-7, in which 1 = very restricting and 7= not restricting at all, how restricting do you find the vest to be in terms of body movement?	7	7	6	7	7	7	6,833333333
	Reasoning	I feel like the lowest vibration motor might interfere with my sitting on a chair. I might not be able to lie on the grass/foor with this on. But movement is not restricted.	I do not feel it at all	When rotating my upper body I feel the middle threads and also a bit of the weight of the modules	Nothing that restricts me	I can dance in it	It does not restrict motion, but I am aware of the main module's presence	
6	On a Likert Scale from 1-7, in which 1 = unaesthetically and 7 = very aesthetically, how aesthetically do you find the vest to be?	5	6	5	3		4	4,6
	Reasoning	I would most likely not buy this vest, but another one iwth similar functioning. I don't have a problem with the electronics on the back, but the vest itself… there's btter brands with better fit on the market	The pockets add a sense of symmetry on the fabric that makes the shirt look fashionable/stylish. The pockets make it look like a fashion product instead of only function.	Looks fine. The submodules are nicely covered and have a good fit. However, the main module is fairly bulky and prominent. Not my favourite design of this	The white unit looks less nice due to the fact that there is this thing on your back, but the jacket is not the ugliest thing I've ever seen	I cannot answer this question since it is not a final product but still a prototype with many colours	I have no strong feelings either way, I like how it comes alive as soon as the main module slots in	
7	If you could improve anything, what would it be and why?	I would want the back pane to be something I can purchase separately and fit it on a vest of my choice	The main module can be smaller and slick. I am a big fan of Apple devices, really slick design. Maybe you can do something for the main module	Embodiment/cover-up of the main module, due to aesthetic reasosns. And usecues of the sub-modules since function wasn't immediately clear	I would make the white box smaller and make the colour the same as the jacket to blend in	Change the pockets of the vibration motors to make it as easy to handle as the main module	Perhaps if the main module was softer (more spread), it would be less noticable	
8	Do you have any final remarks you would want to share?	When is it going to hit the market!?	How can this technology be applied in sports? Example football?	Cool that you were able to embed the electronics into a garment!	If I were to work with it all day, then I would be interested in how that would look. I do not know the product at all, I think it is something that vibrates if you do not sit up straight. The main module is the braínds and the smaller modules incorporate vibration motors. All these things can communicate over the sewn lines. The main module stood out Good luck!	No	No	

Some interesting images taken during the user research

Figure 294. Setup of the test

Figure 295. User placing modules on top of pockets

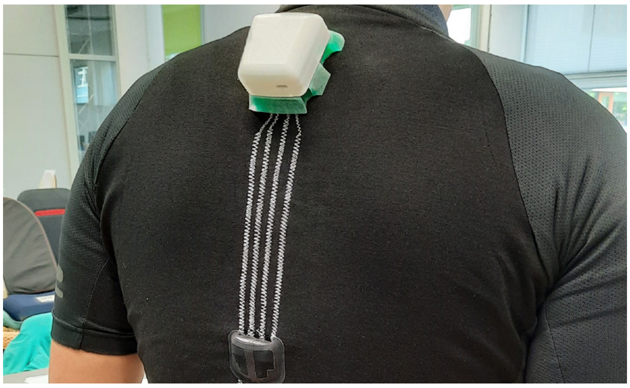


Figure 296. User wearing the vest

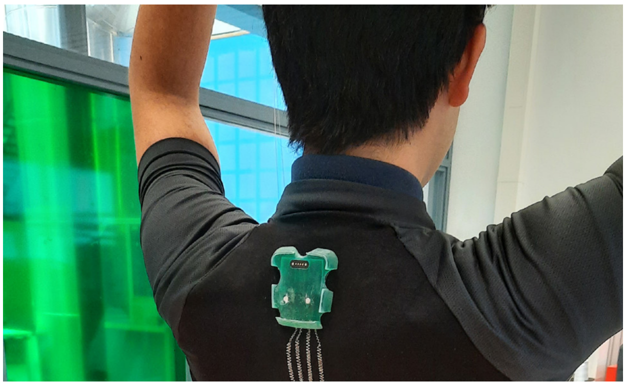


Figure 297. Participant stretching with vest

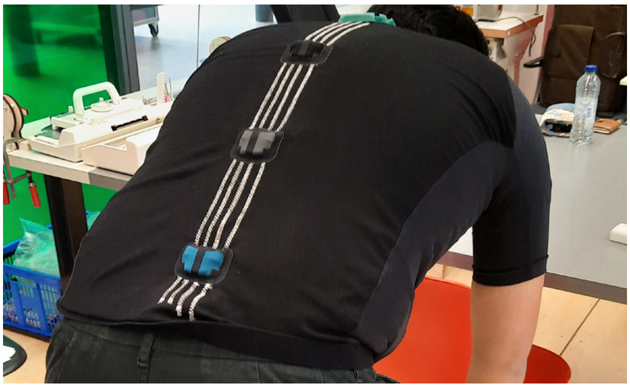


Figure 298. Participant bending over with vest

Figure 299. Participant taking of main module from back while wearing the vest

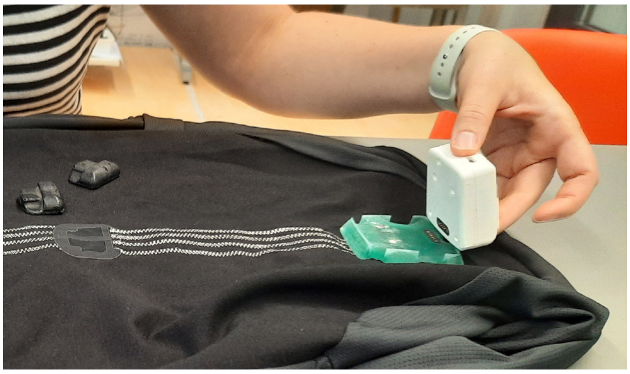


Figure 300. Participant placing main module

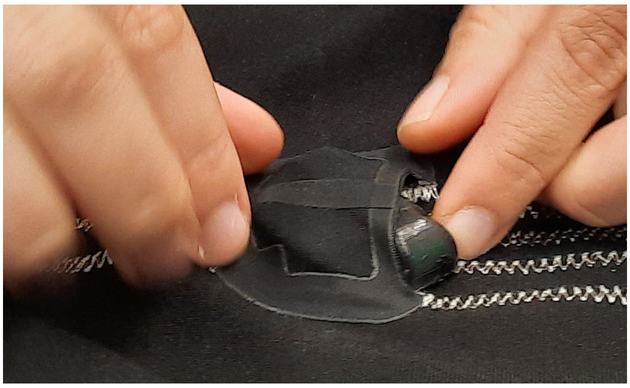


Figure 301. User placing tactor module