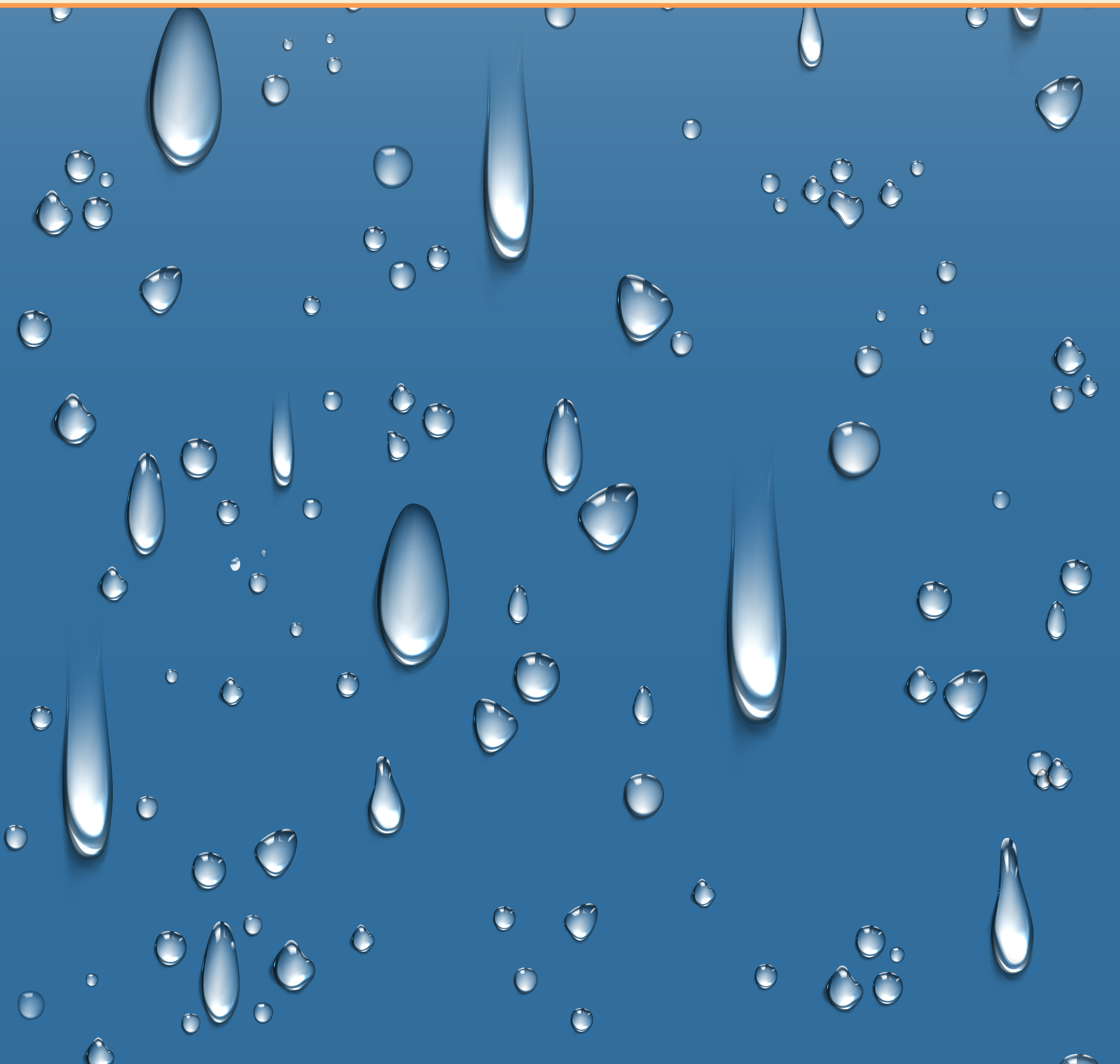
HYBRID COOLING SOLUTION FOR TETRAPLEGICS

MASTER THESIS INTEGRATED PRODUCT DESIGN

ELSEMIEK ATEN



COLOPHON

Delft University of Technology
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U.S. Air Force (2009)

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This graduation has gotten many help from all corners, for which I am forever grateful. I would like to take this opportunity to thank everyone who helped me.
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EXECUTIVE SUMMARY

Hyperthermia is becoming a bigger problem with higher temperatures. It has gotten more attention in the news for the upcoming Olympic Games in Tokyo, and for big marathons where this is becoming an increasing problem. Whereas able-bodied persons are able to dissipate heat by means of sweating, a tetraplegic most likely can not. When the lesion is above T6 there is a possibility of having a dysregulated thermoregulatory system. This means that the temperature signals are not received, and therefore no reaction will occur due to a rising core temperature. The fact that they can not control their own body temperature gives them a high risk of hyperthermia.

Research was conducted concerning the problem. The solutions currently used are wet towels, water beads, water spray, and cooling products such as evaporation and ice pack vests. The downside for these products is their limited duration. Products based on evaporation need to be refilled after several hours, depending on the temperature. Phase change material packs need to be restarted at a cool place, such as a fridge or freezer. There is currently only one active cooling product which cools the wheelchair user's back by means of air. The research showed that the users have a big need for an active cooling product, which could keep them cool for an entire day. Making use of a hybrid cooling product should have the highest efficiency. Due to the lack of sweating for tetraplegics, it has been decided to implement air and liquid cooling. For tetraplegics the area in which the most heat is found is the upper chest and back, which are the areas with the highest sweat rate for able-bodied as well.

The design goal of the project is to develop an active cooling system to prevent hyperthermia while outside, which can also be used by tetraplegics during their everyday lives. The goal is achieved when the user has a reduced increase of core temperature during their day outside.

VENTS is a shirt that helps the user stay cool during warm days. VENTS has four fans, two on the front and two on the back, which will create an airflow and improve convection. There is a temperature sensor included to make it a fully automated cooling product. If the fans are not enough to slow down the temperature increase within the body, the water pump will start distributing water droplets across the torso of the user. This is done by having tubing at the collar of the shirt, with outlets to create the small droplets. This process will re-enact sweating as well as help with convection and evaporation heat loss. If the product works on full cooling power it can extract about 28 Watts worth of heat from the body. With the help of the Fiale model and the user testing data, a simulation was conducted with VENTS in an environment of 35°C and 80% humidity, along with an activity level of 4 metabolic equivalent of task (MET). This simulation shows a 3.94°C decrease of skin temperature compared to not using the product.

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1. INTRODUCTION

When you are moving and being active your metabolic heat production rises. Normally your body would react to the rise in temperature and activate your sweat glands. When you are aware of the higher temperature, you will show cold seeking behaviour. However, what if your body does not react to the rising core temperature? For people with tetraplegia this is the case. Tetraplegics have a reduced thermoregulatory input, paired with a loss of vasomotor control and sweating capacity. This causes a high risk of hyperthermia.
This project is part of a research project named CAS (Citius Altius Sanius). In this research project the goal is to create injury-free exercise for everyone. A clarification of what CAS is will be presented in this chapter, together with the design brief and the stakeholders.

1.1 DESIGN BRIEF

A design brief was set up for the project. The original signed design brief can be found in Appendix A. The original problem definition was as follows:

The goal of the project is to develop an active air cooling system that can be used by people with tetraplegia while sporting, in order to prevent hyperthermia. The goal is achieved when the user can sport, while having a reduced increase in body temperature.

1.2 CAS

CAS (Citius Altius Sanius) is a project set up with the goal to create an injury-free exercise for everyone. The project is an NWO Perspectief program with nine sub-projects, that started in April 2018 (Technische Universiteit Delft, n.d.). The sub-projects are as follows:

- P1: Sensors
- P2: Data Science
- P3: Feedback
- P4: Fitness, over use
- P5: Running, over train
- P6: Soccer and hockey, hamstring and groin
- P7: Tennis and baseball, shoulder and elbow
- P8: Paralympic, thermal injury
- P9: Cycling, falling

P4 to P9 have an injury focus which are named after the sport focus, whereas P1 to P3 are the fundamental research lines.
This specific research is part of P8 to monitor and prevent thermal injuries in endurance and Paralympic sports. The project members are VU (Vrij Universiteit Amsterdam), TUD (Delft University

of Technology), RUMC (Radboud University Medical Center), NOC*NSF (Nederlands Olympisch Comité*Nederlandse Sport Federatie), HvA (Hogeschool van Amsterdam), Sunweb, IZI Bodycooling, Nijmeegse Vierdaagse and Watersportverbond.

1.3 READING GUIDE

The thesis is separated in four main phases: analysis, synthesis, final design, and evaluation. The analysis phase is about exploring the problem and finding new information that could help solve the problem. This includes looking into the current solutions available to tetraplegics, current cooling products on the market, understanding the thermoregulatory system, and talking to the users.
The synthesis phase explored some additional research, and contains the ideation process. The ideation phase consists of a brainstorm, both individually and with a group, after which tests have been conducted to quantify the effectiveness of the idea.
Once the synthesis phase is done, the final design with the implementation of the research is complete. With this design a prototype was made and tested with four users. There has also been thought put into the user scenario, costs, and electronics.
The evaluation uses the Fiale model to simulate the effect of the product in different situations. The final design will be evaluated with the requirements and wishes, along with recommendations that were made. The completed research has been reflected upon, and discussion points have been made about factors that influence the research, along with the outcome.

ANALYSIS

The following part will analyse the problem by looking into the thermoregulatary system, current cooling products, the users, and adaptive clothing for the user. This will all be used to create a new problem definition and set-up the requirements and wishes concerning a solution for the problem.

Harris and Graves (2017)

2. SPINAL CORD INJURY

The spinal cord is a collection of nerves that go from your brain down your spine (Eck, 2019). These nerves pass along signals from the brain to other body parts in order to perform an action, but they also carry messages from the sensory receptors to the brain. These sensory receptors detect and transmit senses like touch, pain, temperature and body position.

The spinal cord is protected by the spinal canal which is located in the spine (Rubin, 2020). The spine consists of four parts, namely, 7 cervical vertebrae, 12 thoracic vertebrae, 5 lower lumbar vertebrae and 5 sacral vertebrae, which are illustrated in figure 1.

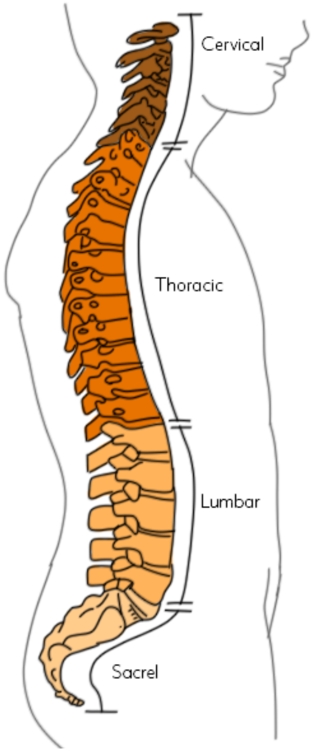


Figure 1: Overview of the spinal cord.

2.1 CAUSES OF A SPINAL CORD INJURY

A spinal cord injury (SCI) is the result of a traumatic, or a nontraumatic event (Mayo Clinic, 2019). Traumatic means that the cause is external, for example accidents or violence, whilst nontraumatic spinal cord injuries happen due to medical circumstances. In 2015, around 35% of spinal cord injuries were caused by traumatic events, and 65% were a result of nontraumatic events (Dwarslaesie Magazine, 2018). The main reasons for spinal cord injuries caused by trauma is as follows: falling (57%), followed by traffic accidents (19%) and sport incidents (14%). Whereas, the main reasons for nontraumatic spinal cord injuries are tumours (25%), degeneration of the vertebrae (22%), vascular (18%) and inflammation (12%). The overview can be found in figure 2.

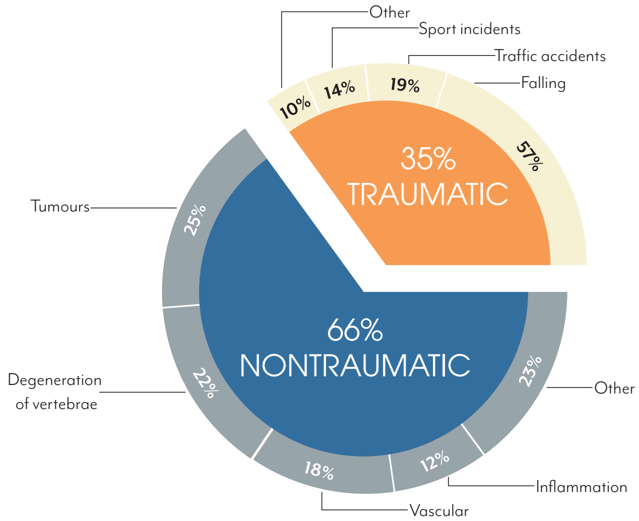


Figure 2: Causes of a spinal cord injury

2.2 CLASSIFICATION OF A SPINAL CORD INJURY

The American Spinal Cord Injury Association has created the AIS (American Spinal Cord Injury Association Impairment Scale), which is a rating to classify a spinal cord injury (ASIA, 2019). The AIS is defined as follows:

"A = Complete. No sensory or motor function is preserved in the sacral segments S4-5.
B = Sensory Incomplete. Sensory but not motor function is preserved below the neurological level and includes the sacral segments S4-5 (light touch or pin prick at S4-5 or deep anal pressure) AND no motor function is preserved more than three levels below the motor level on either side of the body.
C = Motor Incomplete. Motor function is preserved at the most caudal sacral segments for voluntary anal contraction (VAC) OR the patient meets the criteria for sensory incomplete status (sensory function preserved at the most caudal sacral segments S4-5 by LT, PP or DAP), and has some sparing of motor function more than three levels below the ipsilateral motor level on either side of the body. (This includes key or non-key muscle functions to determine motor incomplete status.) For AIS C – less than half of key muscle functions below the single NLI have a muscle grade ≥ 3.
D = Motor Incomplete. Motor incomplete status as defined above, with at least half (half or more) of key muscle functions below the single NLI having a muscle grade ≥ 3.
E = Normal. If sensation and motor function as tested with the ISNCSCI are graded as normal in all segments, and the patient had prior deficits, then the AIS grade is E. Someone without an initial SCI does not receive an AIS grade. Using ND: To document the sensory, motor and NLI levels, the ASIA Impairment Scale grade, and/ or the zone of partial preservation (ZPP) when they are unable to be determined based on the examination results"

Of the spinal cord injuries reported in specialised rehabilitation centres 38% had a low spinal cord injury (below thoracic vertebrae 6), 32% AIS D and 30% AIS A-C (Dwarslaesie Magazine, 2018).

2.3 TETRAPLEGIA (QUADRIPLEGIA)

Tetraplegia means that the injury happened above the first thoracic vertebrae (C1 to C8) (Villines, 2020). This results in complete or partial paralysis of the arms and legs. The severity of the paralysis depends on where the injury occurred and whether the injury is complete or incomplete lesion. However, the symptoms of the injury also depend on age, overall health and the quality of care directly after the injury.

The consequence of a spinal cord injury differs depending on which vertebrae is affected. The consequences for the cervical vertebrae are defined below (Shepherd Center, 2019). In figure 3 you can see a schematic overview of which vertebrae influences which area in the body.

C1 to C4

- Paralysis in arms, hands, torso and legs
- May not be able to breathe by his or herself, cough or control bowel or bladder movements
- The ability to speak is sometimes reduced

C5

- Able to raise arms and bend elbows
- Complete or partial paralysis in wrists, hands, torso and legs
- Breathing is weak, but able to speak

C6

- Wrist extension (backward bending of your wrist) is affected
- Paralysis in hands, torso and legs
- Able to speak, but weak breathing
- Able to move in and out of a wheelchair and bed with assistive equipment
- Little to no control of bowel and/or bladder

C7

- Elbow extension and finger extension is possible
- Able to straighten arms and have normal movement in shoulders
- Little to no control over bowel and/or bladder

C8

- Able to control some hand movements
- Should be able to grasp and release objects
- Little to no control over bowel and/or bladder

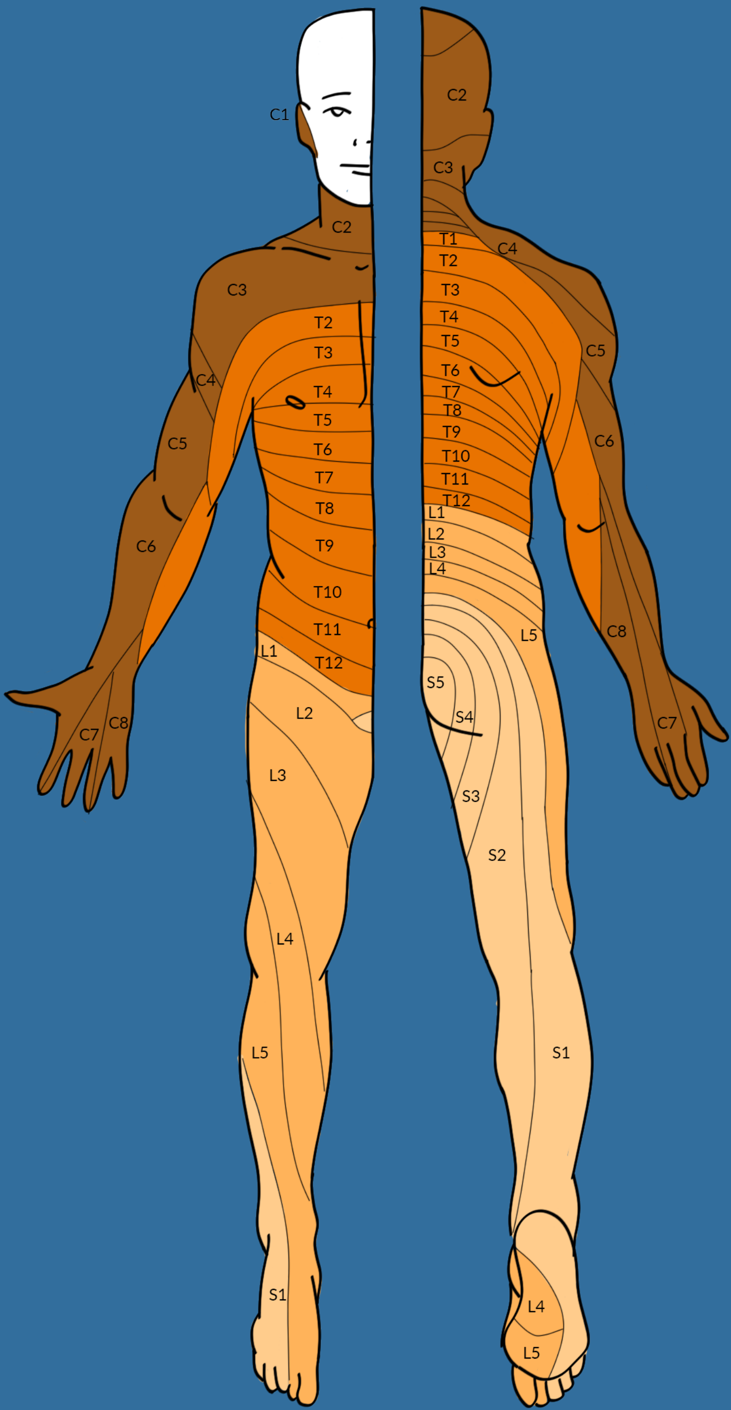


Figure 3: The schematic overview shows which spinal nerves are responsible for sensory and motor control of areas in the body. Based on image from Mayfield Clinic (2019).

3. THERMOREGULATION

The thermoregulation of the body is primarily controlled by the hypothalamus and its effector mechanisms (Schmidt & Chan, 1992). The signals from the temperature sensors in the body go through the spinal cord's neural pathways to and from the hypothalamus. The hypothalamus gathers the information and decides whether or not the body temperature is too high or too low. The working and details of the system will be explained in this chapter.

3.1 HEAT BALANCE

The human body has its own thermoregulatory system to keep the core temperature as stable as possible. Within the body there is a heat balance, which can be explained by the following equation (Teunissen, 2012):

$$M \pm C \pm R - E = S$$

M is the metabolic heat production. C is conduction and convection, which can be either positive or negative depending on the difference between skin temperature and ambient temperature. R represents radiation, which can be positive or negative depending on the difference of the ambient and skin temperature. E represents evaporation, which is always negative but depends on the temperature, air flow and humidity of the environment for its effectiveness. These values represent the net heat storage (S). The optimal value of S is 0, which equals a heat balance, resulting in a stable core temperature. When the value is above 0 the core temperature rises, and when it is below, the core temperature decreases.

Based on the equation it is concluded that the heat balance depends on the air temperature, radiant temperature, humidity, air movement, metabolic heat caused by human activity and clothing (Mokhtari Yazdi & Sheikhzadeh, 2014). Furthermore these factors are influenced by individual characteristics, such as body composition, fitness, etc.
Within the body there are several systems that help maintain a constant core temperature; vasomotor tone (the alteration of diameter from the blood vessels), sweat glands, shivering and nonshivering thermogenesis.

3.2 HEAT PRODUCTION

The human body not only produces heat during an activity, but also during rest. To determine the energy expenditure of a physical activity, METs (Metabolic equivalent of task) are used (Ainsworth et al., 2011). One MET is an individual's resting metabolic heat production, which is 58 W/m^2. With this number you can calculate the total metabolic heat production in the human body by multiplying the MET value with the Du-Bois area (1.8 m^2). Which results in a resting heat production of 104.4 W.
Below you can find table 1 with the MET value for wheelchair basketball, alongside several other physical activities with the same value, to give an idea of the intensity of this activity. The full list can be found in Appendix B.
The MET of wheeling at their self-chosen pace is 3.8 on average (Popp et al., 2018). This means that the heat production is (3.8 * 58) * 1.8= 397 W. Typically about 80% of the human body's energy is converted to heat, which means that 317 W will be heat (Stevens, 2016). The human body would have to remove the excess 317 W in order to avoid warming up. For more MET values for SCI patients, see figure 4.

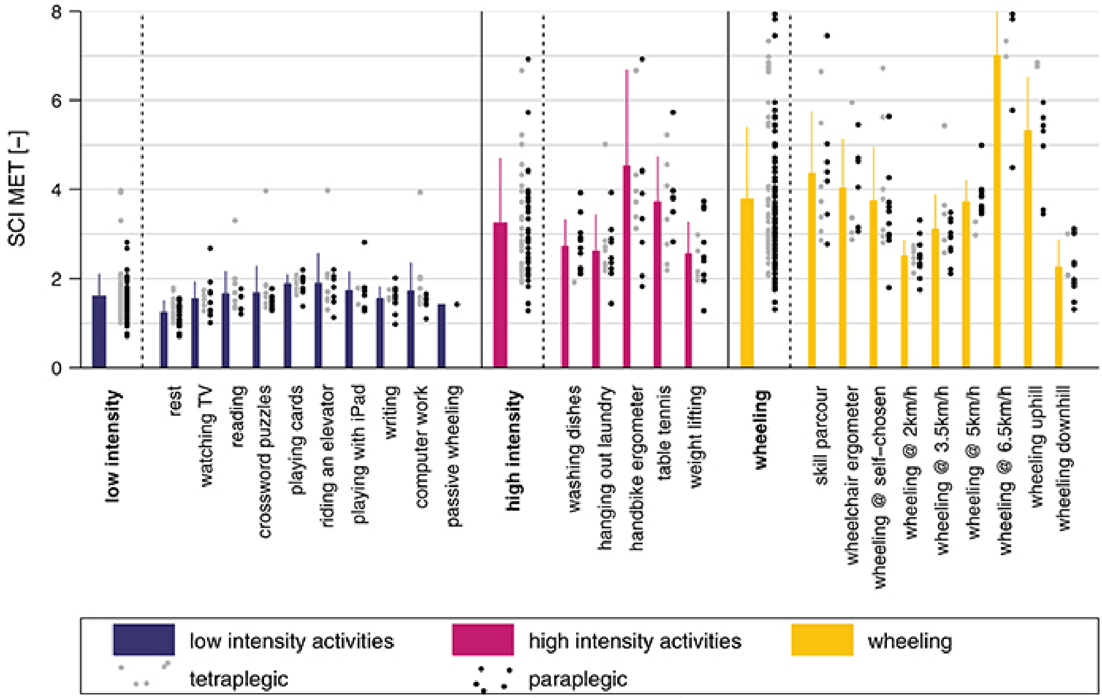


Figure 4: MET values measured during activities of SCI patients (Popp et al., 2018)

3.3 COOLING MECHANISMS

As explained earlier there are four ways to cool the human body: radiation, conduction, convection and evaporation (Nave, n.d). An overview of the four mechanisms can be found in figure 5.

RADIATION COOLING is only a possibility when the environmental temperature is cooler than the skin temperature. Radiation is also dependent on the area of the human body and the emissivity of the skin.

CONDUCTION means transferring heat to anything that is touched by the body. For instance this can be air for example, but also water and other materials/substances you come into contact with. The conduction rate is dependent on the area of the human body, the thermal conductivity of the material and the distance through the material.

CONVECTION is the process of losing heat through movement of gas and liquid molecules across the a surface. The amount of heat lost through convection is dependent on the airflow or the water flow over the skin. This also needs to take into account the area of exposed skin.

The last mechanism is EVAPORATION. The heat transfer by vaporization happens due to the fact that when a liquid evaporates, it will cool the remaining liquid since it has to extract the necessary heat to go through the phase change of liquid to gas. The amount of evaporation depends on ambient temperature, humidity and airflow.

Another cooling mechanism that occurs in the blood vessels is VASODILATION. Due to vasodilation the blood vessels become wider, which provides greater heat transportation from the core to the skin, where it dissipates.(Seladi-Schulman, 2018).

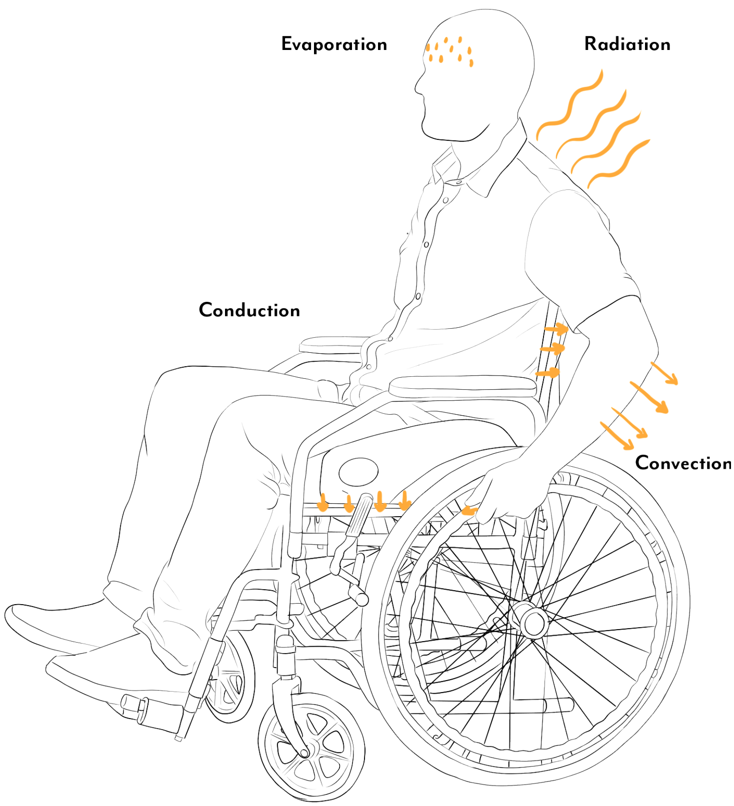


Figure 5: Cooling Mechanisms

3.4 HEAT COMFORT AND SENSATION

Not only is the physical temperature of your body important, but also the thermal comfort a person experiences. Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" by ANSI/ASHRAE Standard 55-2004. There are six main factors that influence the thermal comfort, namely:

- Metabolic rate
- Clothing insulation
- Air temperature
- Radiant temperature
- Air speed
- Humidity

These six factors are the same as the previously mentioned ones for determining the body's heat balance. However, for thermal comfort there are personal factors that determine the level of comfort. The metabolic rate and clothing insulation are the individual factors whereas the others are the environmental factors. There is one more important factor namely, the thermal perception. Thermal perception is dependable on the persons preference, experience, emotions and more personal factors.

Besides the ANSI/ASHRAE Standard 55-2004, there are four main criteria for a ready-state thermal comfort defined by Fanger (1970). Namely,

- The body is in heat balance
- Sweat rate is within comfort limits
- Mean skin temperature is within comfort limit
- Absence of local thermal discomfort

The thermal comfort can be defined with the help of the PMV/PPD method. For this method thermal sensation is used. Thermal sensation is defined as "a conscious feeling commonly graded into the categories cold, cool, slightly cool, neutral, slightly warm, warm and hot; it requires subjective evaluation." by ANSI/ASHRAE Standard 55-2004. The relation between thermal comfort and sensation can be seen in table 1.

Vote	Thermal sensation	Comfort sensation
	Very hot	Very uncomfortable
+3	Hot	Uncomfortable
+2	Warm	Slightly uncomfortable
+1	Slightly warm	
0	Neutral	Comfortable
-1	Slightly cool	
-2	Cool	Slightly uncomfortable
-3	Cold	
	Very Cold	Uncomfortable

Table 1: The relation between thermal sensation and comfort sensation

3.5 HEAT STRESS

Heat stress occurs when the thermoregulatory system is unable to cool down the body fast enough to mitigate the increasing core temperature (The University of Iowa, n.d.). Heat stress can be caused by exercising, warm climate and insulating clothing.

When exercising about 80% of the metabolic energy is converted into heat. When this happens the body will start to sweat in order to lose some of the heat. However, depending on the evaporative conditions and exercise intensity this might not be enough to maintain the heat balance.

The climate has several elements that contribute to causing heat stress. The elements are air temperature, humidity, radiation, air flow, precipitation and air pressure. Especially climates with high humidity and low air flow are dangerous since they negatively impact the heat loss mechanisms.

Clothing creates a microclimate around the body. Clothing has a thermal insulation value and this translates into how efficiently the heat can be transported from the body to the environment. There are properties that can weaken or strengthen the heat mechanisms in clothing, namely: breathability, liquid absorption, insulation and air flow around the body.

Heat stress can result in heat disorders if the body is unable to control the heat balance. Heat disorders are heat cramps, heat exhaustion and heat stroke. The last one is a life-threatening situation, which can result in coma and death.

3.6 THERMOREGULATION WITH SCI

People with spinal cord injuries have a decreased ability to regulate their body temperature. Especially people with a spinal cord injury above the T6 level have a problem with maintaining a normal core temperature for humans (36.1 to 37.2°C) in response to the environmental temperature changes, but also with their own metabolic heat production. There is also a problem maintaining blood flow to the muscles (Hopman & Binkhourst, 1997).

Theoretically, sweating and other reactions to rising temperatures will be absent below the injury (Griggs et al., 2015). However, it can occur as a non-thermoregulatory reflex which happens independently of the main thermoregulatory system. The fact that the hypothalamus does not receive any temperature information from below the injury means that the person does not realise that his or her body is too warm or too cold below the lesion. Therefore, they do not have the cold-seeking behaviour a person without the injury would have. Unless the areas where they can feel are also feeling warm. Despite the fact that these problems are starting from a lesion at T6 it has been concluded that people with a high lesion (C1 to C8) have a higher rise in the core temperature than people from T1 to T6. This is because they have a smaller area of skin to dissipate heat from than people with a lower spinal cord injury. According to Griggs et al. (2019) athletes with a T1 to L2 lesion often reach a core temperature of above 39.5°C during a rugby match which takes four times 8 minutes. This can even occur when the sport is performed in a controlled environment with a temperature of 19 to 21°C, without any external heat load. After the game their core temperature still rises for a longer period of time than able-bodied .

Berman&Simmons (2020)

4. CURRENT COOLING PRODUCTS

There are currently several cooling products on the market, which use different ways to cool the user. In this chapter the different methods of cooling will be discussed. Research of the current market shows what's currently available, and what price range these products are in. The full product market research can be found in Appendix C.

4.1 PHASE CHANGE

Phase change products work by using the latent heat of the material (Mokhtari Yazdi & Sheikhzadeh, 2014). The material that is in the garments go from solid to liquid. During this process heat is absorbed and extracted from the environment and your skin alike. The melting temperature of the phase change material depends on which products are used. Ice, for example, can be used with a melting temperature of 0°C, but paraffin wax could also be used, which melts at 18.3°C. By mixing and adjusting the ratio, a big range of melting points can be realised to fit every situation. When you want to use the PCM (phase change material) first need to activate it. This can be achieved by placing the product in an environment below its melting point. Phase change garments use the radiation and conduction principle to cool the body.

TIME 2-4 hours | **PRICE** $ 100-189

Figure 6: Phase Change Material garment (Bad Backs, 2018)

4.2 EVAPORATION

Evaporation cooling garments depend on evaporating the liquid that is in the garment. These garments are only effective when there is no relative high humidity and they need to have air movement (National Urban Security Technology Laboratory, 2016). The principle works the same as sweating. The evaporation of water contained within the garments will cool down the environment, and therefore your skin cools down. The garment requires being put in water in order for the product to work, and you are unable to wear the product under outer garments. However, evaporative cooling garments are inexpensive, portable, and do not require an external power source.

TIME 5-10 hours | **PRICE** $ 22-119

Figure 7: Evaporation garment (Koelproduct.nl, 2020)

4.3 AIR COOLING

The body's main way of cooling down in a hot environment is by sweat evaporation. A litre of sweat takes approximately 2400 kJ of heat from the body. However, the efficiency of this process depends on the humidity of the environment. Blowing air on the body helps with the evaporation and the convective heat loss. Air cooling products are most efficient when used in a lower relative humidity environment (National Urban Security Technology Laboratory, 2016). According to studies on ambient air systems, they increase a person's perceived comfort, but improve the physiological response to a lesser degree than other methods.

TIME	PRICE
-	$ 103-230

Figure 8: Air cooled garment (AliExpress, 2020)

TIME	PRICE
-	$ 219-1000

Figure 9: Liquid cooled garment (The Warming Store, n.d.)

4.4 LIQUID COOLING

In a liquid cooling garment there are tubes inside the garment and a battery powered pump, either implemented or kept separate from the garment. A heat sink is often used to make sure the liquid does not warm up. The tubes are sewn on the fabric and enables you to wear the tubes against your body, which gives the highest efficiency. The diameter of the tubes are 1.5-1.7 mm and 2.9-3.4 mm and the tubes have a total length of 90 to 110 m (Mokhtari Yazdi & Sheikhzadeh, 2014). This covers about 15 to 20% of the body's surface area. Liquid cooling is based on conduction in order to cool the body. Liquid cooling garments are in general relatively expensive and heavy, but very effective (National Urban Security Technology Laboratory, 2016).

4.5 MIXED COOLING

Following research of Griggss et al. (2019) and Bongers et al. (2015) it is concluded that using mixed methods of cooling is the most effective way to cool the body. According to Bongers' research the effect size of the mixed cooling method is in general higher in comparison to cold water immersion, cold water/ ice slurry ingestion, cooling packs and cooling vests. Currently, there are only a few mixed cooling method products on the market.

TIME	PRICE
5-10 hours	$ 110-200

Figure 10: Mixed cooling garment (Safety Workwear Shop, n.d.)

4.6 ADJUSTED COOLING PRODUCTS FOR WHEELCHAIRS

There are several products on the market that are specifically designed for cooling while being in a wheelchair. The products discussed below can be seen as direct competitors to a product that cools down a tetraplegic.

WheelAir

Wheelair is, according to their own web-page "the first temperature control system designed specifically for, and to fit all wheelchairs" (https://wheelair.co.uk/). Wheelair attempts to solve the problem of the backrest, where a lot of heat and moisture gets trapped, which results in a microclimate of heat and high humidity. The Wheelair, with the help of two fans located under the backrest, produces an active airflow to distribute air throughout the backrest (figure 11). The product claims to have a 24 hour battery life (3.7 V 8000 mAh), 6 cooling settings, a wireless remote, 43 DB of fan noise and a 1.5 hour charge time. According to their research, the back temperature decreases by 8°C in 30 minutes. This is achieved by improving convective, conductive and evaporative heat loss.

Figure 11: Sling Back on a wheelchair (Mobility Health, n.d.)

To ensure compatibility the company currently has four different products that utilise the same cooling technology, but differ in the remaining areas. The pricing of these products start at $650. These products can be found in figure 12.

Sling BackV2

Rigid Back

Custom Moulded Seating

Powerchair

Figure 12: Products of WheelAir (WheelAir, 2019)

TechKewl Phase Change Cooling Wheelchair Back & Seat Cushion

TechKewl is a division of the company TechNiche, which focuses on Phase Change Material products. The wheelchair back and seat cushion are therefore made in conjunction with PCM, see figure 13 (TechKewl, 2020). This cushion should, according to the specifications, stay at approximately 14°C for up to three hours. You have to recharge the product for 20 to 45 minutes in a freezer, or in ice water. This means that if you want to reuse the product you need to take it off the wheelchair and have access to a freezer or ice water. The price of the product is $74.99.

Figure 13: TechKewl wheelchair cushion (Natural Healthy (2020)

Kool Max Cooling Seat Cushion

Polar Products, the leading US manufacturer, produces body cooling and hot & cold therapy products. Kool Max is the brand name of their body cooling products (Polar Products, 2020). The cushion is made with water-based cooling packs, see figure 14. The product will provide cooling for about 3 to 4 hours. Due to having two layers of insulation on one side, and one layer of insulation on the other side, you can choose if you want a mild long-lasting cooling, or the maximum effect. The product is being sold for $57.81.

Figure 14: Kool Max Cooling Seat Cusion (Polar Products, 2020)

Figure 15: Stealth Products cushion (Stealth Products, 2019)

Stealth Products wheelchair cushions

The Stealth Product cushions have several options (https://cushions.stealthproducts.com/) .There are cushions focussed on positioning, skin protection, skin protection and positioning, and custom applications. All these cushions are equipped with the Coolcore Technology cover, see figure 15. CoolCore is a fabric that adapts to the environment and regulates temperature by means of managing heat and moisture. The price is between $200 and $370 for the cushions.

4.7 COOLING GARMENTS

The above mentioned garments are all vests, which is a deliberate choice for making fair price comparisons. However, there are several different garments on the market. An overview of different garments can be found in figure 16.

4.8 EFFICIENCY

The efficiency of a cooling garment depends mainly on the metabolic heat change. Your body need to be in heat balance if there should be no increase or decrease in temperature within the body as explained in chapter 3. This balance depends on four environment factors, air temperature, radiant temperature, humidity and air flow. Two factors are specific per person the metabolic heat generated by a person and the clothing worn by the person. The efficiency of the cooling garments depend per situation and means it can be different for everyone. Therefore, if you want to test if one cooling garment is more efficient than the other you would have to test both products in the same situation.

4.9 CONCLUSION

Most products on the market are focussed on phase change material or on evaporation. Evaporation garments are the cheapest, followed by phase change material. Liquid cooling is the most expensive, due to the need of a pump, and often a liquid cooler with it. Although earlier research showed that using a mixed method of cooling is the most effective, the research concludes that there were only a few garments on the market that make use of more than one cooling mechanism. When the garments have two cooling mechanisms, it is often evaporation and phase change. Due to the effectiveness of hybrid cooling methods, research will focus on implementing at least two cooling methods in the solution for the problem definition.

Figure 16: Different cooling garments on the market

5. AIR COOLING PRODUCTS

To test the current active cooling products on the market concerning air cooling, two jackets were purchased. These jackets were analysed for their implementation of the system, feeling and efficiency. Both of these jackets were obtained from Aliexpress.com.

5.1 ALIEXPRESS AIR COOLING JACKET NO.1

The first jacket is made of polyester and has a battery included of 12,000 mAh. The battery will give you 8 hours on high speed, 12 hours on medium speed and 16 hours on low speed, according to the advertisement. The fans that are included are positioned in the back of the jacket to blow the air up inside the jacket. The jacket can be found in figure 18.
The first impression of the fans is that they are quite bulky. This is due to the fact that the fans are flat on the outside, but convex on the inside. The fans are shown in figure 17 and 19.

In order to use the product you first have to place and secure the fans in the jacket. As shown in figure 18 the fans are attached to the jacket by means of a screw thread. The left part of the fan is attached to the jacket from the outside by screwing the right part of the fan on from the inside. Once this is done, the next step is to connect the wire between the fan and the battery.
The battery also acts as the jacket's fan controller, this is shown in figure 20. On the battery there is a single button for on/off and the change of settings. The lights on the battery show which setting the fans are currently operating at: low, medium or high.

Figure 17: Fan on the inside of jacket

Figure 18: Jacket no.1 (AliExpress, 2020)

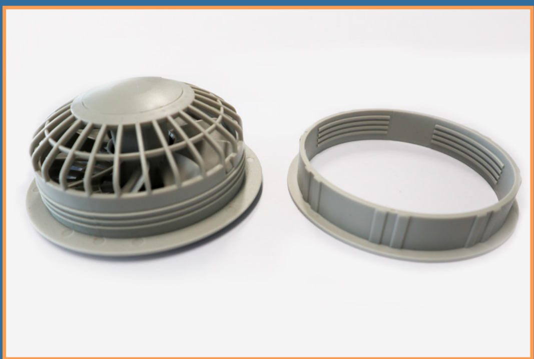


Figure 19: Fan from jacket No.1

Figure 20: Battery from jacket No.1

5.2 ALIEXPRESS AIR COOLING JACKET NO.2

The second jacket is made from waterproof, breathable fabric. The jacket weighs about 300 grams, without the inclusion of a battery. As opposed to having the controls on the controller, as in jacket no.1, they are located on the USB cable adjacent to the connector, see figure 23. This jacket also contains two fans which can be placed at the back. The full picture of the jacket can be found in figure 22.
In general the jackets work identically. Like jacket no.1 this jacket also has three settings, which are indicated by the green, orange and red lights. The benefit of having the controls on the USB is that you can use any power source that you have available that is delivered by USB. Since it can be plugged into a computer or power bank, the battery is replacable because it is separated from the controller. The fans in this jacket are also attached to the jacket by means of screw thread, see figure 21 and 24. However, despite the assembly process being identical, they differentiate by the fact that the housing is fairly equally divided amongst the two parts.

Figure 21: Fan on the inside of jacket

Figure 22: Jacket No.2 (AliExpress, 2020)

Figure 23: Controller on USB plug

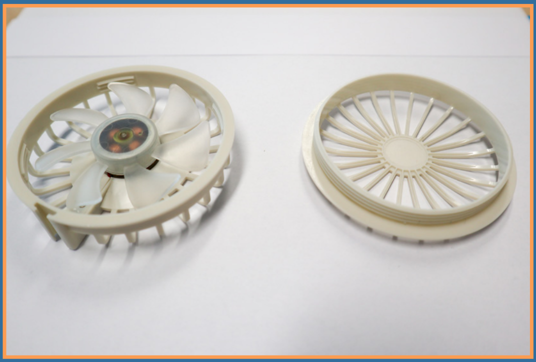


Figure 24: Fan from jacket No.2

5.3 WIND SPEED

Both the jackets are tested with the same method, in order to measure their wind speed and cooling ability. To measure the wind speed an anemometer, the Testo 425, was used. This device measures the wind speed in m/s. This test has been repeated for all the settings of both jackets to see how much the wind speed increases with each setting. Measuring the wind speed gave the following results, which are shown in table 2.

Product No. 1

Speed 1	1.90 m/s
Speed 2	2.50 m/s
Speed 3	3.60 m/s

Product No. 2

Speed 1	1.53 m/s
Speed 2	2.56 m/s
Speed 3	3.20 m/s

Table 2: Wind speed of jackets

5.4 COOLING

The cooling ability was measured with the help of iButtons. The iButtons measure the temperature of the surface or environment they are placed in. To measure the skin temperature an iButton has been placed on the skin at the arm, and to measure to ambient temperature an iButton has been placed on the table out-of-the-way from the airflow of the fans. One fan from each jacket was in turn selected and used to direct airflow onto the arm. Figure 25 shows the test set-up.

Each test was conducted for 10 minutes at each setting. To get a baseline comparison for normal skin temperature, a measurement without any fan was also conducted. When analysing the results for the first product, there is a noticeable difference between each setting and the cooling it resulted in. The difference between air cooling and the lack of cooling is almost 6°C. However, it must be noted that this result was achieved by direct airflow, as opposed to circulation.

Figure 25: Measuring cooling effect

The difference between the settings of product No.2 is less significant than those of product No.1. Despite this, it managed to cool down the skin by an average of 3°C. This proves that air cooling is able to, at least locally, cool down the skin. The outcome of the tests can be found in figure 26 and 27.

When using the jacket your body may be perceived as cooler, but in reality it is unlikely to actually change your core temperature in any significant way. The perception of the lower temperature is due to the extra air flow created by the jacket itself. It is a similar experience to standing in front of a fan. While both of the products create quite some noise, the jacket produces a direct air stream onto your face when you move your head around, due to leakage.

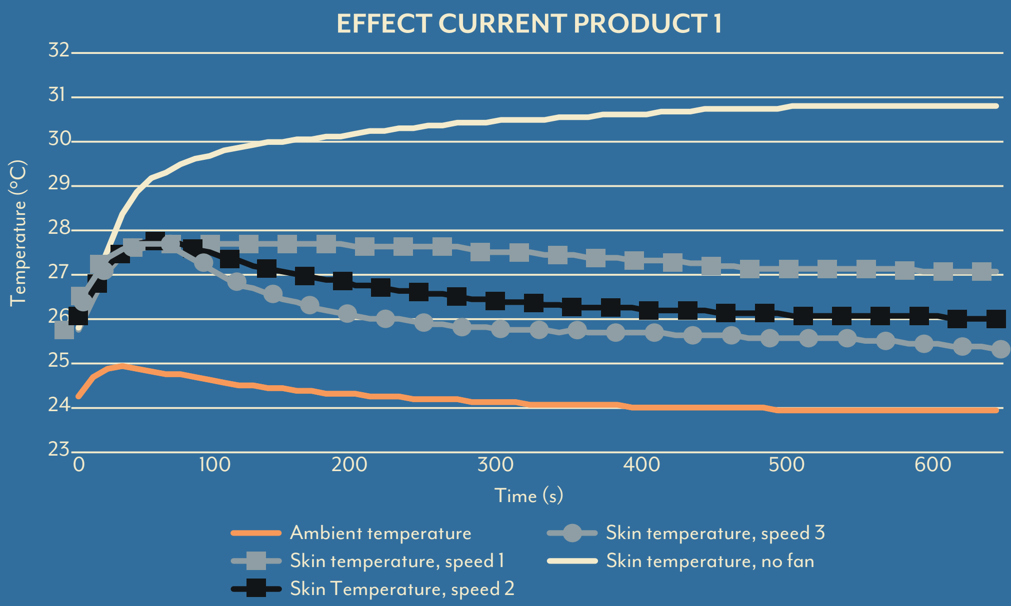


Figure 26: Effect current product 1

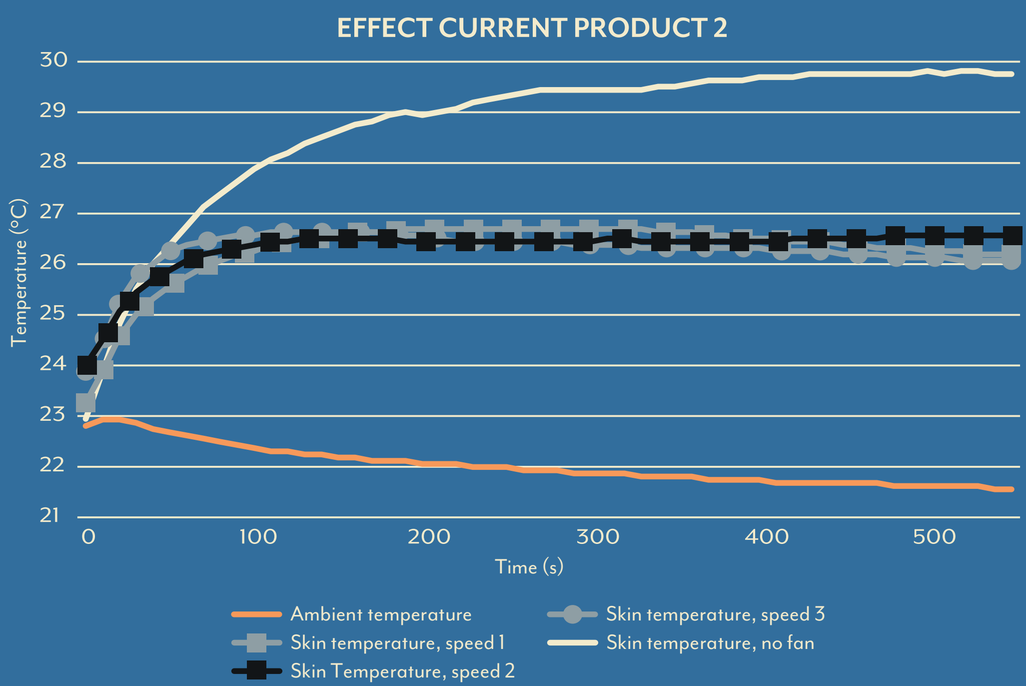


Figure 27: Effect current product 2

6. USER

The main stakeholder of the product is the user. The user is in this case someone with tetraplegia, who has a dysfunctional thermoregulation system, but still wants to go outside on a warm day. As explained in chapter 3 tetraplegics often lose the ability to sweat below the lesion, and therefore have a high risk of hyperthermia. However, there are three groups within the tetraplegics concerning core temperature: those who always feel warm, those who always feel neutral, and those who always feel cold. Research has been conducted into the needs and wishes of tetraplegics concerning the cooling of their bodies. Inquiries have been made in regards to their current situation, and how they currently deal with hot weather conditions.

"My skin can feel cool even cold to the touch but inside I feel like I am burning up. Which in turn makes everything feel swollen and I am unable to move. The summer is a killer for me." (Mo, 2013)

The perception of a person greatly influences if they will seek out cooling solutions or not. In this chapter information is gathered from the questionnaire (see Appendix D to I), conversations held with spinal cord injury patients (for the transcripts and research of the interviews see Appendix I and Appendix J), tetraplegic vlogger "Role with Cole & Charisma" (Role with Cole & Charisma, n.d.), and from the forum InspiredSCIforum (http://inspiredsciforum.com/). Several quotes from the forum have been selected to explain their current feeling towards their disordered thermoregulation. More quotes concerning this issue can be found in Appendix K.

6.1 A DAY AS A TETRAPLEGIC

Their mornings start as usual, by waking up. However, they are often incapable of getting out of bed or removing their own blanket, without assistance. After getting up they are assisted with getting dressed, or having a bath/shower. Putting on trousers, which is often executed while still lying in bed, is done before getting into the wheelchair. A shirt can be either put on whilst in bed, or after having gotten into the wheelchair. Positioning the tetraplegic in the wheelchair is done by carrying them, or by using a sliding plate to slide them into the wheelchair from the bed. Once the morning rituals are completed it is time to either work, spend time on hobbies, or work on rehabilitation. At the end of the day the same process takes place as in the morning, but in reverse. An overview of such a day can be found in figure 28.

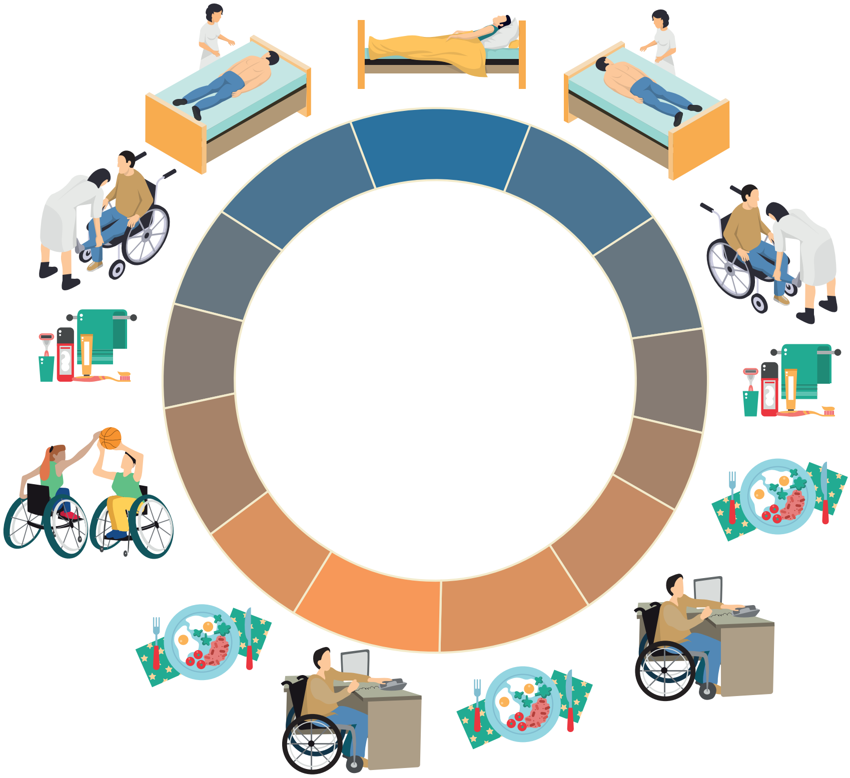


Figure 28: A general day as a tetraplegic

6.2 CURRENT PROBLEMS AND SOLUTIONS

Most tetraplegics have a problem with heat when the outside temperatures start to rise. The following quote shows how the situation can be experienced for people with tetraplegia, once their core temperature goes up and they are unable to do anything about it.

"We do not die, but neither do we go out if it can be avoided." (Tetra, 2018)

When the temperatures start to rise in the summer tetraplegics either stay home when they can, or they use cooling products to make it through the day. The most mentioned cooling solutions on the InspiredSCIforum are ice packs, water beads, and wet towels. The place people cool the most is in their neck, on their shoulders or their back. The cooling required on the neck and the shoulders can be explained by the fact that they often still have sensation in these parts of the body, and therefore get the perception of being cooled down. Another important solution when they are at home or at work is making use of either air conditioning or fans.

"In the summer I become overwhelmed with the heat. My temperature goes up and I cannot control it. Most people with spinal injury have difficulty controlling their temperature. Particularly people with neck injuries. There are guys here who are hooked up to ventilators to keep them alive" (Mikeq, 2018)

The tetraplegics who sport often use a water spray, and consume a cold drink during breaks. Prior to competitions some will use a cooling vest, to cool down their body and improve their performance during the game. (Griggs et al., 2015). The experience with cooling garments, such as caps and shirts, are mainly positive. However, there are some issues with them, such as the weight, which was frequently mentioned as a reason to avoid phase change material products. The fact that you need to carry all the extra weight during the day was seen as a reason not to use it. This, together with the fact that the cool packs often only help for a couple of hours at the most, when they need to last a full day, dissuades tetraplegics from using them. The problem with evaporation products is the limited timeframe that the product can be used within before needing recharging. The smaller the area that the evaporation material takes up, the faster it will dry. For the user the product is only perceived to work for about 20 to 30 minutes, and then is in need of being recharged. The recharging is primarily achieved by submerging the product in a bucket of water, but this requires them to take the product off and put it back on again. This action is often inconvenient for tetraplegics.

6.3 NEEDS

During the research several people were asked what changes they would like to see in the currently existing products, and what product yet to be developed, they would love to see available in the future. The consensus was that people would like a product that is easy to take on and off, should prevent pressure points, be durable, possible to use locally, and focus on cooling the head, neck and/or chest. Another point of attention is the sizing of the garment. People with tetraplegia often have a quad belly. A quad belly is the overstretching of the paralysed abdominal muscle wall, caused by the weight of the body organs whilst sitting (SCI-Nurse, 2008). The quad belly causes a bigger stomach area than normal, and therefore garments are often too tight around this area.

Pond5 (2020)

7. ADAPTIVE CLOTHING

The clothing you buy in the shops are designed and made for our daily life. However, the daily life of people with paraplegia and tetraplegia looks different. Most clothes are not made to be worn in a wheelchair, or to be put on by people with limited function in their upper body. After talking to people this seemed to be a problem that needed to be involved in this project.
Therefore, companies that make adaptive clothing were researched, and the differences between regular clothing and adaptive clothing were defined.

7.1 SHIRT

The issues with a shirt starts when you put it on. To be able to put shirts on you need to lift your arms, which some tetraplegics are unable to do alone. This could be enabled by adding an opening on the sides or the back. When this is done you can slip your arms through it, like a coat. Once the arms are in the sleeves the shirt needs to go over your head and body. However, people with a spinal cord injury are in a wheelchair, and some are incapable of moving their torso. As opposed to a regular person, a tetraplegic needs help to fit the shirt properly between their back and the backrest. When a shirt has buttons or zippers tetraplegics cannot use them, because these parts are too small for them. A solution for this is either bigger buttons, a zipper with a loop at the end, or the use of Velcro or magnetic closures (IZ ADAPTIVE, 2019). When sitting in the wheelchair a shirt has the tendency to crawl up. Especially people with tetraplegia need someone to undo this for them. This can be prevented by having the ability to attach the shirt to the trousers, either at the waistband or belt loops.

7.2 TROUSERS

In order to pull trousers on there are quite a few steps. Firstly, they need to position their legs correctly. Once this is done they have to put their each leg into the corresponding trouser leg. However, this needs to be done with the help of either someone else, or by lifting up their own legs. Once this is done the next step is pulling up the trousers, which can be cumbersome if you are laying down or sitting. Regular trousers are not made for pulling, and therefore it is advised to add pull tabs to reduce the stress on the material. Since buttons are hard to use, an elastic waist and stretch fabric is highly requested. Nonetheless, a special larger zipper with an eyelet is also possible (ROLLITEX, n.d.). When sitting down you want the back of the trousers to be higher than the front. Another sought after feature is that the trousers legs are longer than the regular ones. They also don't have any pockets or decoration at the back, in order to prevent pressure points (SCIA, 2019).


ZIP GRIP

8. PROBLEM DEFINITION

The research started with the following problem definition:

The goal of the project is to develop an active air cooling system that can be used by people with tetraplegia while sporting in order to prevent hyperthermia. The goal is achieved when the user can sport while having a reduced increase of the body temperature.

As a consequence of the research done so far, the problem definition was redefined. This was done with the help of the WWWWWH method (van Boeijen, 2013). This method helps to analyse every part of the problem definition, and makes the scope of the problem clear.

Who?
Tetraplegics with a dysfunctional thermoregulation system, who are at risk of overheating during warm days or intensive activities. The main stakeholders are the users, which are the tetraplegics with this problem and the FIXME.

What?
The main problem is the inability to sweat and sense one's own body temperature. There are multiple cooling solutions on the market, but most focus on a short cooling time or are too bulky to use in a wheelchair.

Where?
The rising core temperature occurs in their whole body. However, it was expected that most heat would be in the upper body, where most movement happens, compared to their legs due to being paralyzed. Therefore, the upper body was the target focus.

When?
The problem occurs when the body temperature reaches the point where able bodied people will start to sweat. The cooling procedure should take place during warm days, when refrigerators and freezers are inaccessible, consequently not allowing you to cool/charge the other products previously mentioned.

Why?
Tetraplegics have complications in regards to dissipating their own heat, due to the inability to sweat. Sweating accounts for a substantial amount of the total heat transfer during hot days. A solution has not yet entered the market, likely due to the limited user group and lack of knowledge when it comes to the best cooling procedures for their own body.

How?

Heat stress gives temporary discomfort, but could also cause permanent damage to the body if exposed for too long. They normally try to cool down by using a wet towel, water spray, or make use of water beads. However, these solutions will only give cooling for a limited time.

New problem definition

With every part of the problem defined, a new problem definition has been set up.

The goal of the project is to develop an active cooling system that can be used by tetraplegics during their everyday lives when they go outside on a warm day to prevent hyperthermia. The goal is achieved when the user has a reduced increase of core temperature during their day outside.

The focus changed from 'while sporting' to 'during day'. This decision was made since the user research showed that people faced the same problem during their daily activities on a warm day. For sports it is easier to utilize the current solutions, since sporting pertains to a shorter period of time, whereas their daily life is a full day with additional challenges.

9. REQUIREMENTS AND WISHES

With the new problem definition defined, the requirements and wishes for this project will be explored. These requirements and wishes will define the scope of the project and will be used to test the concept to ensure it will solve the problem.

9.1 REQUIREMENTS

Usage

- The product must decrease the rise in core temperature.
- The product must not limit the users movement.
- The user must be able to use the product for at least 4 hours in one session.

  A potential user expressed a wish that the product should work for half a day, or up to 6 hours. Therefore, 4 hours is set to the minimum working time, which equates to half a working day.
- The product must have an indicator capable of displaying the remaining power of the battery.
- The product must work at temperatures between 0 and 50°C.

  The product will primarily be used during warm days, when people would normally sweat. However, the product must not break due to lower temperatures.
- The product must be comfortable to wear.
- Must dissipate more heat than the energy required to wear it.
- Must be mobile.
- The product must be capable of being equipped and removed in an easy fashion, with the help of a caretaker, or whilst experiencing limited hand and/or arm functionality.

Function

- The product must make the user feel cool.
- The product must be automatic.
- The product must contain at least two different cooling methods.
- The product must be usable for tetraplegics.
- The product must not rely on the users own thermal perception.
- The product must cool the upper back, upper chest and shoulders.
- Must improve one of the cooling mechanisms of the human body.

Design

- The product must be available in S, M, L and XL.
- The product must not exceed the weight of 2 kg .

  This is the average weight of a phase change material vest, which was seen as too heavy.
- The product must have a separate compartment for the battery, for safety reasons.
- The product must be recognizable as a shirt.

- The user must be able to wear the product with a quad belly.

Materials

- The material should not emit toxic gases when heated or in fire.
- The product must be washable, after electronics are removed.
- The materials must not be hazardous.

Safety

- The battery must not be able to cause explosions.
- The cooling must not create undercooling.
- The product must not create pressure points .
- The product must not make the legs and armpits wet.
- The product must not cause any injuries during normal usage.

Maintenance

- The product should remain fully functional for two years of normal use.
- The cooling components must be easily replaceable.

9.2 WISHES

- Should be as easy to use as possible by someone with tetraplegia.
- Should be able to be used by a tetraplegic without any assistance.
- Should prevent hyperthermia.
- Should be as light as possible.
- Should be made for different body shapes, e.g. quad belly.
- Should not be complex in usage.
- Should avoid the need for the wheelchair to be adjusted.
- Should cover 40% body area with cooling. (Griggs et al., 2015)
- Should work as long as possible.

SYNTHESIS

During the synthesis a more specific research was done for sweating and thermograms. With the new problem definition and the additional research an ideation process has started. The ideation has been done individual and in a group. Once there was an idea for a possible solution it has been tested and iterated further on this idea if it worked.

The University of Queensland (2017)

10. SWEATING

Sweating is the release of salt-based fluid from the sweat glands, according to Roth (2018). Sweating occurs when the core temperature rises. There are two types of sweat glands: eccrine glands and apocrine glands. The eccrine glands are spread throughout the body, whereas apocrine glands are only found in specific areas of the body such as armpits, scalp and groin. The sweat rate differs per person and is based on the climatic conditions, clothing and intensity of the current activity (Sawka et al., 1996). During exercise the sweat rates can reach 1 to 2 litres per hour.

10.1 SWEATING WITH SCI

People with SCI often lose the ability to sweat as explained in chapter 3. However, two researches have been conducted that test the effects of water spray (artificial sweating) on people's core temperature and specifically people with spinal cord injury. The first research was conducted by Pritchett et al. (2010), which evaluated artificial sweat in athletes with spinal cord injuries. A spray bottle was used to create the artificial sweat. The research has been done with 7 participants, of which 3 have a lesion at or above T6. The participants are required to perform arm-cranking in an environment of 21 ± 1.5°C and 55 ± 3% relative humidity for 7 minutes. During the one minute break they were required to use the water spray. The results were compared with the results when they did not use a spray bottle. The conclusion is that there is no significant difference between using a spray bottle and not using one. However, this could be explained by the ambient temperature of 21°C. Another potentially influential factor could be the specific area that was sprayed. However, this was up to the participants themselves and there is no information provided about this. The last factor is the lesion level, where four of the participants have their lesion below T6, and in the paper it is not mentioned whether these people were able to sweat or not.

Trbovich et al. (2019) researched the efficacy of water spray for evaporative cooling in athletes with spinal cord injury. The research compared the core temperature of tetraplegics, paraplegics and able-bodied people while doing a wheelchair intermittent sprint exercise for 90 minutes in 10-22°C and 55-60% relative humidity. During this exercise water spray was applied every 15 minutes, followed by another test without the water spray included. The conclusion of this research was that water spray does affect the rise in core temperatures for people with tetraplegia. The results of the research can be found in figure 29. It should be noted that the results showed no significant difference between the paraplegics and the tetraplegics. However, the researchers thought that this might be due to the small sample group of paraplegics.

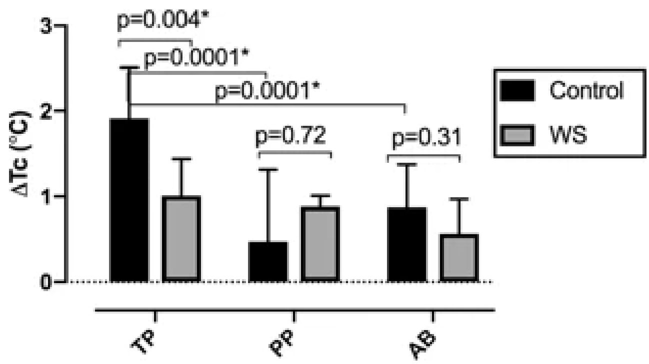


Figure 29: Average change in core temperature during the exercise

10.2 THERMOGRAM

Thermograms are pictures made with an infrared camera. These pictures indicate which part of your body emits the most heat and exactly how warm they are. In figure 31 you can see three images from tetraplegics in a wheelchair. The figures show three different persons from anterior and posterior positions without a shit on. These figures were obtained from Griggs (2016). On the thermogram the white colours represent the highest temperature on the body. As evidence suggests, this area is mainly the chest, shoulders, and back. When examining the person's lower body, you can see that the legs are colder than the upper body, which indicates that cooling is more effective on the upper body for paraplegics. During the research measurements the effect of an ice vest for paraplegics was measured. The results of this test can be seen in figure 30. The first picture is the body temperature before, the second one is after putting on the ice vest, and the third shows the effect of the ice vest after 15 minutes. As expected, the area of skin which was covered by the ice vest was overall colder than the skin that wasn't covered. The anterior skin temperature was reduced by 2.6 ± 0.6°C after having worn the ice vest for 15 minutes. The posterior skin temperature was decreased by 1.6 ± 1.0°C.

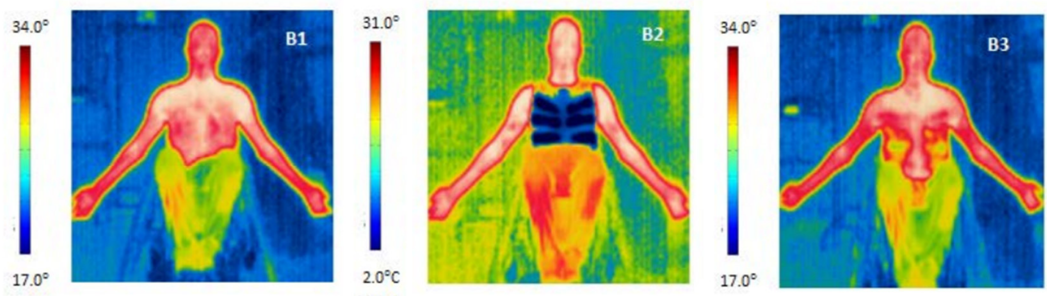


Figure 30: Thermogram with ice vest

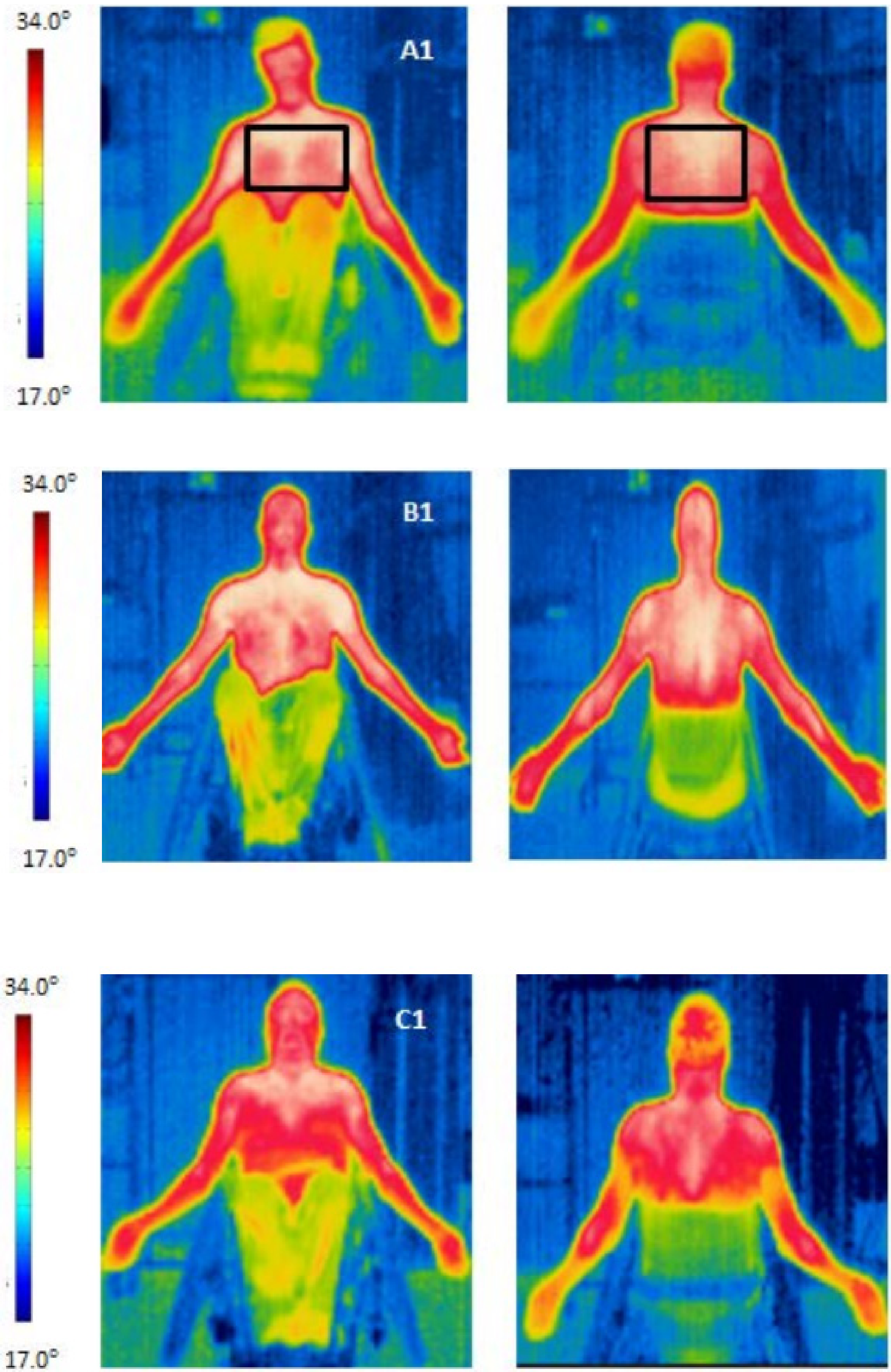


Figure 31: Thermograms of tetraplegics

10.3 SWEAT MAPS

Apart from everyone having their own sweat rates, there are also different sweat rates for different parts of the body. In figure 32 is the sweat rate shown across the full body These metrics are obtained from Smith & Havenith (2011). These are the sweat rates of a control workload of 55% of VO_2 max and a heart rate around 125-135 BPM. It can be observed that the highest sweat rate is found in the middle of the back. The upper and lower back, upper chest and shoulders are the following highest sweat areas together with the medial side of the shins and forehead. However, these sweat rates are only applicable for males. Smith & Havenith (2012) research compared the sweat rates of males and females, the research is nearly identical, but for that the research for female sweat rate were done at 60% VO_2 max instead of 55%. The overview of the sweat rates categorized by sex can be found in figure 32 and figure 33. For females the overall sweat rates are lower than that of males, but in general the highest values can still be found at the back.

The focus for this project was on the upper body, based on the thermograms and sweat rates. With the help of the sweat rates from figure 32 and figure 33 the amount of sweat per hour can be calculated. To calculate these values an assumption was made that 1 mL of sweat equals 1 gram. These values can be found in table 3.

	Area (cm^2)(M)	Area (cm^2)(F)	Median ($g/m^2/h$)(M)	Median ($g/m^2/h$)(F)	Sweat rate (mL/hour)(M)	Sweat rate (mL/hour)(F)
Shoulder	689	520	267	40	18	2.1
Lateral upper chest	366	230	262	58	9.6	2.2
Centre upper chest	370	-	318	-	11.8	-
Lateral mid chest	372	320	244	31	9.1	0.9
Centre mid chest	186	160	370	57	6.9	0.9
Sides	390	340	230	67	8.9	2.3
Lower chest	171	160	174	49	3.0	0.8
Lateral upper back	425	350	515	138	21.9	4.8
Centre upper back	234	190	707	223	16.3	4.2
Lateral M-U back	203	170	431	13	8.7	2.3
Lateral M-L back	191	170	322	16	6.2	0.3
Centre mid back	195	170	771	133	15.0	2.3
Lower back	167	150	677	132	11.3	2.0
Medial upper bra	-	90	-	22	-	0.2
Lateral upper bra	-	100	-	0	-	0
Medial lower bra	-	90	-	0	-	0
Lateral lower bra	-	100	-	0	-	0
Bra triangle	-	20	-	139	-	0.3
Total	**3,959**	**3,330**			**146.7**	**25.6**

Table 3: Sweat rate on upper body

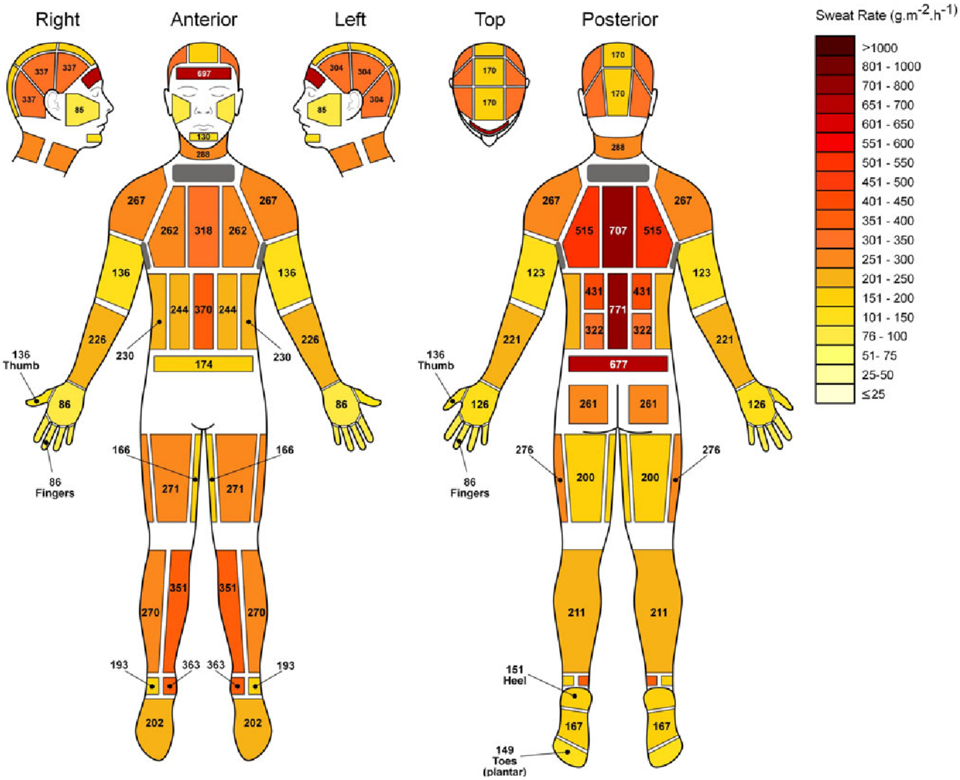


Figure 32: Sweat rates of males at intensity 1

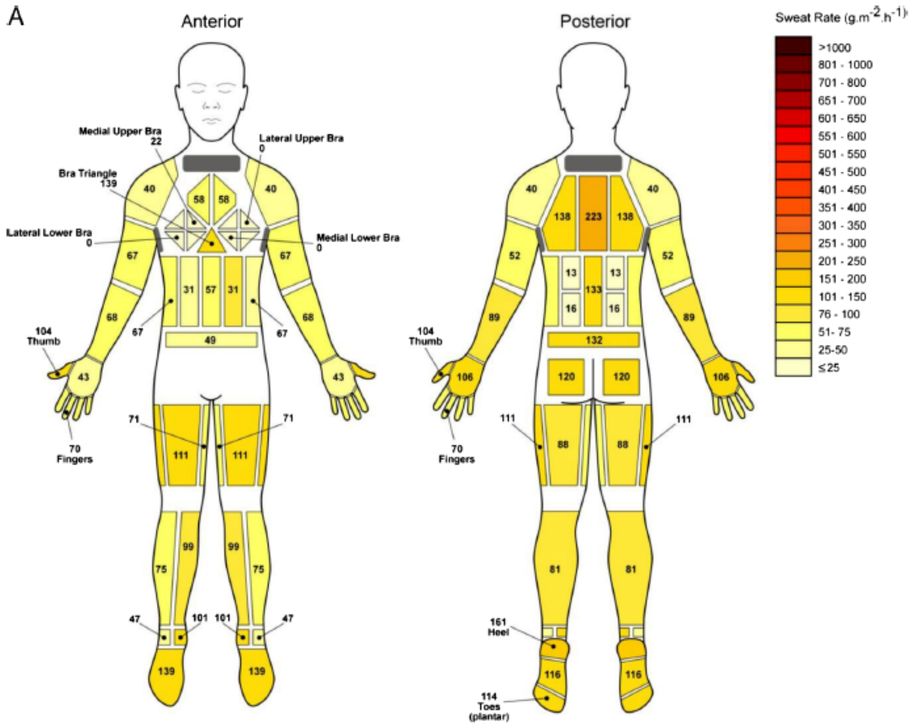


Figure 33: Sweat rates of females at intensity 1

10.4 CONCLUSION

The product stimulates sweating in order to cool down the body. With the help of the aforementioned sweat and heat maps, an optimal area for the cooling is chosen. Most sweating and heat that make up your skin temperature is located on the upper body, and therefore the focus will be directed at cooling this part of the body. The upper chest, shoulders, and upper back are the areas that dissipate most heat, and conveniently these areas have the highest sweat rate of the entire upper body. Therefore, the main cooling will focus on these areas.

11. IDEATION

With the problem defined and research done, the following step is to convert this into a product. To achieve this several questions have been posed in order to solve part of the problem. These questions were asked in a brainstorm session where four people in total had to find solutions. The questions asked were the following:

- How could you cool someone with air?
- How could you let someone think they are cool?
- How could you implement cooling in a wheelchair?
- How could you cool someone with water?

The results of this brainstorm can be found in Appendix J.

With the ideas acquired from this session, more ideas were generated. Due to the wish to not have to adjust the wheelchair, and already having multiple cooling cushions on the market, decisions were made to look into cooling wearables. A lot of passive cooling products showed up during this ideation, see figure 34. However, the main focus was on active automated cooling. In the end the design direction gravitated towards a shirt with fans and an implemented water source.

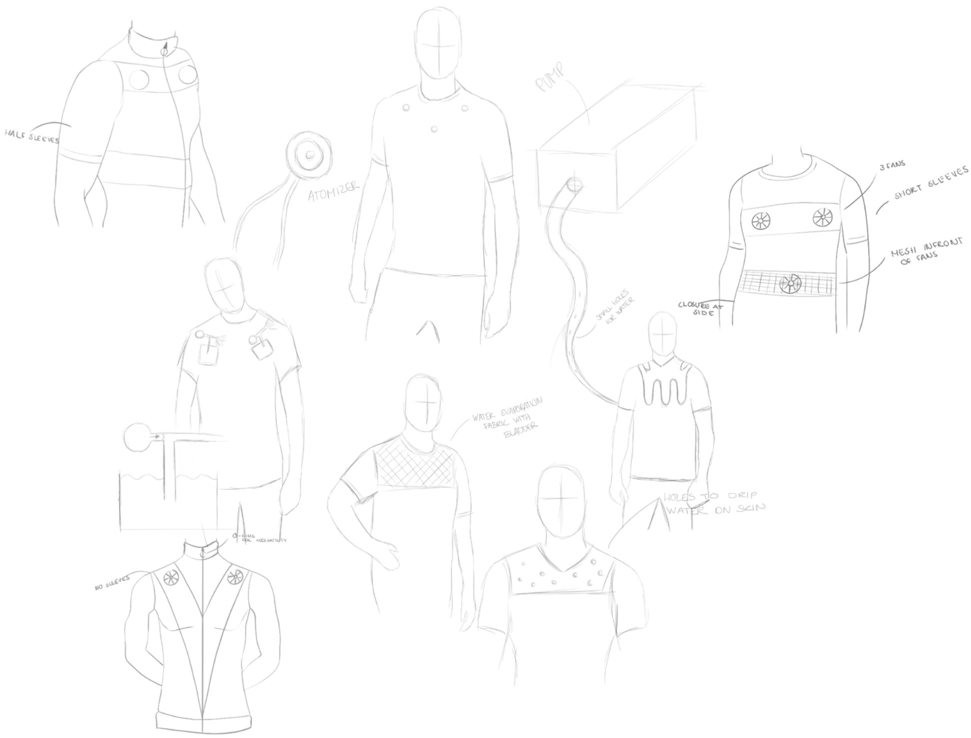


Figure 34: Ideation cooling products

With the design direction defined, efforts were redirected at how to implement the water and the air cooling. Additional air implementation ideation can be found in figure 35. In Chapter 12 the air implementation and circulation was researched and tested based on earlier air implementation ideas. In Chapter 13 the water implementation is explored and tested.

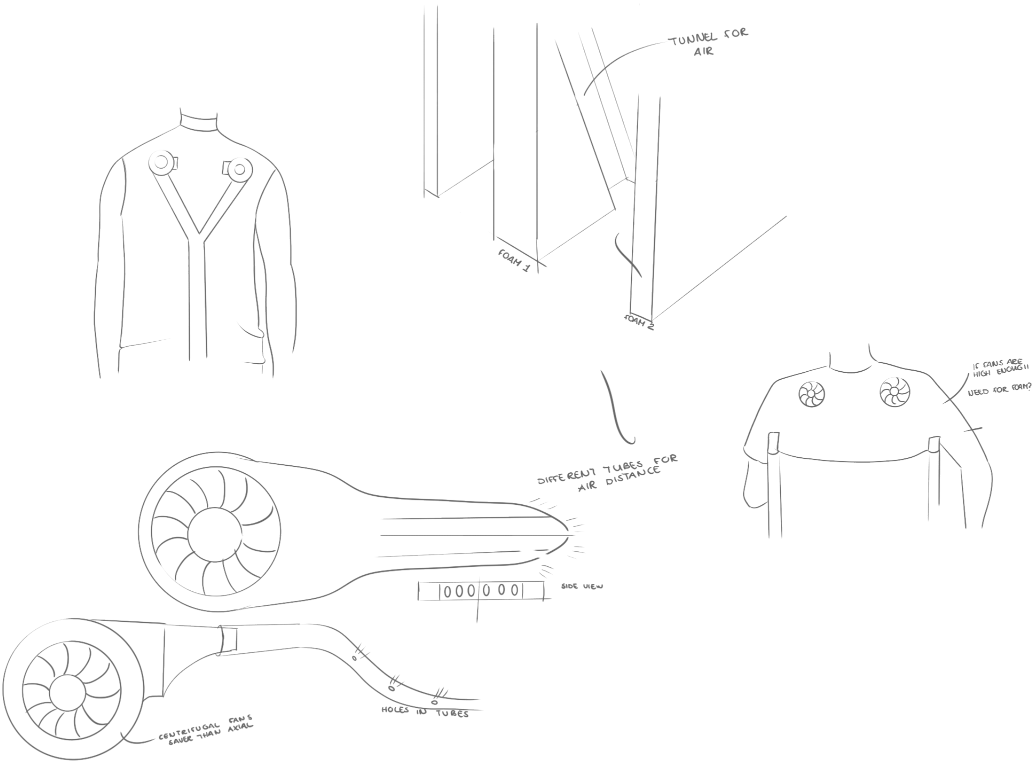


Figure 35: Ideation for air implementation

12. AIR CIRCULATION

The first aspect of the product that was considered was the air circulation within the product and how this cools down the skin temperature.

12.1 FANS

There were two main categories within fans. You have the axial and the centrifugal fans (see figure 36). The axial fans have a high airflow, low pressure and low power input. The centrifugal fans have a higher pressure, lower airflow, steadier airflow, but a higher power input.

The benefit of a centrifugal fan is the fact that it has a directed air stream, and is therefore better suited for this project. The second advantage is that the air is more compressed and is therefore perceived as colder by your skin. The last benefit is that the fan is safer than an axial fan. The centrifugal fan is closed within the case, whereas the axial fan needs to be enclosed in a housing to make sure nothing comes into contact with the fan while the blades rotate. These findings led to the decision to move with the creation of the prototype using centrifugal fans.

For the size of the fans, the airflow, the airspeed, size in combination with comfortability, and the noise all need to be taken into account. The airflow says something about the amount of air it transports, this is dependent on the size of the fan and the RPM. The bigger the fan is the lower RPM it needs to work on to transport the same amount of air as a smaller fan with higher RPM. A lower RPM is convenient since this also results in a lower noise level. In general when the RPM is higher the airspeed is also higher. The best fan would have a low noise level but still transports a decent amount of air at a wind speed of 3 on the scale of Beaufort.

Figure 36: Centrifugal (upper) and axial (lower) fans

12.2 TRAVEL DISTANCE AND WIND SPEED

In an attempt to use as few fans as possible inquiries were made into how much the air speed decreases over distance. To measure this the device Testo 425 was used, tubing with the diameter of 3.8 mm and 5.6 mm (47% bigger), and fans with a diameter of 50 and 60 mm.
The test was set up by taping the 1m tube to the fan and after each measurement cut off 5cm. A picture of this can be found in figure 37.
The air volume flow of the first fan is 2.91 CFM and the second fan 4.51 CFM, which is a 55% increase in the air volume flow. The results can be found in figure 38. It must be noted that the inconsistencies between the measure points are due to accuracy of the test and the device. The results show that the larger airflow of the fans increase the overall wind speed, as predicted.
The 60 mm fan results in a higher starting air speed at 0.1 m than the one of the 50mm, the same can be said about the final air speed at the length of 1m. The 50 mm fan seems to be way less consistent in its airspeed, but this could also be due to the measuring device since it gave varying results on the same length.
The second test was done by changing the tubing to a wider diameter. The air velocity relies on the air volume flow and the area, which is demonstrated in the following equation:

$$Air\ velocity = (Air\ volume\ flow)/Area$$

As displayed in the graph the air velocity was bigger with a larger diameter tube. These differences are explained by the equation mentioned above. The highest wind speed recorded was 11.44 m/s with the 5.6 mm tube, and 8.1 m/s for the 3.8 mm tube respectively. These wind speeds correspond to a wind strength of 6 and 5 on the Beaufort scale.

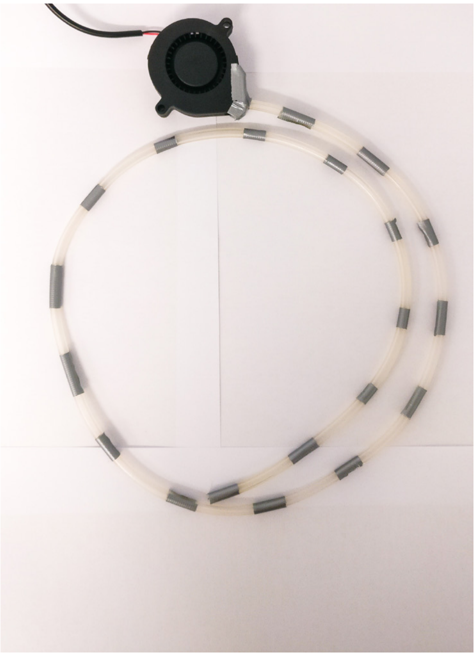


Figure 37: Test set-up to measure wind speed over length

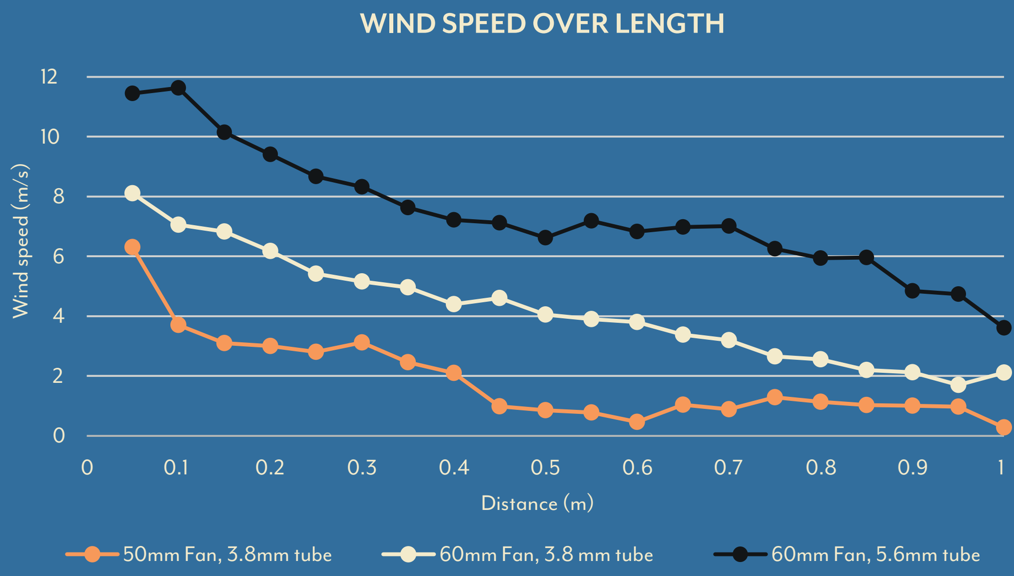


Figure 38: Wind speed over length

12.3 INFLUENCE OF DIFFERENT FABRICS

Different fabrics have different specifications, which is why the influence of different fabrics in regards to air flow have been tested. For keeping the air inside the garment it is mostly recommended to work with an airtight fabric. However, airtight fabric is often denser, and perceived as less soft to the touch than cotton, and can therefore reduce comfort. The two fabrics used in comparison to each other are cotton, which is mostly recommended to wear on a sunny day, and airtight fabric, commonly found in running jackets.

Method

In order to measure the difference between the two fabrics, one cotton shirt and one running vest were used. In these shirts four holes were cut out to tape the 60 mm centrifugal fans in the shirt, see figure 39. During the test four iButtons were placed on the chest and shoulders (see figure 40) measured the skin temperature for 30 minutes with the shirt and the jacket. During the test the participant sat still and did not do any physical activity. The test was performed at room temperature, which measured 23.7°C ± 1.0.

Results

Figure 41 shows the difference between the two fabrics, and the ability to keep the air inside. This is done in order to cool down the skin, which can be seen in table 4, where the differences in temperature are displayed. However, during the test the starting temperature of the skin was not equal to that of the fabrics, and this will influence the results of the test.

Results show that the air tight fabric displays a larger decrease in temperature at the beginning of the

Figure 39: Cotton shirt (left)and windproof jacket (right) used for test (fans were placed at same spot for testing)

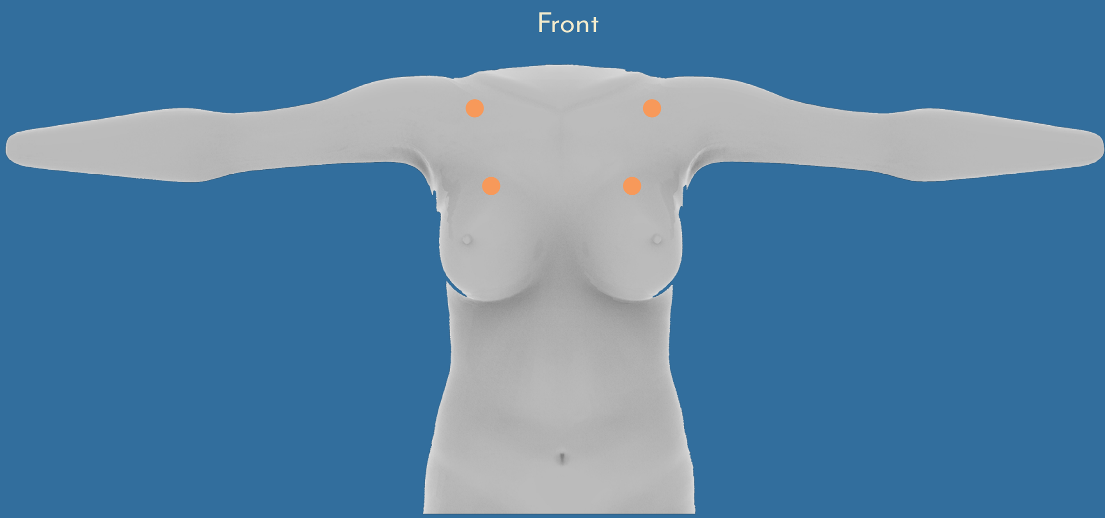


Figure 40: Placement iButton

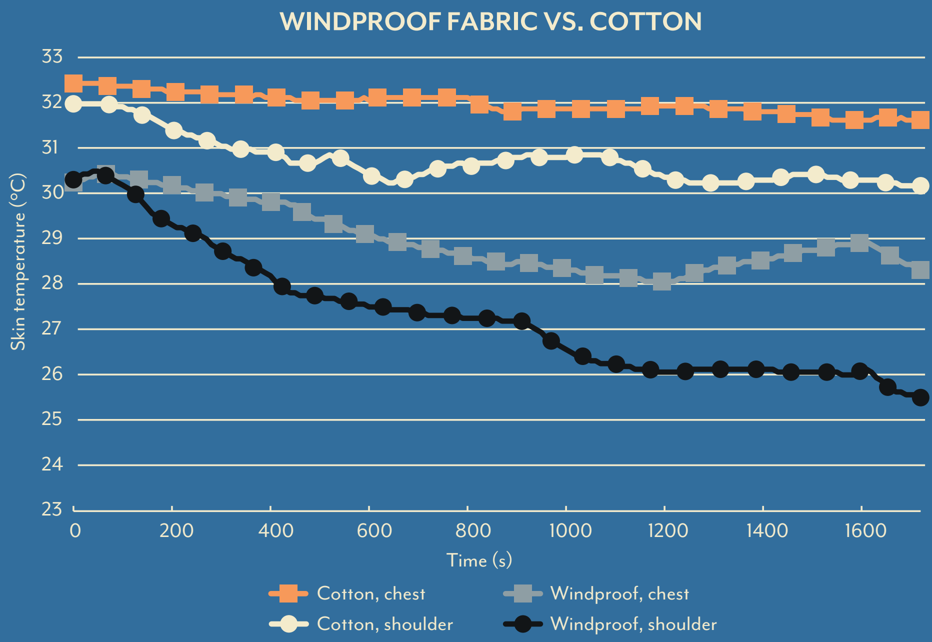


Figure 41: Windproof fabric versus cotton fabric

Cotton, chest	0.8°C	Windproof, chest	2.4°C
Cotton, shoulder	1.8°C	Windproof, shoulder	4.9°C

Table 4: Temperature differences at begin and end

test, and it keeps declining. Meanwhile, the cotton shirt only shows a decrease of 2°C where the chest specifically demonstrates a more stable temperature. Therefore, it seems as if the air tight fabric is indeed better suited to cool the skin when only air cooling is used.

12.4 MIXED SHIRT

Due to the results of the aforementioned test, a new shirt was made. This shirt has a cotton outer layer, but on the inside of the chest and back area windproof fabric is placed, see figure 42. The reason why it is placed on the upper part of the shirt is because this is the place where cooling is needed the most, and simultaneously the most important place to keep the air inside. This new shirt was compared to the windproof jacket. For this test the sensors were placed on the shoulders and back as shown in figure 43, and the test took 20 minutes.
The results of this test can be found in figure 37, and the temperature differences in table 5.
Worth noting is that the starting values of the tests are different, which could have occurred due to various testing parameters not being accounted for.
The results show that the mixed shirt performs worse than the windproof jacket, since the measurements for the mixed shirt stabilize quicker than those of the wind tight fabric. However, when comparing it to the results of the cotton shirt in figure 44 there is a bigger decline in the beginning of the test of the mixed shirt.
Eventually the mixed fabric option was chosen for the design to maximize the performance and comfort ratio. During the decision making period both aesthetics and attempts at making it appear as regular as possible were taken into account.

Figure 42: Mixed shirt

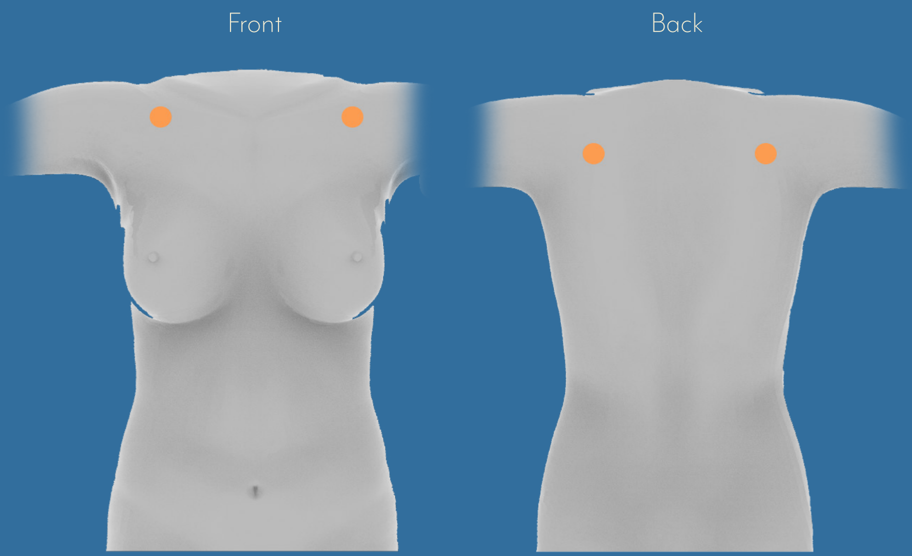


Figure 43: Plaacement iButton

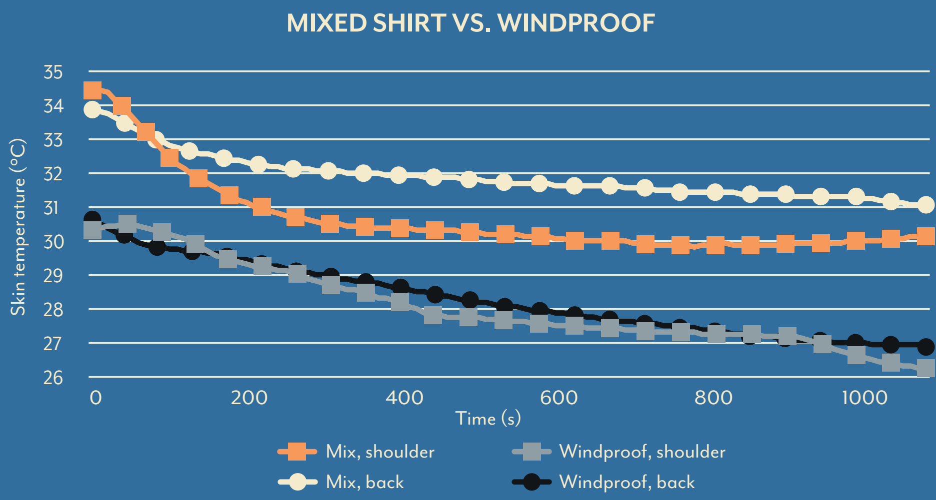


Figure 44: Mixed shirt versus Windproof shirt

Mix, shoulder	4.3°C	Windproof, shoulder	4.1°C
Mix, back	2.8°C	Windproof, back	3.8°C

Table 5: Temperature differences at begin and end

12.5 AIRFLOW DIRECTION

The chest, back and shoulders are the warmest place of the upper body and will therefore be the focus area to cool down. This choice was made with the help of sweat and heat maps, which can be found in chapter 10. Research showed that the front of the shirt provided optimal airflow. The desired path of the airflow is shown in figure 45. This figure shows that most air should be directed at the shoulders, upper back and upper chest, where the warmest areas and highest sweat rates of the upper body are found.

To achieve this airflow several set-ups of fans were explored, as shown in figure 46. As demonstrated these set-ups consist of axial and centrifugal fans. The centrifugal fans are used for more directed airflow and the axial fans are used for a more spread airflow. When blowing air into an enclosed space it can inflate and make the user look weird. This is not the desired effect and therefore tests with a fan that blows the air away from the enclosed space were performed. However, this was unnecessary when using a breathable fabric, since this effect was not present.
The axial fans used had little protection and were easy to get hair between or go against the skin which caused it to stop. These fans also cause a big hole in the shirt which makes the inner environment of the shirt be less controllable.

Therefore, decisions were made to focus on the set-ups with centrifugal fans. To test these possibilities one fan was placed focussing on the left side of the chest, and one fan focussing on the shoulder and right side of the shirt. For this test the mixed fabrics shirt from the earlier tests was used. The skin temperature was measured with the iButtons, that were placed at the chest and shoulders as shown in figure 47.

The results of this test can be found in figure 48, together with the temperature differences in table 6. The fan focussing its airflow to the shoulder creates a bigger temperature difference on the chest and the shoulder than the fan focussing on the chest. A possible explanation for this is that since the air that gets blown onto the chest can easily leave the shirt through the cotton, whereas the air blowing onto the shoulder cannot leave through the fabric since the air tight fabric is there. Due to this effect the fans on the front of the shirt will face towards the shoulders, to keep the air inside the shirt for as long as possible.

There are two additional fans placed at the back of the shirt, on the shoulder blades. For the back you want the main focus of the airflow to be directed from the shoulder blades down towards the spine. This is done because the front fans are already focussed on cooling the front and back of the shoulders.

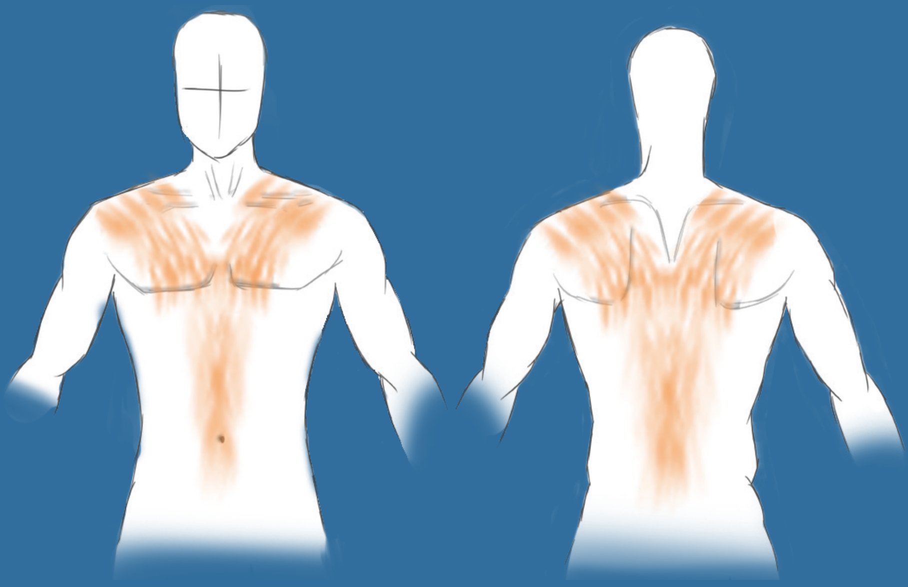


Figure 45: Desired airflow across the body

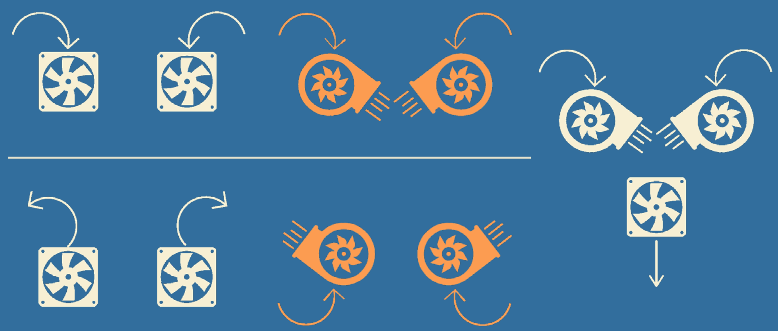


Figure 46: Tested fan directionsa

Figure 47: Air direction test set-up

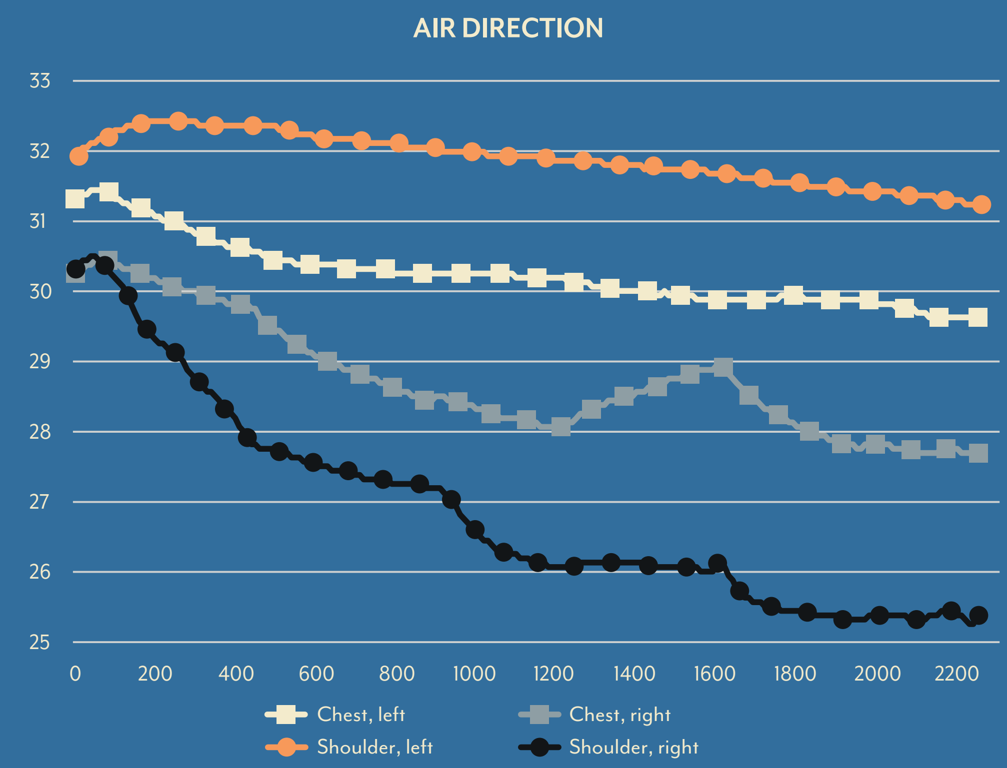


Figure 48: Air direction graph

Chest, left	1.7°C	Chest, right	2.6°C
Shoulder, left	0.7°C	Shoulder, right	4.9°C

Table 6: Temperature differences at begin and end

12.6 FAN CASING

In order to implement the fans in the shirt, a system to attach the fans to the shirt was devised, while keeping the possibility to remove them when the shirt needs washing. The current products that were tested (Chapter 5) both made use of a threading. Screw thread enables you to remove the fans before washing the garment. A different top and bottom part were chosen, which is necessary since the chosen fans were centrifugal fans. The measurements of the original fan casing was selected when designing the new screw threaded fan casing. These were fastened by rotating clockwise, which abides by the general standard. The new casing also makes it less likely for something to accidentally come into contact with the fan blades as they are rotating. For all four fans there are three parts. There are two different versions of the bottom case which are mirrored, accompanied by a top part that fits both of the bottom parts. Two different bottom parts are required to ensure the same amount of air flow for the left and right side of the body. This also makes the cables more accessible when connecting them to the fans. The final design of the fan casing can be found in figure 49. The technical drawing of the casing can be found in Appendix K.

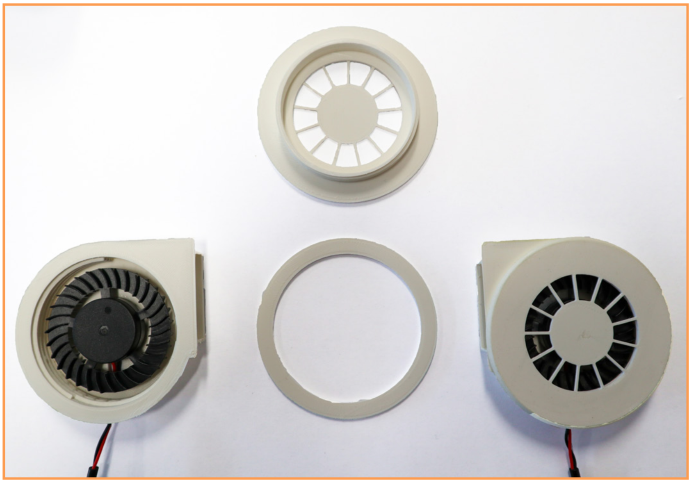


Figure 49: Fan casing

13. WATER CIRCULATION

The emphasis on the first part was the air circulation with the product itself, and how it cools down the skin temperature. The second part of the cooling system consists of the water circulation.

13.1 PRELIMINARY TEST

Thus far, only research concerning water spray in combination with a cooling garment from phase change material, along with water spray on its own, had been explored. There is lack of evidence to support the theory that water spray in combination with additional airflow contributes to increased cooling, compared to water spray, which alone has been proven to be effective in reducing skin temperature. As a result, a test was conducted to determine whether or not using water spray in combination with additional airflow resulted in better cooling performance. This test can be interpreted as proof of concept that this product's core function works as intended. Furthermore this gives a good indication of how big the improvement would be compared to the performance of air flow alone.

	ΔT_{skin} (°C)
Fan speed 1	0.6
Fan speed 1, with water	3.2
Fan speed 2	2.1
Fan speed 2, with water	5.2
Fan speed 3	1.7
Fan speed 3, with water	3.0

Table 7: ΔT skin measured during the test

For this test the fan from the first tested jacket (chapter 5.1) was used, together with a water spray, which is used to spray plants. The test was performed during 10 minutes on all settings, and then compared with the results of the test which only used the fan as cooling. To measure the skin temperature iButtons were used. The test set-up was the same as in Chapter 5.3 but with water spray added. The results of the test can be found in figure 50. Figure 50 proves that utilizing water in combination with air flow is superior when it comes to cooling down skin temperature, compared to only using air flow.
The actual differences can be found in table 7. To calculate the differences the first peak was ignored. The conclusion is that the fan with water spray cools skin temperature significantly better than a fan alone is able to.

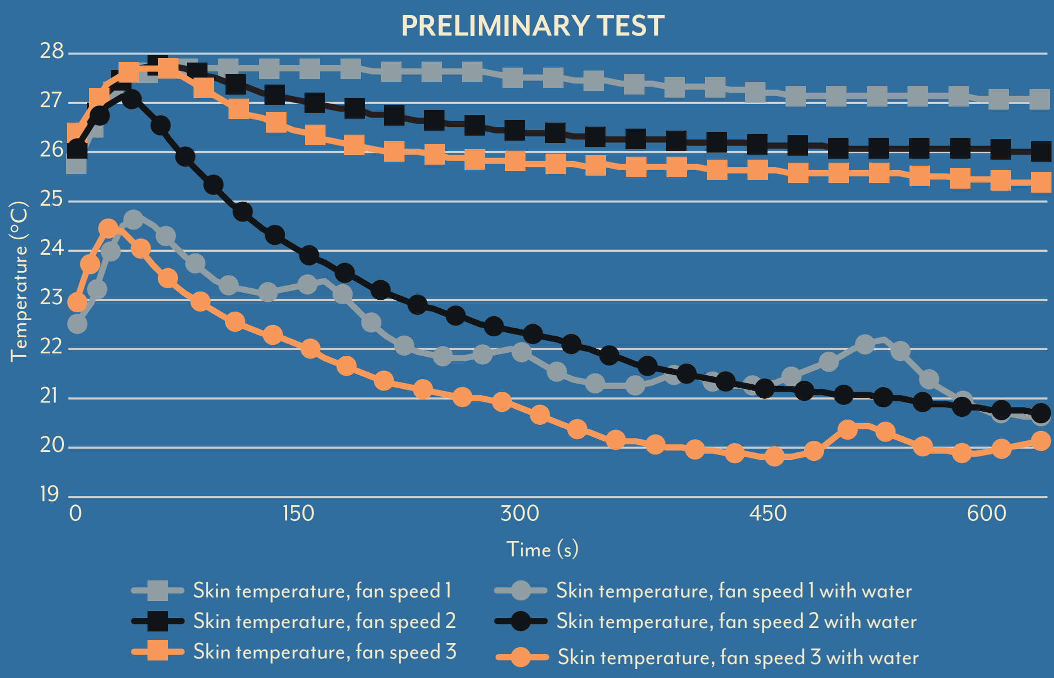


Figure 50: Graph preliminary test

13.2 DIFFERENT POSSIBLE WATER SYSTEMS

There are two options for the water function of the garment: electronic or manual. A necessity for the future is to create a system that has the possibility to be automated whilst remaining reliable, and would trigger the currently potentially available manual systems to be phased out. When looking into automated watering systems and sprays there are two main groups. There is the piezo atomizer, which uses high frequency to create mist or using a pump to build a pressure in tubing.

Piezo atomizer

The piezo atomizer is a device that transforms water into a state resembling mist. This is done by the atomizer producing a high frequency, which creates small water droplets. These are so small that they are perceived as mist. The water is absorbed from the bottom of the atomizer and emerges through the top as mist. Therefore, in order for it to function it is required that the top is not submerged. To implement the piezo atomizer within the prototype shirt would require it to have its own dedicated water supply. This was achieved by putting them through partially sealed plastic bags, where the piezo atomizer was penetrating the center, resulting in an outlet for the mist on the opposite side. This is shown in figure 51.
The viability of the atomizer was tested by placing two of these packages in a shirt and measuring the skin temperature with iButtons. The atomizers were placed below the outlet of the fans, in order to avoid immediate evaporation due to exposure to direct air flow. The test was conducted for 16 minutes, with both front fans and atomizers running. The result showed that there was no difference in temperature as demonstrated in figure 52.

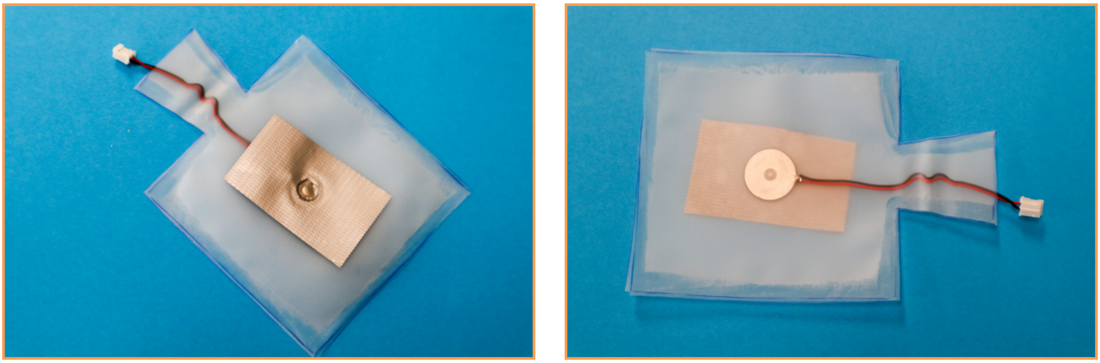


Figure 51: Piezo atomizer for prototyping

Water pump

The second option for the water circulation was making use of a water pump. A suitable water pump for this project would be a centrifugal water pump. The water pump works by forcing out water and is mainly used to transport fluids. For testing, the MakeBlock water pump was used, which operates at 12 V (figure 54). In order to conduct tests with the pump a 3D printed add-on was created. The inlet and outlet of the pump were originally both 6.5 mm in diameter. The outlet has since been decreased to 4 mm. This add-on was essential since the required surgical tubing was 3.6 mm, which needed to be attached to the outlet. The technical drawing for the add-on can be found in Appendix L.

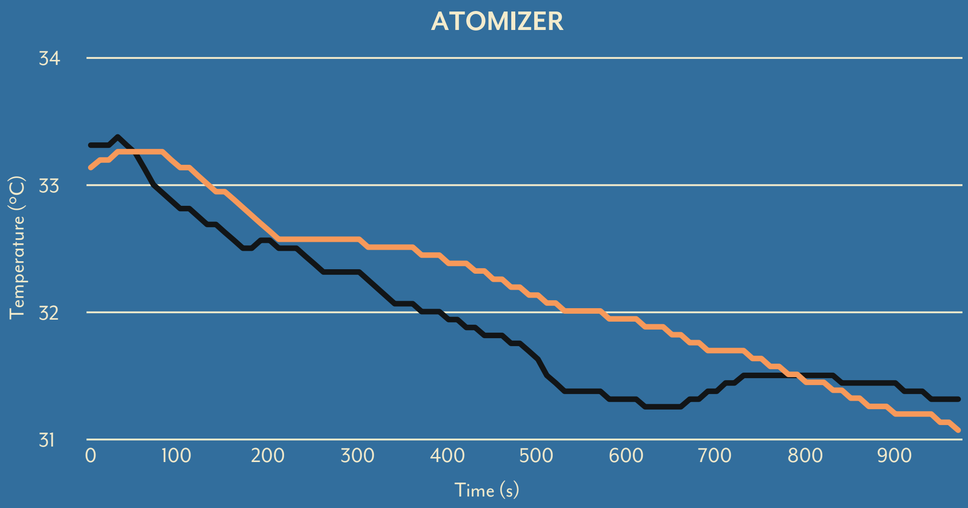


Figure 52: Graph fans versus atomizer and fans

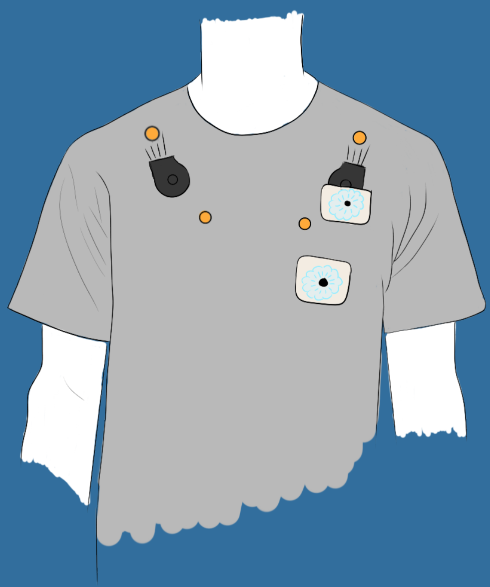


Figure 53: Positioning of atomizers and iButtons

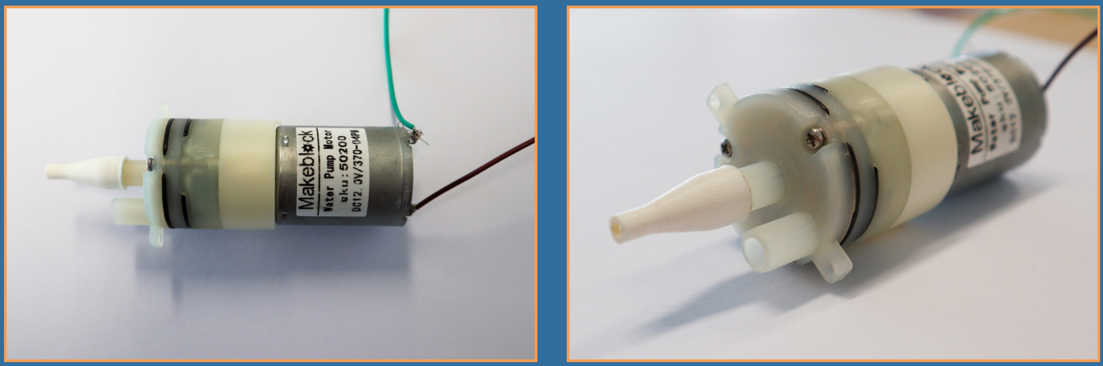


Figure 54: Used water pump

13.3 WATER PUMP VARIABLES

As mentioned earlier the Make Block water pump operates at 12 V DC and the sizing is 27 mm by 75 mm. It can pump 1 to 1.2 Litres per minute. However, for the testing a 9 V power source was selected, to achieve less litres per minute of water. When looking at the Arduino code for this pump (figure 56), there are four different variables that can be changed. The motor speed (0 to 255) when it is on, and the time it is on (in milliseconds), and the motor speed (0 to 255) when it is off, and for how long it is turned off (in milliseconds). Each of these variables influence the pump in a different way. To see the effects for each variable, three settings to alter the values of were selected, while keeping the other variables constant. The graphs in figure 57 show the effects of the settings when altered. The constant settings can be found in table 8.

onSpeed	125
onTime	16
offSpeed	35
offTime	25

Table 8: Constant setting of water pump

When looking at the change of water going out per step, the highest impact is reached by the offTime. If the motor is off for a longer period of time, there will be less water travelling through the tubes. The onSpeed and onTime are quite equal in impact, and transport around 75 mL more water when the value is upped by one. The offSpeed has the lowest impact, since the motor barely transports water at that speed.

13.4 WATER PUMP SETTINGS

By testing multiple speeds, and knowing the impact of the different variables, an average setting was concluded. The average setting was based on the goal of reaching the male sweat rate from chapter 10, which was 147 mL per hour. The settings are found in table 9.

onSpeed	118
onTime	14
offSpeed	35
offTime	29

Table 9: Constant setting of water pump

```
int motorPin = 6;
int FanPin1 = 5;
int FanPin2 = 7;

void setup()
{
  Serial.begin(38400);
  pinMode(motorPin, OUTPUT);
  pinMode(FanPin1, OUTPUT);
  pinMode(FanPin2, OUTPUT);
}

void loop()
{
  motorOnThenOffWithSpeed();
  analogWrite(FanPin1, 255);
  analogWrite(FanPin2, 255);
}

void motorOnThenOffWithSpeed()
{
  int onSpeed  = 118;                           // a number between 0 (stopped) and 255 (full speed)
  int onTime   = 14;
  int offSpeed = 35;                           // a number between 0 (stopped) and 255 (full speed)
  int offTime  = 29;
  analogWrite(motorPin, onSpeed);
  delay(onTime);
  analogWrite(motorPin, offSpeed);
  delay(offTime);
}
```

Figure 56: Arduino code used for waterpump

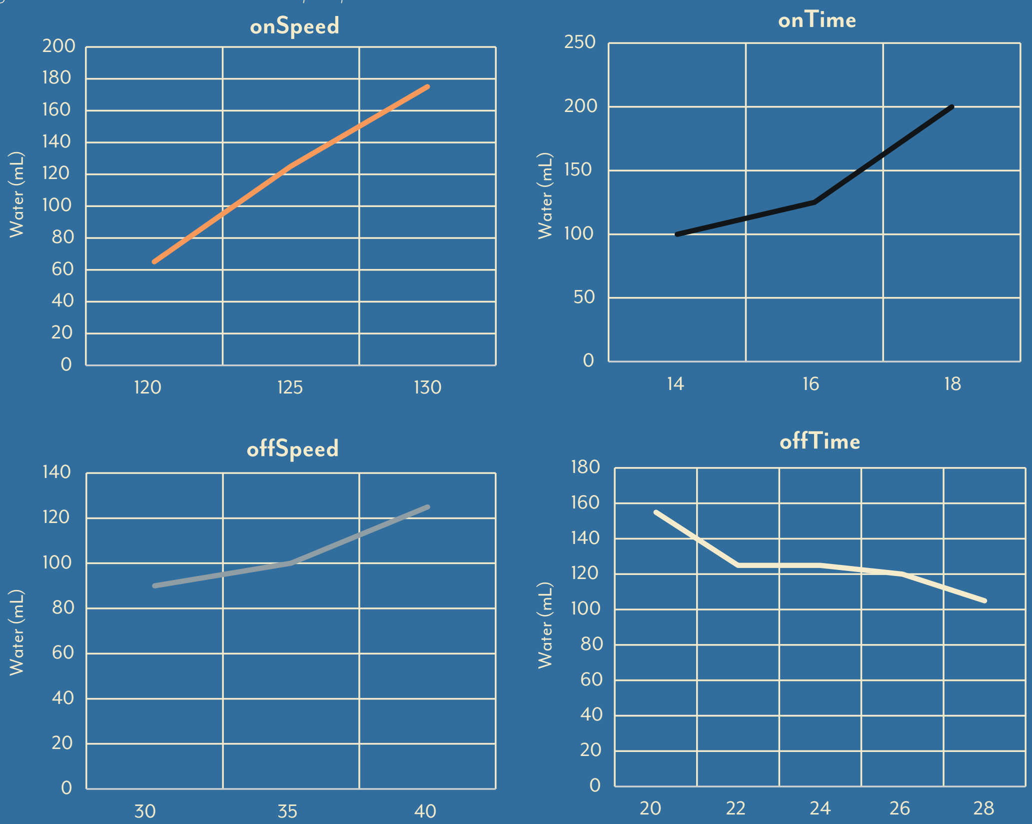


Figure 55: Water pump variables visualised

13.5 TUBING

In order for the water pump to function, tubing must be added since it is not included in the box. The ingoing tube provides the pump with water, and the outgoing tube helps transport and distribute the water

The water hole diameter for the pump is 6.5 mm. During the prototyping stage the incoming water went through a silicone tube with an inner diameter of 5.3 mm.

The outgoing tubes are the ones that will be implemented into the product. Fashion Designer Linda Plaude advised to use 3.6 mm tubes, due to having been tested and used in an earlier project, and felt comfortable when coming into contact with the skin. The water needs to be distributed across the chest, shoulders, and back in the form of small droplets. This is expanded on in chapter 10. Since the upper back and chest have the highest sweat rates, the tubing of the water pump will be placed at the collar of the shirt. Simultaneously, this is the optimal place to prevent excessive liquid dripping, which can cause damage to the skin due to additional friction.

The tubing needs outlets in order to distribute the water equally along the upper body. These outlets are 3D printed using the Ultimaker 2+ (figure 57). Each of these outlets are defined with the help of the sweat maps and heat maps. In figure 58, 60 and 61 the current tubing is shown. The red part is the connector to the tube towards the motor (technical drawing for this part and the normal outlets are found in Appendix M). This connector is currently placed at the back of the shirt. The measurements between each outlet are shown in figure 59.

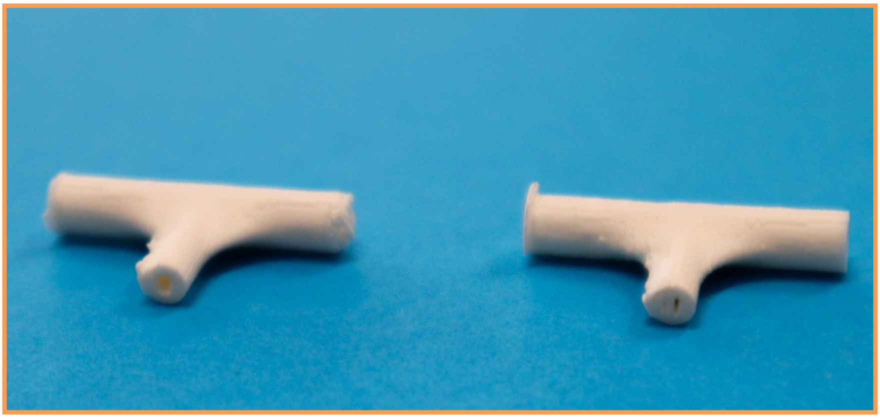


Figure 57: Outlets, left for connection to motor, right for outlet of droplets

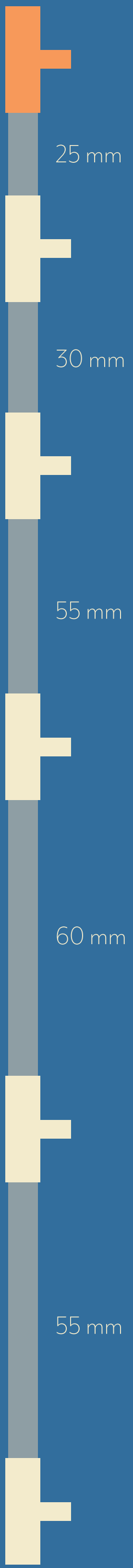


Figure 59: Tubing sizes


Figure 58: Tubing used for testing


Figure 60: Tubing at the collar


Figure 61: Placement tubing shown in prototype

14. CONCEPT TESTING

With the air and water circulation defined in the product, its effectiveness needs to be tested. To test this the shirt has been equipped with four fans, and the watering system has been attached to one side. iButtons were used to measure the skin temperature during the test. Four were used to place on the skin (shoulder and back on both sides), and the fifth was used to measure the ambient temperature. The pump speed was set to 118, and a measuring cup filled with 800 mL of ambient temperature water used as the water supply. This was done to see the water consumption during the test. The test was 30 minutes long while the participant was in a resting state. The settings of the water pump can be found in table 10.

During the test, the test subject did not wear anything under the shirt, except a bra. It is imperative to note that the test was carried out under conditions in which an able-bodied person would not sweat, as well as the fact that an able-bodied person's thermoregulatory system would react to the decrease of skin temperature. The feedback from the first test concluded that the initial droplet of water felt cold and unexpected, but that you eventually got used to the feeling. The side with the water system feels colder than the one without, which means that the product also changed the wearer's thermal sensation. After around 18 minutes goose bumps appeared, which indicates that the body is trying to retain warmth.

The excessive water ended up at the waist, which is right below the point where the waterproof fabric ends. The back of the shirt was also against the skin, which decreased the air flow within the shirt. After 30 minutes the back was perceived as feeling the coolest. The shirt showed exactly where there was an excess of water, since the fabric became half see-through in this place. The most excess of water was found at the back, and under the armpit. During a 30 minute test, 50 mL of water was used. This did not reach the minimum sweat rate of 147 mL per hour, although as previously noted, this was not in a situation where the test subject would normally sweat. The results of the test can be found in figure 62. It has to be noted that the iButton on the left chest failed, and only produced four measurement points. These points can be used as a guideline for how the results would have been, but it would only be an indication due to lack of certainty. As displayed in the graph, the skin temperatures on the side with the water system have decreased up to two times more. Both the temperature sensors reached close to the ambient temperature within 30 minutes.

onSpeed	118
onTime	20
offSpeed	5
offTime	20

Table 10: Setting water pump

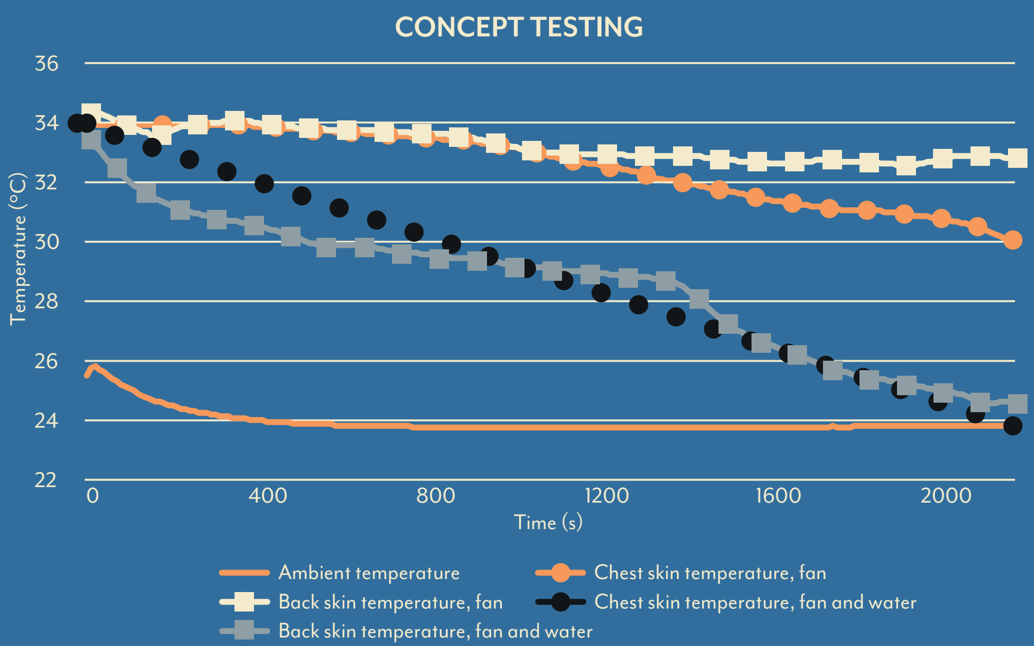


Figure 62: Concept testing

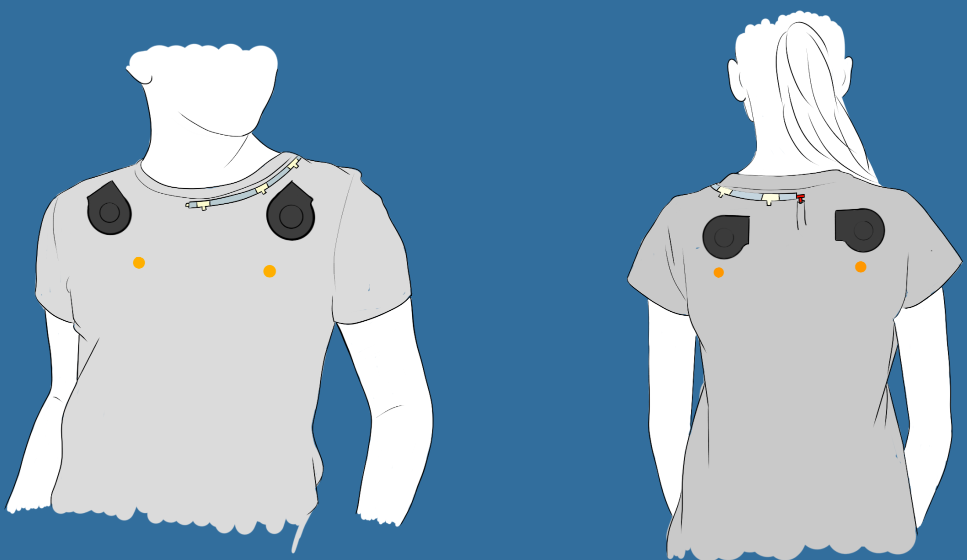


Figure 63: Concept testing setup

15. LOOKS

The product is an everyday product that the user wears instead of a normal shirt. The main target group for the shirt, within the scope of this project, are males aged 20 to 29 years. This age group has been chosen based on the demographic information about people with a spinal cord injury. This information states that males between the ages of 20 and 29 years carry the highest risk, alongside 70+ year old males (World Health Organisation, 2013). The situation where the shirt will be used is outside during the summer, to support the user during a situation where an able-bodied person would normally sweat. Together with fashion designer Linda Plaude several requirements have been set up in order to know what to aim for when designing the shirt. The requirements together with an explanation can be found below.

- Avoiding dark colours. Dark colours make the product warmer while the goal is to cool down the user. Therefore, it is preferred to make use of lighter colours.
- Made of breathable fabric, such as cotton.
- Normal round neckline. The tubing with outlets is placed around the neckline of the shirt. Therefore, the most practical solution is to have a shirt with a normal neckline.
- Short sleeves. In the summer most people wear either short sleeved shirts, or sleeveless shirts. To make the product resemble any other shirt, a choice was made to select a short sleeved shirt.
- Side seams. People with a spinal cord injury might struggle, or perhaps need help with, putting on the shirt. Opening the side seams and/or shoulder seams can assist with the process of putting on the shirt. These side seams are then closed with either Velcro or magnetic buttons.
- Not tight fitting. The shirt contains fans and other electronics. To disguise the abnormality of the shirt and for extra comfort, a decision was made to have a loose fitting shirt.
- Fabric needs to have structure. The shirt contains multiple rigid parts, which can be heavy and defom the shirt. Therefore, the shirt should have structure in order to keep its shape, while having all the electronics present.

Other than these requirements the shirt should contain the fans, water reservoir, controller with batteries and air tight fabric at the upper chest and upper back.
With these requirements settled shirts for males have been researched. On the right page you can find an overview of males shirts on the market. The shirts are either uni colour or contain a pattern. Together with Linda Plaude three options have been chosen to use as inspiration and start designing the shirt for the final test with. These three options can be found in figure 64.

Figure 64: Inspiration for looks

The first option was selected as an inspiration because of its vinyl print on the chest. This could be an aesthetically pleasing way to integrate the fans into the design of the shirt. The fabric for this shirt is stretchy, and the model is tighter than desired. However, the look is sportive, but at the same time something casual that can be worn outside the gym. The second option is more loose and casual than the first option. The shirt is made out of cotton and is constructed by connecting the parts with laser bonding, instead of needle and thread. This shirt has space to create a custom vinyl print at the top, allowing for easier incorporation of the fans into the shirt's design. The last option makes use of colour blocking. This design creates a separation between the upper and lower part of the shirt, and could be a way to implement the airtight fabric into the product's design.

With these shirts as inspiration the shirt in figure FIXME was selected for the final user tests. The shirt is from Lyle & Scott and is called "PANEL STRIPE - T-Shirt print" which was obtained from Zalando. These shirts are made from 100% cotton and have a round neckline. For the prototypes the colours grey marl/white and blue dust/navy were chosen.

Figure 65: The two shirts that were used for testing

15.1 FORM STUDY

Based on the chosen shirt, a form study has been conducted. The goal of this form study was to find a way to implement the fans without it looking out of place. The chosen design will be applied to prototype. The studies can be found in figure 66.

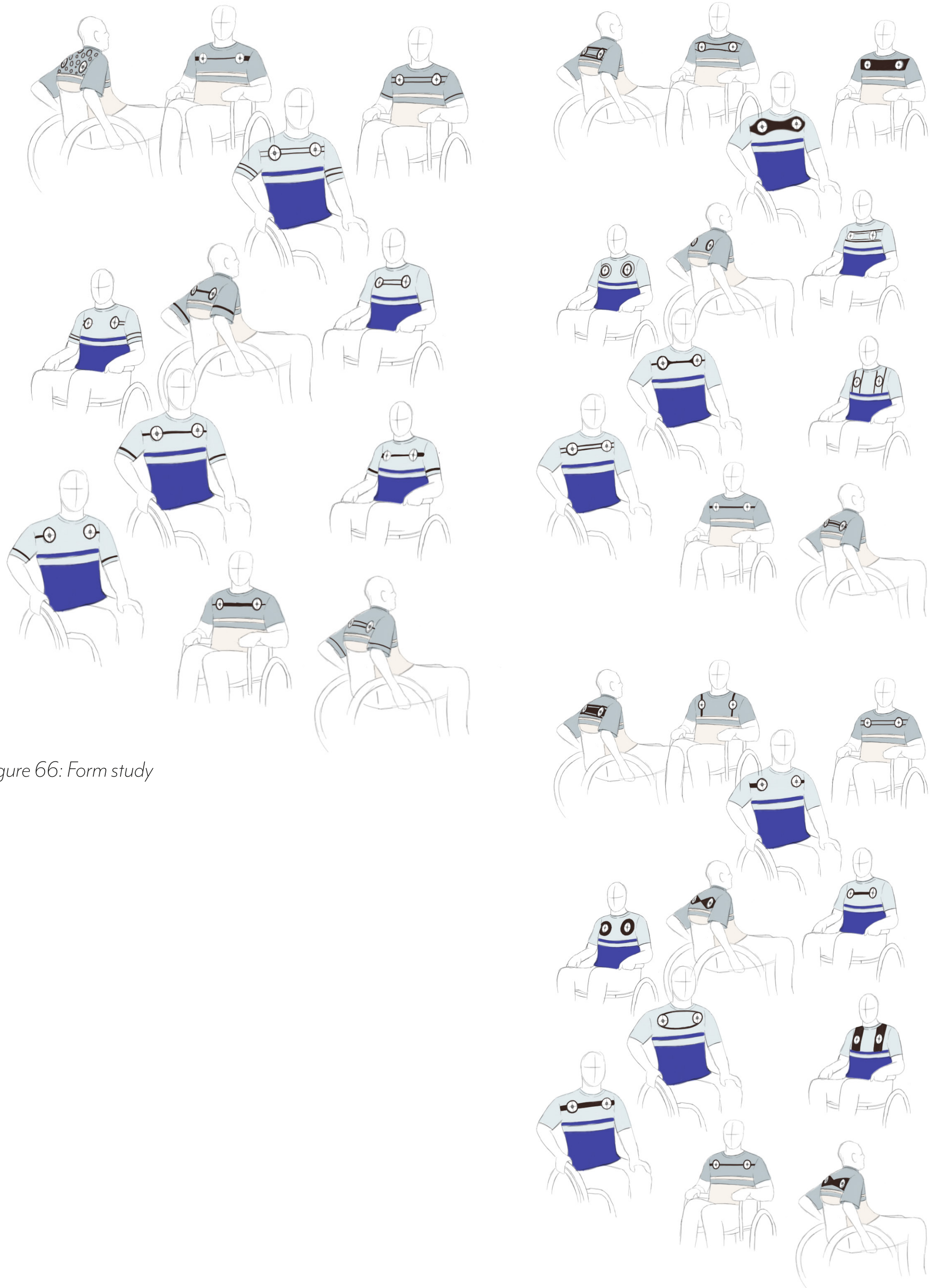


Figure 66: Form study

FINAL DESIGN

With the ideation completed and tested a final design was made. This design is a product that implements all the findings of the testing and research. Firstly, the main design is shown together with the prototype used for user testing. Secondly, the user test results are explained, the electrons, user scenario, and the rough estimated costs.

aba26us (2017)

16. FINAL DESIGN

VENTS is a wearable cooling shirt for tetraplegics. The goal of the shirt is to help to stay cool during a warm day. The shirt looks just like a normal shirt and is made of cotton fabric. The product contains an integrated air and water cooling system together with a water reservoir. The user only has to wear the product and turn it on to enable the product to keep the user cool. With the help of the included temperature sensor it registers the skin temperature. When the skin temperature increases it will start the cooling. The cooling starts with the four integrated fans which create extra airflow to optimize the convective heat loss. If the fans alone are not enough cooling, the water cooling will start. With the help of a water pump the water will be distributed at the collar of the shirt to drip down the body, and evaporate by the airflow created by the fans. If the water runs out you can easily refill it by opening the pocket on the right shoulder and pour water into the water reservoir. The whole system is managed by a controller and powered by a battery pack. While the electronics and water pump share the same box they have their own individual compartments inside of the box that separates them.
The electronics could either be placed in a pocket on the side of the shirt, or could be strapped to the wheelchair. This depends on the users own preference.

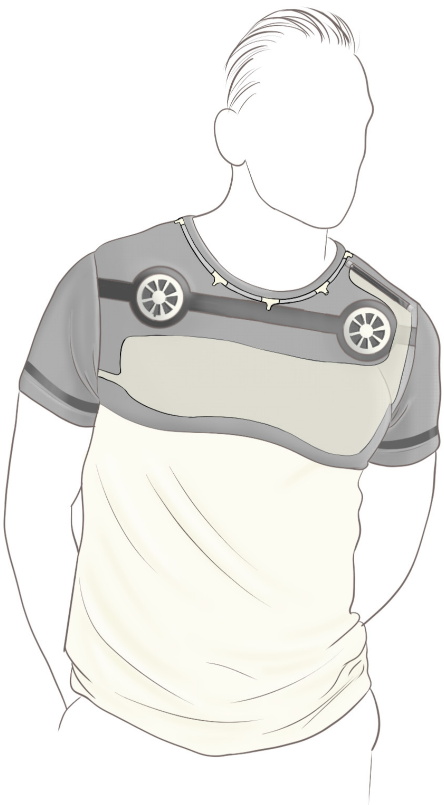


Figure 67: Placement tubing and water bladder

Figure 68: Front and back view of the product.

16.1 PROTOTYPE CREATION

The goal of the prototype was to test how well the product functioned, and to see if the product caused any discomfort. In order to exempt bias due to the lack of style, an entirely new prototype was made which is representable for how it should look once it is on the market.
The prototype is built up with different parts, namely the outer shirt, an inner airtight layer of fabric, a water reservoir, electronics, and tubing. During the user testing phase of the prototype, the water reservoir was in place, but not used.

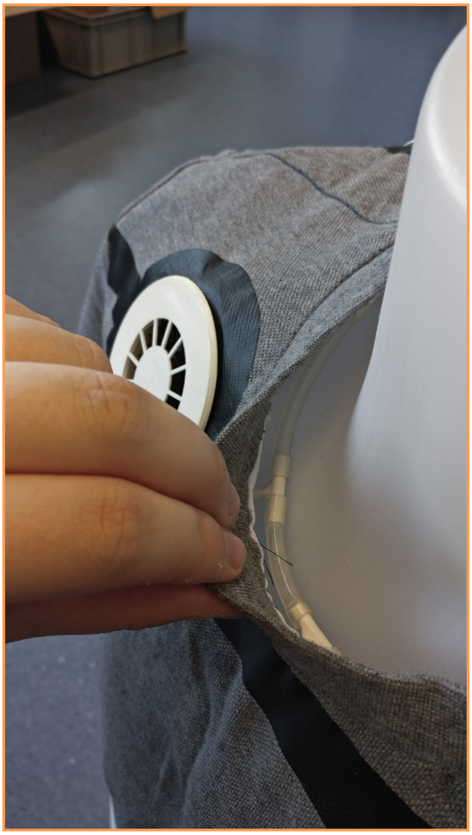
As previously mentioned, the outer shirt is a PANEL STRIPE - T-Shirt from Lyle and Scott. On the outside vinyl is added, in order to make the areas of the fans more stiff, and to incorporate the fans in the whole design. The inner fabric used for this specific prototype is Taslan Para fabric. This fabric is water and air resistance. The water reservoir is made by using PE (Polyethylene) sheeting and cutting these in the wanted shapes. Once this was done the edges were heated to create a bond between the different layers, in order to make it waterproof. The tubing used is surgical tubing of size 3.6 mm and 5.3 mm. For electronics, four centrifugal fans with a diameter of 60 mm, two Arduino Nano controllers paired with a Grove Board, one MakeBlock water pump, one MOSFET, and lastly a 9V battery were used. Photos of the prototype can be found in figure 69.

Inside of the shirt, showing the air tight fabric

Figure 69: Finished prototype

Attachment of the water reservoir to the zipper

Pocket to fill the water reservoir



Placement of the tubing at the collar

17. USER TESTING

The user testing has been conducted in order to test if the shirt causes any discomfort while wearing it, to gather first impressions in regards to looks, and a general overview of the effects. For this test four people participated, aged between 53 and 61. Two of the participants were males, and two were females. The first two tests were done outside in the sun at 16.8°C, with the temperature of the water being 15°C. The last two tests were conducted at 20.7°C ambient temperature, and at 19°C water temperature. The main research questions for these tests are:

- Does the product give any discomfort during a long time period?
- What are people's impressions on the shirt?
- Does the product cool the whole upper body?

17.1 DISCOMFORT

To answer the first research question the participants have been asked to wear the product for 30 minutes while sitting down. During these 30 minutes they had to fill out a discomfort map of the upper body at the 0, 15, and 30 minute mark. Then they had to grade each area on the chart, where 1 is no discomfort and 10 is high discomfort. The reason for measuring discomfort is because the product is not made with additional comfort in mind, but could be seen as discomfortable to wear after a long period of time. The results of the discomfort map can be found in Appendix N. The main opinion regarding the shirt was that some of the cables caused discomfort at times. This could be due to the fact that the cables of the fans are quite thick and stiff at the start, and therefore might feel unconventional against the skin. The back fans were seen as less comfortable than the front fans. For some people the fans were on the shoulder blades, and consequently they were slightly angled, which caused pressure and made the experience more discomfortable. For females the lack of stretch in the airtight fabric caused a slight discomfort, because it extends into the breast area, causing pressure. At the 15 minutes mark all participants graded the discomfort as higher. The main reason given for this was that they felt cold. Three of the four participants were wearing short sleeved t-shirts before the test, and none of them were sweating due to heat. Therefore, the drop in temperature was likely seen as discomfortable, because it was seen as an unnecessary action by the body. Between the 15 and 30 minute mark there was less difference than between that of the 0 and 15 minutes mark. The average discomfort map of all three times can be found in figure 70.

17.2 IMPRESSION

During the testing period people expressed their impressions of the shirt. All the participants knew about the product's objective beforehand, and that it uses fans and water. The first participant said "I expected more fans, but there are only four." when she first saw it. Another comment that was said

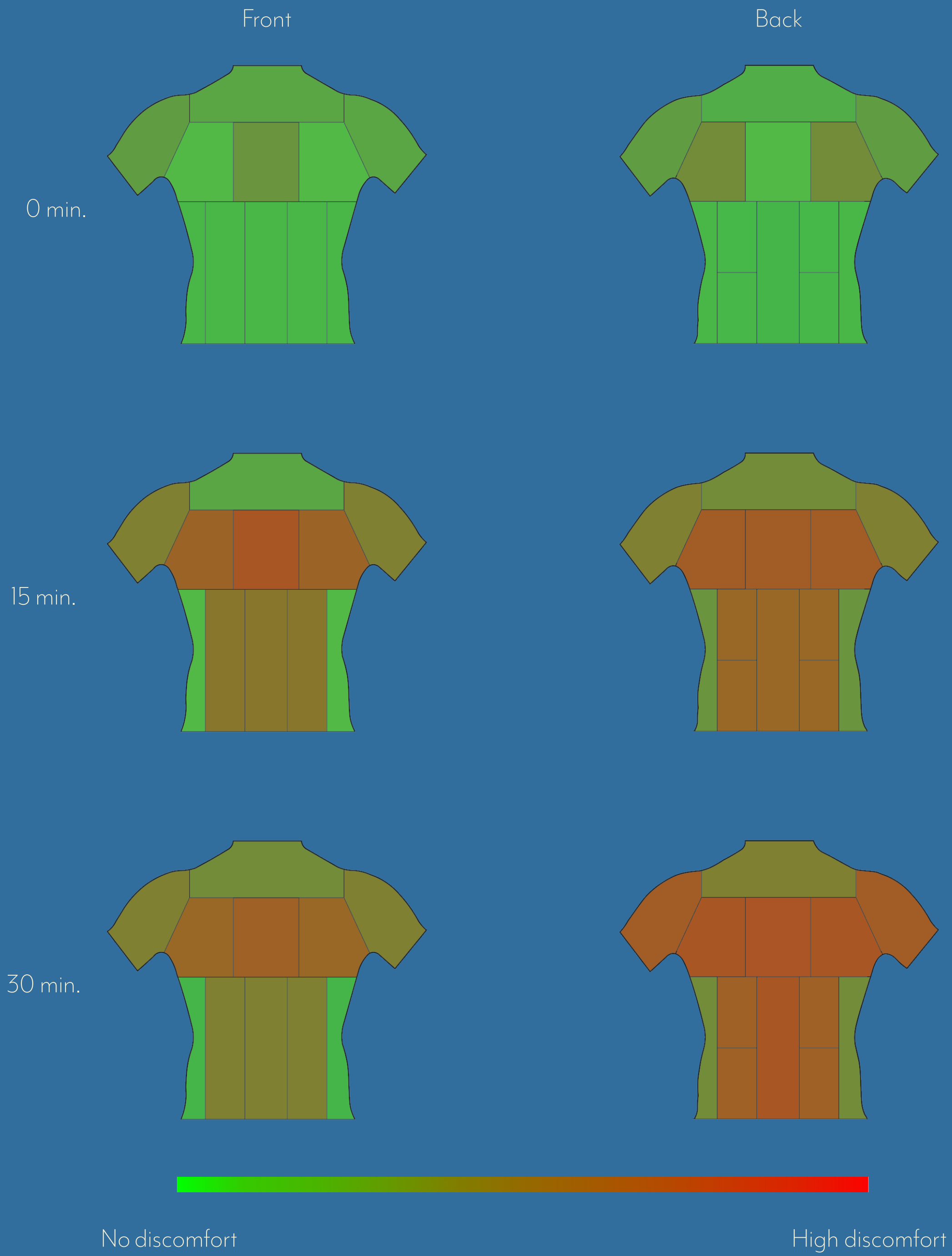


Figure 70: Discormfort maps

is that the shirt looks sporty. The general opinion was that the shirt looked fine. When inspecting it up close, you can see that the shirt has electronics incorporated into it, but from afar it will appear as a normal looking shirt for other people. One user thought that the fans were quite loud, especially if you rotated your head. Multiple people thought that the product would be nice to use either during work, or when it was around 30°C outside. People saw potential in using it during their daily lives.

17.3 COOLING

The shirt is designed to cool the upper body with the main focus being on the upper back and chest. To see the effect of the shirt on the participants a thermogram was taken both before and after the 30 minute test. The pictures are taken with the FLIR TG165, which is an imaging IR Thermometer. The emissivity was set to 0.6. This must be set to 0.98 for images with persons, but due to a mistake this was all done at 0.6. This should not influence the results when comparing the pictures, but the actual temperatures will be shown as lower than what they are in the pictures. In figure FIXME, it can be seen that every participant had a lower skin temperature than before the testing began. The thermograms of the back mainly show an improvement at the top of the back, whereas the front seems to have an overall more equal cooling. The reason as to why it was primarily the upper back that got cooled could be explained by the fact that at least two participants were sitting in a chair with a low backrest. The backrest restricted the water and air flow in the lower back area, which would also be the case for people in a wheelchair.

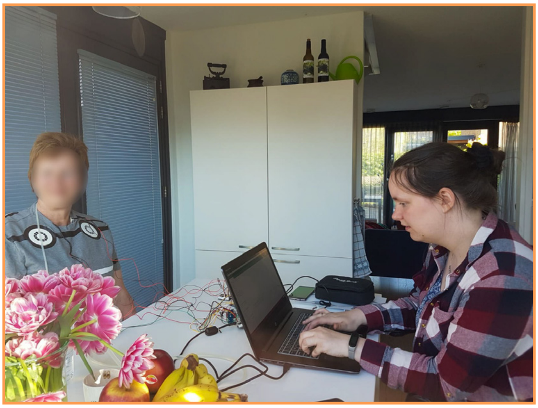


Figure 71: Testing with participants

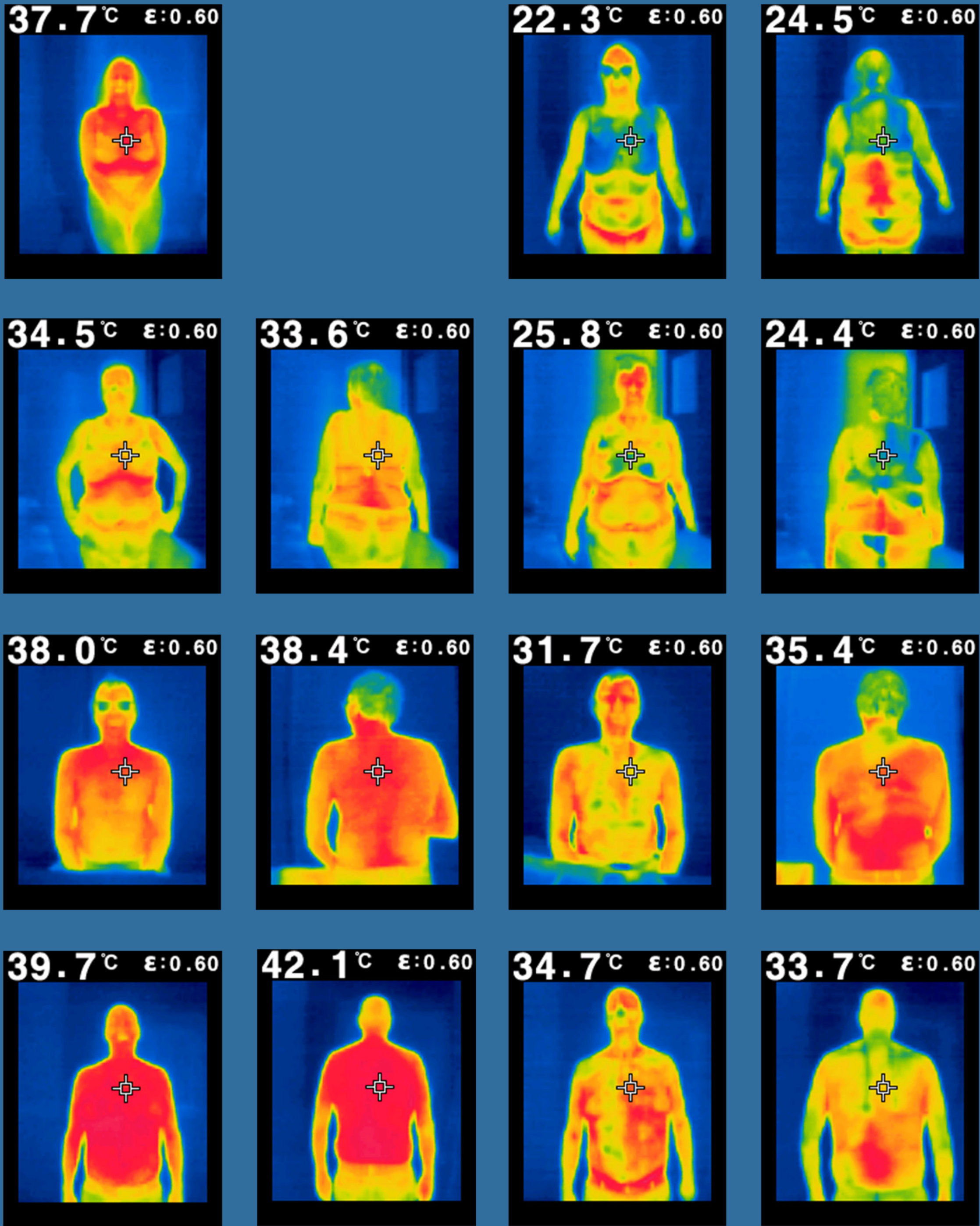


Figure 72: Thermograms of the participants

18. AUTOMATED SYSTEM

Despite the goal of the product being to cool down the user, it should not overcool the user. To prevent overcooling, and to not rely on the users own input, it was decided to have an automated system that relies on a sensor, to measure the skin temperature. The optimal solution for this would be a sensor measuring core temperature. However, these are often invasive and/or not reliable.

18.1 SENSOR

When looking into an automated system for the shirt there is a need for a sensor. The sensors that have been used throughout the project were iButtons. However, to test the automated system, a sensor was chosen that could be connected to the Arduino. For the testing a Grove - Temperature & Humidity Sensor (High Accuracy & Mini) was chosen. This specific sensor was chosen for its size and accuracy. Originally there was an idea to work with the humidity and temperature, but this was eventually never used. To measure the accuracy of this sensor compared to the iButton, a small test was conducted. Both sensors were placed on my arm for about 10 minutes. In figure 73the graph can be found that corresponds with this test. As shown, the Arduino sensor gives a higher temperature than the iButton, with a maximum temperature difference of 0.84°C. The values of the Arduino sensor also fluctuate more than those of the iButton. To make an automated system, a more accurate sensor is needed.
A thermometer like the DS18B20 could be used, but to acquire accurate values from the sensor, calibration of the sensor is needed at least once or twice a year.
The placement of the temperature sensor would also be critical in the design for measuring correct values. An optional placement would be at the armpit or the neck. The armpit would in this case be more practical than the neck, as it would be possible to integrate into the shirt since it has short sleeves already. The placement for tetraplegics needs to be tested, to conclude if an alternative placement could generate reliable results.

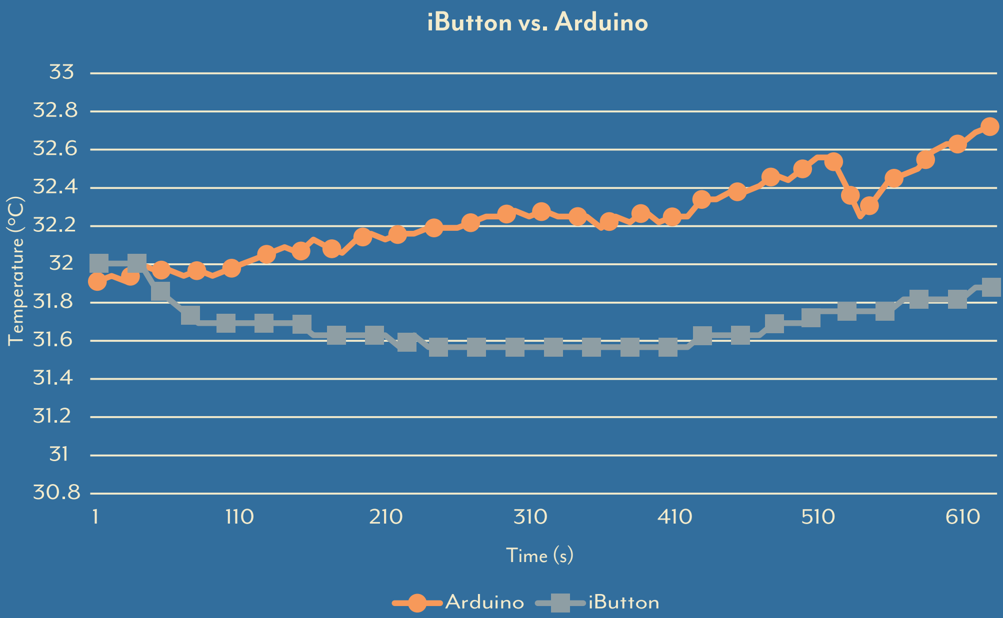


Figure 73: iButton versus Arduino

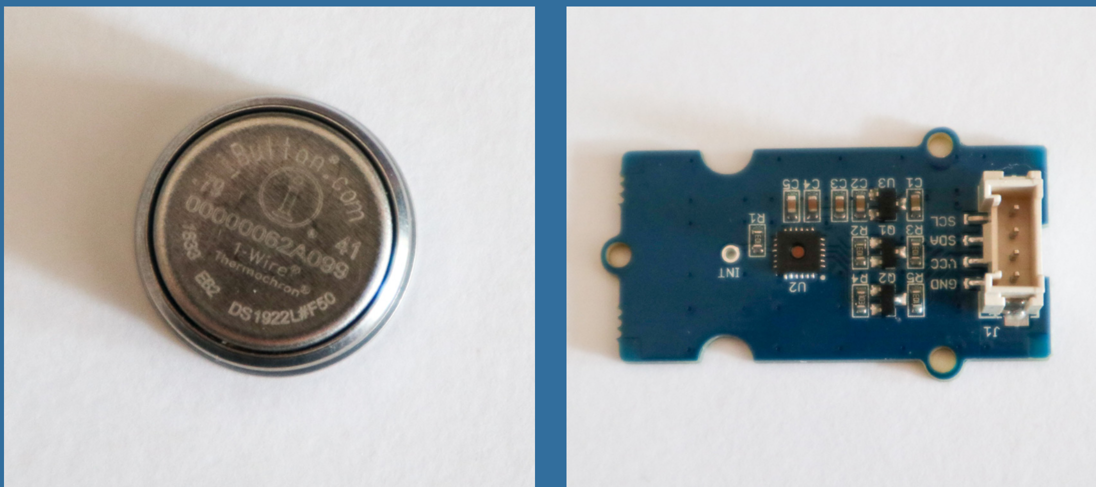


Figure 74: iButton (left) and Arduino sensor (right)

18.2 PROGRAMMING

Such a program needs multiple components to make it work. You need a controller, for example the Arduino, a sensor, and an actuator. That is how an automated system looks like in general. The actuators in this case are the four fans and a water pump, whereas the sensor is the temperature sensor. There are two options concerning how to program the system. You can work with threshold values, for example when the sensor measures above 33°C the fans will start, or you can work with the temperature differences. The second option would be making use of a PID controller. For now the first option is selected, currently making it possible to use different stages of cooling. The sensor measures the skin going above the threshold value, and starts all four fans to cool down the skin. However, in some cases the fans alone might not be enough. To fix this an implementation is made, so that when it reaches another temperature threshold it will also start the water pump. The Arduino code that could be used to achieve this can be found in figure 75.

```
#include <TH02_dev.h>
#include <Wire.h>

int motorPin = 6;
int Fan1 = 10;
int Fan1val;
int Fan2 = 11;

void setup()
{
  Serial.begin (9600);
  pinMode (6, OUTPUT);
  pinMode (Fan1, OUTPUT);
  pinMode (11, OUTPUT);
  TH02.begin ();
}

void loop()
{
    float temp = TH02.ReadTemperature ();
    float humi = TH02.ReadHumidity ();

    if (temp<33{
        Fan1val = 0;
        analogWrite(Fan1, Fan1val);
        analogWrite(Fan2, Fan1val);
        delay(1000);
      }
    else {
        Fan1val = map(temp,27,31,0,255);
        analogWrite(Fan1, Fan1val);
        analogWrite(Fan2, Fan1val);
        delay(1000);
    }
        if (temp<36){
         analogWrite(motorPin, 0);
        delay(1000);
       }
    else {
        motorOnThenOffWithSpeed();
         delay(1000);
    }

    Serial.print("Temperature:");
    Serial.print(temp);
    Serial.print(",");
    Serial.print("Humidity:");
    Serial.print(humi);
    Serial.print(",");
Serial.print("Fan Speed:");
    Serial.println(Fan1val);
}

void motorOnThenOffWithSpeed()
{
    const int onSpeed = 125;
    const int onTime = 16;
    const int offSpeed = 40;
    const int offTime = 20;
    analogWrite(motorPin, onSpeed);
    delay (onTime);
    analogWrite(motorPin, offSpeed);
    delay(offTime);
}
```

Figure 75: Arduino code for automated system

18.3 ELECTRONIC CIRCUIT

When making the automated system the electronic circuit will have two Arduino Nanos, one DS18B20 temperature sensor, four fans, and one water pump. A possible electronic circuit is shown in figure 76. Each Arduino controls two fans, and the sensor or the water pump. The Arduinos would be required to communicate with each other to determine if the signals of the sensors indicate whether or not the fans and water pump need to be on.

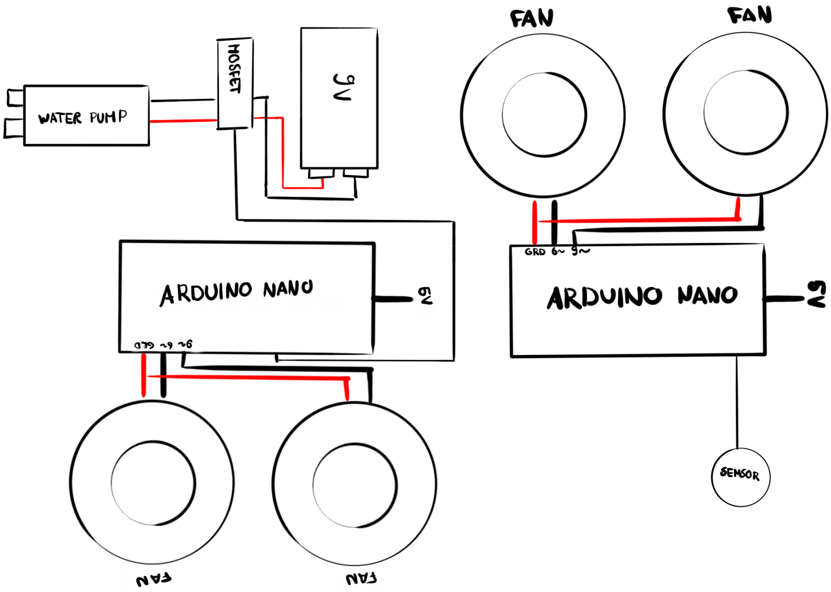


Figure 76: Drawing of a possible electronic circuit

18.4 POWER USAGE

As mentioned earlier the product needs a battery. The battery powers the fans, motor, and sensor. The voltage, current, and power for each part are shown in table 11.

	Current (A)	Voltage (V)	Power (W)
Fan	0.3	5	1.5
Water Pump	0.32	9	4.9
Temperature Sensor	0.004	5	0.02

Table 11: Details of electronic components

With these specifications and a minimum battery life of 4 hours for the product, the mAh (milliampere hour) can be calculated. The mAh is calculated with the total ampere. The product consumes 1,520 mA when using the fans and water pump at maximum performance, which translates into 6,100 mAh. This is the minimum capacity that the battery would need in order to use the product for 4 hours. Currently, the power bank market is mainly dominated by 10,000 mAh power banks, which would be enough for this product. However, there are power banks on the market with 20,000 mAh, which could give the product at least 12 hours of battery life.

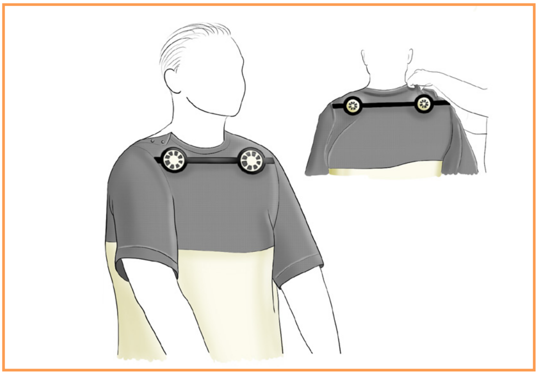
19. USAGE

With the system and product defined, further research will be made on how the user should interact with the product. The user scenario includes turning the product on and off, the feedback the user receives during this process, the feedback about the remaining battery life, and when the fans and/or motor will turn on.

19.1 USER SCENARIO

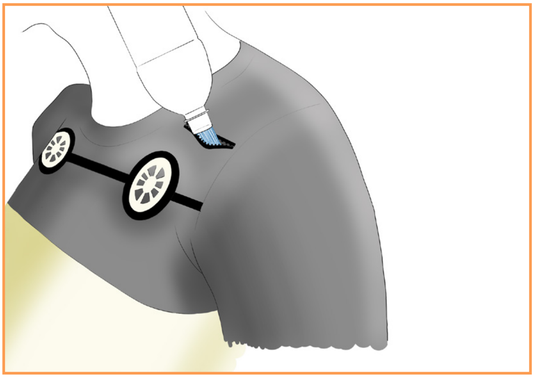
In order to define the interaction between the product and the user, a user scenario was made. This scenario shows the whole process of how you could use the product. The steps are as follows:

- Putting the shirt on
- Turning the product on
- Go outside, normal day activities
- Fans go on
- Water pump goes on
- Battery power depleted
- Charging the product
- Turning the product off

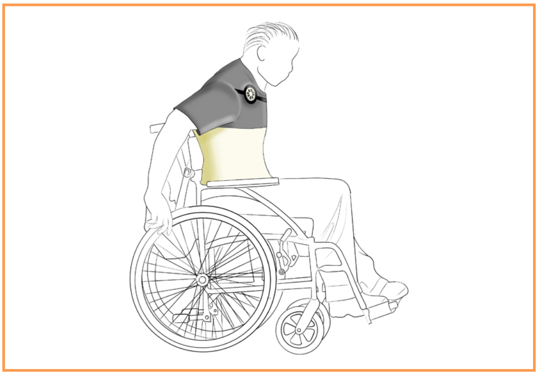


When the user wants to use the product for a day, they firstly have to put it on, and then screw in the fans. To make the shirt easier to put on, the right shoulder seam is open and can be closed with magnetic buttons. This step is often done with the help of a caretaker.

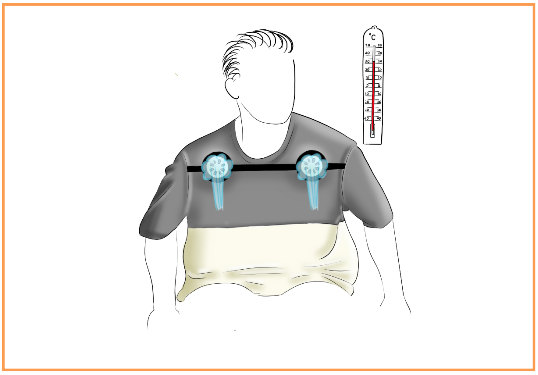
In order to turn the product on, the user has to press the on/off button on the controller for an extended period of time. All lights will light up as feedback to inform that the product is now on. The connector from the fans and water pump also need to be plugged into the power supply.



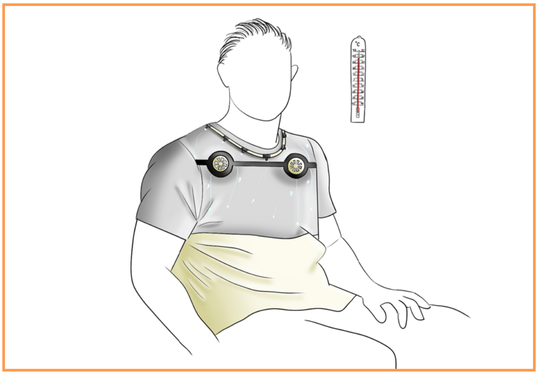
Once the product is turned on, the user/caretaker fills the shirt's water reservoir with water. The pocket to fill can be found on the shoulder, for easy access.



The user is now free to go out and do what the user had intended to do that day.



Once the sensor measures a too high skin temperature it will turn on the fans. The fans are the first phase of cooling down the user.



If the fans alone are not sufficient enough to cool down the user, the water pump will turn on to increase the maximum cooling capacity of the product.

Once the user returns home and does not require the product anymore, they can turn off the product by holding the button for an extended period of time. To check the battery power, a short press of the button will by using four lights indicate at what percentage the battery is currently at.

19.2 FEEDBACK

As seen in the user scenario, the user will receive feedback from the controller about the battery status and whether the product is on or off. The user will be dependent on the product, and it could cause dangerous situations when the product malfunctions, or when the battery depletes during usage. In order to avoid this last situation, another feedback must be implemented. This can be in the shape of a light on the shoulder, sleeve, or on the chest. But it could also be a sound the product makes when the battery power is low. Due to the time constraint, it has not been possible to do further research together with tetraplegics. The user themselves should provide opinions as to where they would like to see such feedback, and how they want to be notified in such a situation.

20. MANUFACTURING

The goal for this product is to eventually go into production, and support people with SCI to keep them cool during warm days. To have an idea about the costs, the possibility of manufacturing of such a product is explored. This includes the making of the shirt, electronics, and assembly. These will result in an average cost, which will be different from the actual cost, but will give an insight as a rough estimate.

20.1 PRODUCTION SIZE

To get an insight into the production costs, it must be determined which production size the product will have. Around 8,000 to 10,000 persons have a spinal cord injury in the Netherlands (Dwarslaesie Organisatie Nederland, 2017). Around 62% have a high lesion (Dwarslaesie Magazine, 2018), which results in 4,960 to 6,200 people with a high spinal cord injury. Not everyone with a high injury will have problems with their thermoregulation, and not everyone will buy the product. Therefore, for now the production size will be limited to 20% of the 4,960, which results in 992 units.

20.2 MATERIALS

The materials of the product define the looks and the feel, but also has the function of the product in mind.

Outer fabric

The outer fabric must be like that of any other shirt, breathable and comfortable to wear in the summer. Cotton is chosen as the main fabric for the shirt. This decision has been made since cotton is a breathable fabric, and is able to absorb any water that has not yet been evaporated. This will ensure that the water will not drip to the lower body. The evaporated water needs to be transported outside the shirt, and therefore it is important to have a breathable fabric. Cotton feels soft to the touch and does not irritate the skin.

Inner fabric

The function of the inner fabric is to keep in the water and create an airflow. In order to achieve this there is a need for an airtight and waterproof fabric. During the test a participant mentioned that the change from cotton to the inner fabric was not very comfortable. This could be due the fabric being used in the prototype not being stretch. Therefore, to increase the comfort, the inner fabric should also be stretch fabric. An example of such a fabric is GORE-TEX Fabric with Stretch Technology (Gore Fabrics, 2020). This fabric is water and windproof, as well as being stretchy.

Fan casing

The fan casing needs to be UV and water resistant. The polymer should not be conductive either, in case the fan becomes faulty. The weight of the fan casing should be lightweight, in order to reduce the overall weight of the product. And lastly, the polymer must be as cheap as possible. All these properties of the polymer can be found in Polyethylene (PE). This material is widely used in other products and is resistant to fresh and salt water, food, and most water-based solutions (CES EduPack software, 2019). PE is cheap and easy to mould and fabricate.

Electronics

The whole electronic system is built up using a controller, four fans, one water pump with tubing, temperature sensor, and a power supply. Each of these parts can be bought separately, and would not have to be produced by the company that produces the product.

Water bladder

The water bladder can be made of PE or waterproof fabric. The edges of the bladder will be sealed together and access to this bladder will be provided by a zipper on the left shoulder.

20.3 PRODUCTION AND ASSEMBLY

The production of a garment is normally done by first sending a pattern to a patterns expert. This person will adjust the pattern and produce it in multiple sizes. Once the patterns are ready to be used for manufacturing they will be sent to a company that CNC cut fabric (Thompson, 2014). CNC cutting cuts multiple layers of fabric at the same time, which makes the whole process more efficient. This process leaves a clean edge and makes efficient use of the fabric by leaving as little space between each part as possible. The edges can still fray after the CNC cutting, and it is therefore advised to overlock the edges to avoid this. Before all the parts are attached together, the vinyl print should be pressed applied.

Once all the parts are cut, they will be joined together. This will be done on a sewing machine using a normal lock stitch. During this process the water bladder must be added as well, since this will be between the outer and inner fabric.

The fan casing will be injection moulded, which requires a mould. For such a small production size, injection moulding comes at a high cost. The mould for such a product would be at least $13,500 (Rex Plastics, 2013), which translates to $13.60 per product. After this project is completed, more research is required in regards to the manufacturing methods and costs involved in making this product.

The electronics will first have to be soldered together and assembled. The fans need to be glued into their casing, and connectors must be made in order to separate the electronics and the shirt, to make the product washable.

The controller, battery, and water pump can be in the same case with a clear separation between the electronics and the water pump. Putting these three components in one case will limit the complexity of using the product, since the user would only have to plug in the wires from the fans, and tubing for the water pump.

20.4 COST ANALYSIS

The production cost of such a product depends a lot on where it is produced and assembled. According to fashion designer Linda Plaude the selling price of the shirt will be five times the cost of the material. However, this will be without the electronics. The bill of material for the shirt and the electronics can be found in table 12 and table 13. The length and sizes of these components are based on personal experience working with fabric. For the actual price of such a product it is advised to talk with the company that will produce it. This calculation is only meant as an overview of the cost it can reach, rather than an exact cost.

No.	Part Name	Material	Weight [g]	Area [m^2]	Length [m]	QTY	Total price [$]	Source
1	Outer fabric	Cotton	-	2	-	-	2.40	Alibaba [1]
2	Inner fabric	GORE-TEX Fabric with Stretch Technology	-	1	-	-	Estimated at 6.00	Backpackinglight (2007)
3	Waterproof zipper	Plastic			0.15	1	0.45	Alibaba [2]
4	Water bladder	PE		0.5			0.87	Alibaba [3]
5	Magnetic button (10mm)	Metal				3	0.03	Alibaba [4]
6	Vinyl print	Vinyl			0.3		0.90	Alibaba [5]
7	Thread				10		0.17	Alibaba [6]
8	Tubing	Latex			1		0.10	Alibaba [7]

Table 12: Bill of materials of the product without electronics

No.	Part Name	Material	Weight [g]	Area [m^2]	Length [m]	QTY	Total price [$]	Source
1	Fan casing	PE	73.16	-	-	-	0.99	CES EduPack software (2019)
2	Fan					4	6.00	Alibaba [8]
3	Water pump					1	1.50	Alibaba [9]
4	Battery	Lithium-ion				1	0.10	Alibaba [10]
5	Sensor					1	1.00	Alibaba [11]

Table 13: Bill of materials of the electronics

The overall price without the electronics included is $10.92, which translates into €10.09 at the time of writing this. The overall price for all the electronics including the fan casing is $9.59, which equates to €8.86. This results in an overall material cost of $20.51. When considering Linda Plaude's statement that the selling price would be 5 times the cost of the material, it would mean that the product should sell for about $102.55. It must be noted that this is a rough estimation, and the actual price will likely be higher, because the production of the fan casing was not accounted for.

EVALUATION

The results have been evaluated with the help of the Fiale model and were used to see the effectiveness in different climates. The limitations of the research and how they could have affected the outcomes will be discussed. Recommendations were made to show what the next steps would be for future research

Pinterest (n.d.)

21. FIALE MODEL

To evaluate the effect of the product, earlier test results have been used to fill in the Fiale model. The Fiale model is a thermophysiological model in which there are certain variables which influence the outcome. This program has been used to give a rough estimate of the heat loss of the product. Once this has been defined, it is reviewed how the product works in different situations. The full results can be found in Appendix O.

21.1 SIMULATION 1

The heat flux says something about the energy per square meter. In order to find the heat flux of the product, the test results of chapter 13 were used. The first step was to create a control test. This test was done at 23.6°C and 40% humidity, and 1.0 MET. The scope of the model is 37 minutes, the same length of time as the earlier test. When running the model it shows the following effect:

	Start	End
TRectal (°C)	37.01	37.15
TSkin average (°C)	32.53	30.80
TThorax anterior (°C)	33.52	31.76
TThorax posterior (°C)	33.19	31.11

Table 14: Fiale model, control group, 23.6 °C, 40% humidity, 1 MET

	Start	End
TRectal (°C)	37.01	37.15
TSkin average (°C)	32.53	30.80
TThorax anterior (°C)	33.52	31.76
TThorax posterior (°C)	33.19	31.11

Table 15: Fiale model, 240 W/m², 23.6 °C, 40% humidity, 1 MET

This shows that the skin temperature rises and the core temperature goes up. The next step was to re-enact the results of the earlier conducted test. This was done by trial-and-error until the thorax skin temperature reaches the same end temperature as during the test. In order to achieve this a heat flux of 240 W/m2 was used. This results in a body heat loss due to the extra cooling of 28.47 W on average

21.2 SIMULATION 2

All the tests so far have been done at a maximum of 24°C, which were situations where the participants did not sweat themselves. Therefore, research was done using the Fiane model at 35°C and 80% humidity at 1.0 MET for 37 minutes. This is the climate the sporters will have to endure in the Tokyo Olympic Games of 2021, and is seen as one of the highest risk climates for overheating. The results of the control test can be found in table 16. The results of the test with 240 W/m^2 as heat flux can be found in table 17.

	Start	End
TRectal (°C)	36.98	37.12
TSkin average (°C)	35.21	35.49
TThorax anterior (°C)	35.16	35.49
TThorax posterior (°C)	35.14	35.49

Table 16: Fiale model , Control test, 35 °C, 80% humidity, 1 MET

	Start	End
TRectal (°C)	36.98	37.25
TSkin average (°C)	35.21	34.44
TThorax anterior (°C)	35.16	25.91
TThorax posterior (°C)	35.14	25.91

Table 17: Fiale model , 240W/m^2, 35 °C, 80% humidity, 1 MET

The results show that at 35°C and 40% humidity the product still cools down the skin with 9.58°C, compared to the control group. However, the core temperature did increase with 0.23°C. This could be due to the vasoconstriction in the skin of the thorax, to ensure that the heat will go to the core. Due to the limited heat production, the body does not need extra heat loss. The average body temperature, which is calculated by (0.3*TSkin average + 0.7*TRectal), is slightly lower with the cooling.

21.3 SIMULATION 3

While all the previous tests have been done while sitting down, you will however produce more heat while being active. See 1 MET. For this simulation the activity level got changed. For the MET value, the wheeling at self-chosen speed was used, from Popp et al. (2018). This value is around 3.8. For the simulation in Fiale model 4.0 METs is used. The whole simulation was identical to the previous one, except for; the activity level, 35°C, 80% humidity, and 4 MET for 37 minutes.

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	Start	End
TRectal (°C)	36.98	38.07
TSkin average (°C)	35.21	36.02
TThorax anterior (°C)	35.16	36.19
TThorax posterior (°C)	35.14	36.19

Table 18: Fiale model , Control test, 35 °C, 80% humidity, 4 MET

	Start	End
TRectal (°C)	36.98	38.05
TSkin average (°C)	35.21	35.43
TThorax anterior (°C)	35.16	32.25
TThorax posterior (°C)	35.14	32.25

Table 19: Fiale model , 240W/m², 35 °C, 80% humidity, 4 MET

While all the previous tests have been done while sitting down, you will however produce more heat while being active. See 1 MET. For this simulation the activity level got changed. For the MET value, the wheeling at self-chosen speed was used, from Popp et al. (2018). This value is around 3.8. For the simulation in Fiale model 4.0 METs is used. The whole simulation was identical to the previous one, except for; the activity level, 35°C, 80% humidity, and 4 MET.

21.4 CONCLUSION

During the hot conditions, all the temperatures rose even when using the product. However, the rise in temperature was slower than what it would have been if the cooling product would have been used. The cooling ability of the shirt does get less over time, which can be explained by the person's own thermoregulation. Once the skin cools down the natural heat transfer will be lowered. This effect is not expected to be there for tetraplegics. These simulations show the potential cooling effect at higher temperatures and humidity.

22. DISCUSSION

The requirements which were defined after the research need to be present in the product together with as many wishes. However, during the research there has been several limitations found which could influence the outcome of the research. This chapter will finish with recommendations for further research and a conclusion concerning the research.

21.5 EVALUATION ON BASIS OF REQUIREMENTS AND WISHES

At the beginning of the project several requirements and wishes were set up. These were to ensure that the product would solve the problem definition, suit the users, and integrate all the information of the research. These were all split into several main topics; usage, function, design, materials, safety, and maintenance.

Usage

In the end, the simulation with Fiale shows that the product decreases the rise in core temperature for able-bodied people. However, it has not been possible to test the product with the intended user group, the tetraplegics. This is due to the Coronavirus, and since this user group is already prone to infection, it was not possible to test directly with them. Therefore, it cannot be concluded that the product will decrease their rise in core temperature. or if the product is easy to take on and off. Using a standard 10,000 mAh power bank, it is possible to use the product for at least 6 hours. This is calculated while having the whole system turned on, including all the fans and the water pump.

Function

The product made everyone feel cool and even cold during the testing. The discomfort that the users experienced was mainly due to the cooling ability of the product. The product is able to work fully automatically with the help of a sensor added, which controls the air and liquid cooling. The cooling is mainly focussed on the upper body, which means the upper chest and upper back. The air flow helps with convection, and the liquid cooling enables evaporative cooling and conduction.

Design

The product weight should not exceed 2 kg when the water, the battery, and the water pump are all added. For four hours of usage a male needs 600 mL of water, which equals 600 grams. The battery can weigh up to about 300 grams, and the fan casing is 73 grams. This means that there is almost 1 kg left for the actual shirt, fans, and electronics.

Materials and maintenance

The shirt is made of cotton with an extra layer of air tight fabric at the upper chest and back, to keep the airflow inside. The fans and electronics are all removable, which makes the shirt washable.

Safety

To ensure the product does not create any pressure points, a research was conducted. In this research, people were asked to grade their discomfort while wearing the shirt. The only comments were the wires which were stiff and thick electrical wires, and can definitely be improved upon while the product is manufactured. The product needs to be adjusted to the person, e.g. a woman normally sweats less than a male. However, if the same differences occur in tetraplegics is currently unknown and needs to be further researched.

Wishes

According to the research of Griggs et al. (2015), the optimal cooling would cover about 40% of the body surface. The product cools mainly the upper chest and back, but the cooling takes place across the full torso, which was shown in the thermograms. The torso accounts for about 36% of the full body area, which is close to the advised 40%. It is unlikely that the product will be able to prevent hyperthermia, but it could temporarily postpone this inevitable outcome. The duration of the product is defined by the power and the water source. If you refill the water bladder and replace the battery, the product is ready to be used again.

22.1 DISCUSSION OF LIMITATIONS

Throughout the project there have been several limitations, which could have influenced the outcome.

Tested on able-bodied

All the tests which have been conducted were done with able-bodied participants. Therefore, the reaction of tetraplegics is still unknown. Due to the current situation in the world with Corona and the limited participants with tetraplegia, it was decided to test on able-bodied participants. By doing this it also reduced the risk of undercooling, and creating pressure points for the tetraplegics

Limited generalizability

All the research has been performed with limited resources, and a small number of participants. Even though there was a trend found in the research, larger groups are needed for significant data. All the participants for the physical tests were from the Netherlands, and only the input from the InspiredSCI forum members were acquired from outside the Netherlands.

Limited knowledge of cooling tetraplegics

There has been limited research in how cooling affects tetraplegics. Able-bodied people react when their skin cools down, which was confirmed in the Fiale model. However, it is uncertain if tetraplegics are missing this reaction, and if they do it is uncertain what happens with their body temperature.

Uneven starting skin temperatures

Multiple researches have been conducted throughout the project. The skin temperature differs during each test, since it was not possible to control the skin temperature. This could have influenced the research.

Undefined variables

During the research with participants, it was not written down what kind of clothing the users wore, and how much they weighed, together with their fat percentage. The environment's humidity has also not been measured. These factors could influence the measurements, and should have been taken into account.

22.2 RECOMMENDATION

More research could be conducted, and these are the following recommendations to explore:

Testing with tetraplegics

As mentioned in the discussion, the product has not been tested with tetraplegics. This would be the first step to take when continuing this research. Tetraplgics might react differently to the product, and it might be more effective for this user group in situations where a person would normally sweat.

Cost and production

The costs were only calculated for the materials needed, and did not include production. These costs will only give a rough estimate of the actual costs, since no decision has been made about the specific parts.

Testing in a warm climate and during activity

The product was mainly used in a condition where none of the participants were sweating, and therefore not in need of the product. A warming climate has been simulated in Fiale, but a test at 30 degrees would be preferable, and will show how the product will act in the real situation.

Filter the air through the fan

The main concern throughout the project was that you could get your fingers in the fan blades. This was addressed by making a fan grill, which prevented the insertion of fingers into the fan. However, when the product is used in a dusty environment, or a fly manages to fly inside the fan, it will be spread inside the shirt. The dust can also reduce the lifespan of the fan, which is not desired. Therefore, it must be researched if a filter could be placed in front of the fans. This could be a mesh for example.

22.3 CONCLUSION

The goal of this project was to create a cooling system for tetraplegics who have a dysregulated thermoregulation system. This is needed since this user group has a higher risk of hyperthermia, due to the fact that they have lost their ability to sweat and register their own body's temperature. Currently, people use a wet towel, water beads, water spray, or an evaporation cooling vest to cool themselves down. These ways of cooling have a limited duration. Another option would be the use of ice packs, but for this the user needs to have access to a freezer. Therefore, it was desirable to make an actively cooled product, which does not depend on a fridge or freezer, or needs to be removed to function again.

There has been limited research about how cooling tetraplegics influence their core temperature. However, there is a research that shows that water spray contributes to cooling down. It shows a significantly higher cooling ability for tetraplegics, compared to paraplegics and able-bodied (Trbovich et al., 2019). Based on this information, and together with the user's own input, a choice was made to look into a hybrid cooling system containing air and liquid cooling. The benefit of using a hybrid cooling system is the fact that it has been proven to be the most effective (Bongers et al., 2015).

VENTS shows that by using four fans and water droplets you can cool down an able-bodied person, and reduce their increase in core temperature. The access to active cooling throughout an entire day could enable more people to go outside during warm weather, without having to worry about the heat. This could for instance make it possible for people with tetraplegia to go outside for a longer period of time, without having to worry too much about their body's temperature. The signal of the fans starting to spin could also be used as an indicator to seek shelter from the sun, which could already be helpful for those who don't notice their own increase in temperature.

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