GRADUATION REPORT

APPLICATION OF POLYVINYL ALCOHOL (PVA) FABRIC FOR CYCLING CLOTHING

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Preface

With the completion of this graduation report, my time as a student at TU Delft is coming to an end. I am proud to present to you my graduation project "Application of Polyvinyl Alcohol (PVA) for cyclist clothing". I had a pretty tough time, last year especially with Advance Concept Design (ACD) course and I barely managed to get the minimum required credits to keep my resident permit. I consider myself to be very lucky for not only able to complete the masters in time but also meeting awesome people in last two years. I would like to thank the following people for helping me:

Friends
Tom, Fehmihan, Sonali, Julieta, Nithin, Sagar, Yasaman, Duco, Thijs and many more. Thanks for believing in me during times when I did not believed in myself. Megha, Daniel, Pablo and Stijn, second year was far better than the first and it was because of you guys.

Linda Plaude & Lennart Teunissen
You are truly passionate about Thermo Tokyo project and I feel it while working with you. Thank you for sharing your knowledge. I am 100% sure I had the best mentors.

Rein Bokslag
Thank you for providing an opportunity to work with Inuteq. I really liked your open-mindedness which was crucial for this project to be successful.

Arjen Jansen
From our first meeting I enjoyed talking with you. Thank you for understanding my way of thinking, it is greatly influenced by my mechanical engineering background and is not common for a design student. Your positive energy encouraged me throughout the project. Having you as a mentor was very important to improve my knowledge in design. Thank you for sharing your knowledge.

Relatives
I would like to thank my uncles Sachin and Sangram Patil. You have supported me in every decision I have taken in my life. Surat, Phaltan, Banglore, Delft and whichever place I have decided to go you have helped me. After my parents you are the people I look up to. You have definitely served as an inspiration for me.

Parents
Words are certainly not enough to express my gratitude to you. I am super lucky to have you. It has been 7 years I have been away which is more than enough to appreciate your importance in my life.

Summary

Cycling in hot and humid environment is demanding for the body. Olympics 2020 will be in Tokyo and the weather is expected to be hot and humid. Performance of the cyclist will be below par if they do not adopt various strategies to keep themselves cool. This project focuses on the development of new jersey with PVA fabric integrated in it to provide cooling to the body.

The design process for this project started with a thorough analysis of all thermal aspects of the human body and its environment, Tokyo weather, PVA material, and cyclist clothing. There are four heat loss pathways in order for the human body to lose excess heat: conduction, radiation, convection and evaporation. While exercising, the heat generated is usually higher than the heat loss which results in heat storage and thereby rise in core body temperature. Current and past cyclist clothing were studied. Aerodynamic features of the jersey were found to be crucial. Placement of smooth fabric at the attached flow region and vortex generator at the turbulent boundary region was found to be important in the jersey. Following the UCI rules and regulation is also important, therefore were analysed in depth. PVA fabric has excellent water absorbing properties (6-7 times its weight). The absorbed water slowly evaporates which cools the fabric and the fabric which in contact with the body, will cool the body. It was found that one, the cooling by PVA fabric is less efficient than cooling obtained by sweat and second, lycra had better cooling power. Therefore it was decided not to use PVA for cooling but for sweat management.

Following the analysis, a main problem statement was defined that will be the focus for the rest of this project with the goal to make the PVA fabric suitable for sweat management.

From the problem statement the ideation phase commenced. Several methods and creativity tools, were applied to explore all options and find the best possible solution to the problem. From this, two ideas were found to work well one, making holes in PVA foam and second, using PVA yarn. None of them was found to be superior to other, therefore both were selected for making final prototype.

After prototyping the jersey, they were tested in temperature and humidity chamber in Papendal sport center. Four participants participated in the experimental trial where they had to wear all three jerseys cycle for 30 min. Physiological and perceptual parameters were recorded of the participants. It was found that the new jersey developed in this project helped in reducing the mean and local skin temperature.

Therefore it was concluded that the new jersey could be used for the Olympics however more development is recommended to make it better.

Table of Contents

Approach

The project consisted of four phases that are inspired by the Design Council's (2005) "Double Diamond Design process": 'Discover', 'Define', 'Develop', 'Deliver'. In this project a cyclist jersey was designed using this design process. At the beginning of the project many of these stages were intertwined. At first, literature research was done to understand the context, cyclist requirements, heat impact on cyclist, PVA material and clothing. Ideation was started very early in the process, in unison with the literature research. Initially, Ideation using biomimicry and worst possible solution methods was done to generate many ideas. Information regarding biomimicry method can be found in Delft Design guide and www.interaction-design.org website gives information about the worst possible idea method. Couple of weeks later, when satisfactory knowledge was gained through the research, those ideas were tested in a temperature and humidity chamber to find the evaporation rate. The temperature and humidity chamber was also used to gain insight into the properties of the PVA material.

Interview with Prof.dr. S.J. Picken, expert in polymer technology was conducted to gain more information of the PVA material. Around this time in the project, primary focus was to improve the cooling power of the PVA material which could be obtained by increasing the evaporation rate. Later on it was found out through literature study and by experiments that one, the evaporative cooling of the body with sweat was more efficient than cooling with PVA material, second, cooling with wet lycra was more efficient than cooling with PVA So PVA was not used for cooling purpose. Another application of PVA material for the cyclist jersey was found, which was sweat management. So PVA was not used for cooling purpose. The main goal of this project is to make PVA suitable for sweat management purpose for cyclist clothing. A brainstorming session was conducted and few new ideas were explored.

The selection of the final idea for conceptualization was based on two parameter i.e. weight and cooling power. From the test, two ideas first, the PVA foam with holes and second, PVA yarn were found to be the best possible solution. The difference between them was negligible hence both of them were selected for the conceptualization stage.

The prototype was made and tested in a climatic chamber after the conceptualization phase. A schematic overview of the approach is presented in figure 1.

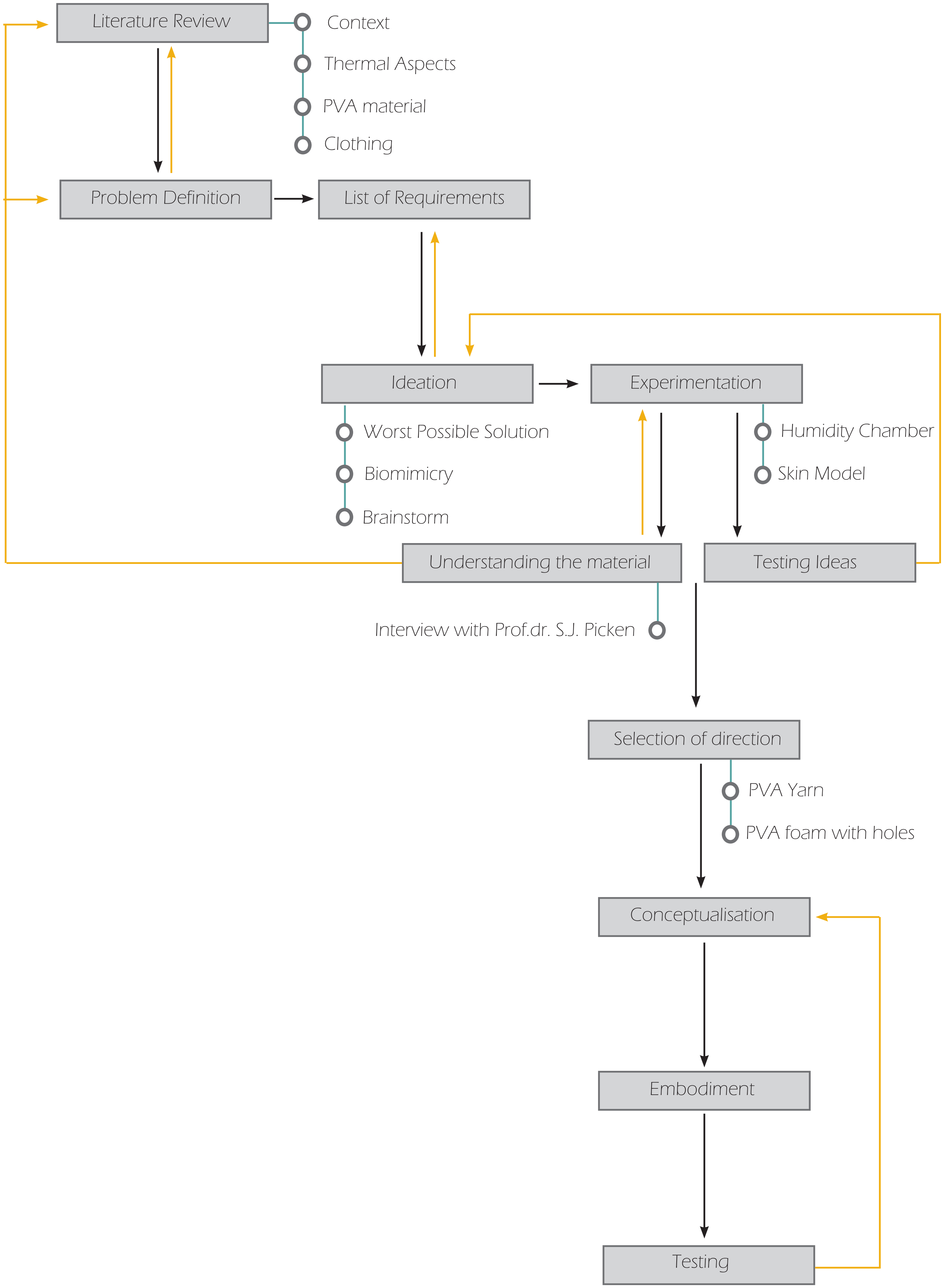


Figure 1: Schematic approach

01 INTRODUCTION

Summer Olympics 2020 will take place in Tokyo, Japan. It will be the first city in Asia to host the Olympic events twice. The event is scheduled from 24 July to 9 August 2020. During this time of the year, Tokyo is expected to be very hot and humid. Cycling is an outdoor event. Many cyclists during the road race will be exposed to this hot and humid environment. Exercise performed in these conditions can lead to excessive sweating, an increase in body temperature and attainment of a critically high body temperature. The metabolic rate also increases during exercise. The combined metabolic and thermoregulatory demands of exercise in the heat, place an exceptional burden on the circulation, more than can be met through cardiac output and blood flow redistribution. The reduction in performance in the heat by the athlete can be increased by progressive dehydration that results from sweat losses, with negative consequences for cardiovascular capacity and thermoregulatory function (Gonzalez Alonso et al., 1999)

Proper preparation can reduce the negative effects of a hot and humid environment, thus offering an advantage to the athlete who is well prepared. For this purpose different strategies can be used by athletes which include acclimation or acclimatization, heat experience, pre-cooling, hydration and proper clothing selection. The primary focus of this project is on clothing hence this report will focus on that aspect.

Inuteq is the manufacturer of cooling garments for leisure, sports and jobs which are exposed to extreme hot conditions. INUTEQ-PVA® technology uses Polyvinyl Alcohol (PVA), a superabsorbent chemical in the cooling garment. When the garment is immersed in water, it absorbs water. The garment provides cooling to the body by evaporating the absorbed water, using the latent heat of evaporation from the excess heat generated by the body during exercise. In this project PVA will be integrated in the cyclist clothing.

The goal of this project is to "design clothing for Dutch Olympic cyclists with PVA material integrated in it so as to reduce the rate of increase of core body temperature during a road race"

The project will be concluded with a demonstrator (a working prototype) that can be tested to validate the design and working principle.

1.1 About the company

INUTEQ® is a Dutch based, world's leading company in developing & manufacturing innovative personal cooling technologies and products. The name INUTEQ comes from merging the words Inuit and Technique. The Inuit are a group of culturally similar indigenous people inhabiting the Arctic regions of Greenland, Canada and Alaska, also called Eskimo's. With over 20 years of experience in personal cooling, Inuteq strive to create the ultimate solutions to fight heat stress and offer cooling relief expertly tailored to every situation.

There are various products offered by Inuteq which includes shirts for athletes, firefighters, and for leisure. Inuteq also sell cool packs with phase change material in it which can be used at different temperatures, (6.5, 15, 21, 29 degree celsius). Customers also buy cooling towels, wristband, hat and necktie which has cooling property. The manufactured products are based on one of the four technologies: Inuteq PAC®, INUTEQ-PVA®, INUTEQ-H2O® and INUTEQ-DRY®. Products with Inuteq PAC® technology uses phase change materials to provide cooling to the body. The phase change materials absorbs the heat of the body. This heat changes the phase of the materials, that means they transition from solid to liquid state or liquid to gaseous state. INUTEQ-PVA® technology use Polyvinyl Alcohol (PVA) a superabsorbent to cool the body by evaporative cooling. INUTEQ-H2O® also uses a different absorbent to absorb water and cools the body by evaporative cooling. This technology is less effective than INUTEQ-PVA® technology in humid conditions (Bokslag, 2019) therefore it is not used in the project, so the details about this technology has not been researched in depth. Products with INUTEQ-DRY® technology have pockets in which water can be stored. The body water can then absorb the heat to cool the body. This project will focus on INUTEQ-PVA® technology

Figure 2. Products sold by Inuteq. From the top left to bottom left, moving in a clockwise direction: Neck cool helmet, phase change material, wristband, cap, body cool shirt, cooling towel

1.2 INUTEQ-PVA®

INUTEQ-PVA® technology provides cooling to the body by evaporating the absorbed water. Higher the evaporation rate of water, higher will be the cooling power provided by the fabric. The evaporation rate of water into the atmosphere is a function of temperature, humidity, and air velocity (Hisatake et al, 1993). While cycling, the gradient of the road affects the velocity of the cyclist and thereby the air velocity. The speed can vary a lot depending on whether the cyclist is climbing or descending. The high humidity in Japan reduces the evaporation rate. In the next section, expected conditions in Japan has been analysed. In this project, many experiments were carried out in a humidity and temperature chamber and the setting used for those tests are based on this analysis

1.3 Road Race

Road bicycle racing is the cycle sport discipline of road cycling, held on paved roads. Road racing is the most popular professional form of bicycle racing, in terms of numbers of competitors, events and spectators. The rider has to ride around 250 km in a day to complete the race. The rider is tested on a flat surface, a climb and a descent. To make the course more selective, races often feature difficult sections such as tough climbs, fast descents, and sometimes technical surfaces. All the riders start the race simultaneously. In the early stages on the race all the cyclist are riding in a same group called as peloton but later some cyclist get out from this peloton and move ahead to it, this group is called as break away or break. Staying in the peloton can save as much as 40% of energy by reducing the effect due to the drag but any accident in a peloton can cause a serious of chain reaction of accidents which seriously damage cyclist chances of winning the race. Riding in the break can ensure that riders can maintain a higher speed than the peloton.. Individual riders can reach speeds of 110 km/hr while descending mountain roads and may reach 60–80 km/hr level speeds during the final sprint to the finish line. The average speed of the riders is around 40 km/hr

1.4 Tokyo 2020

The men's road race is scheduled on 25th July and women's on 26th July. The race will start at 12:00 in the afternoon and will last till the evening. Both the Men and Women's Elite road races will begin from Musashinonomori Park in the north western suburbs of Tokyo and ends at Fuji Speedway. The details of the course profile can be found in Appendix A. Forecast of the weather condition was found on the website of AccuWeather (https://www.accuweather.com) The temperature and humidity in Tokyo is given in table 1. The settings used for testing is 30°C and 85% Relative humidity (RH).

Place	Temperature (°C)	Average.Relative Humidity
Tokyo	26±2 °C	81±2%

Table 1. Temperature & Humidity at in Tokyo

The wind speed will depend on the speed the cyclist is riding the bicycle. The speed of the cyclist depends on the gradient of the road. The higher the gradient it is (usually when the cyclist are climbing a hill) the lower the bicycle speed will be the evaporation rate of the sweat. At 10% gradient, found in the Tokyo race track, the speed of the cyclist will be around 20km/hr. Therefore the frontal part of the cyclist body will have wind speed of around 20km/hr (5.5m/sec). At the back side the wind speed can drop upto 50% (Crouch et al., 2014) which is 10km/hr (2.7 m/sec). Less wind speed will have less evaporation rate .The least value of vaporation rate is important because at the least value, the fabric will hold the most sweat and therefore will be most heavy, which has to be avoided. This information is crucial during the later part of the project. Therefore the required condition is 30°C, 85% RH (2.7m/sec least wind speed for back side and 5.5m/sec on front side.)

02 DISCOVER

A mind map (figure 3) was used in the beginning of the project so as to think of questions which were related to the project. In this section, answers to the following questions can be found. Following are the list of questions-

1. Shirts that cyclist prefer
   What do they prefer ?
   Why do they prefer ?
2. What are the factors which affects the performance of shirts? Aerodynamics? Texture of the surface? Type of weaving techniques? Other factors?
3. What clothing are cyclist using currently? What features are must? What features are already incorporated?
4. What are the Olympic rules and regulations?
5. Olympic cycling race itself
   Time required?
   Research required on the condition ?
6. What are the properties of PVA?
7. Do PVA remains at constant temperature?
8. Why does PVA expand and contract ?
9. How is PVA produce?
10. What is its chemical composition?
11. Why cannot the water absorbing capacity of PVA improve?
12. What is the effect of humidity and temperature etc on PVA materials?
13. Is it possible to reactivate the PVA material during the race.?
14. Where should the PVA placed on the body? Where is the sweating rate high?
15. How does heat affects performance?

This chapter concludes with a short summary and is followed by a list of requirements which is used during ideation.

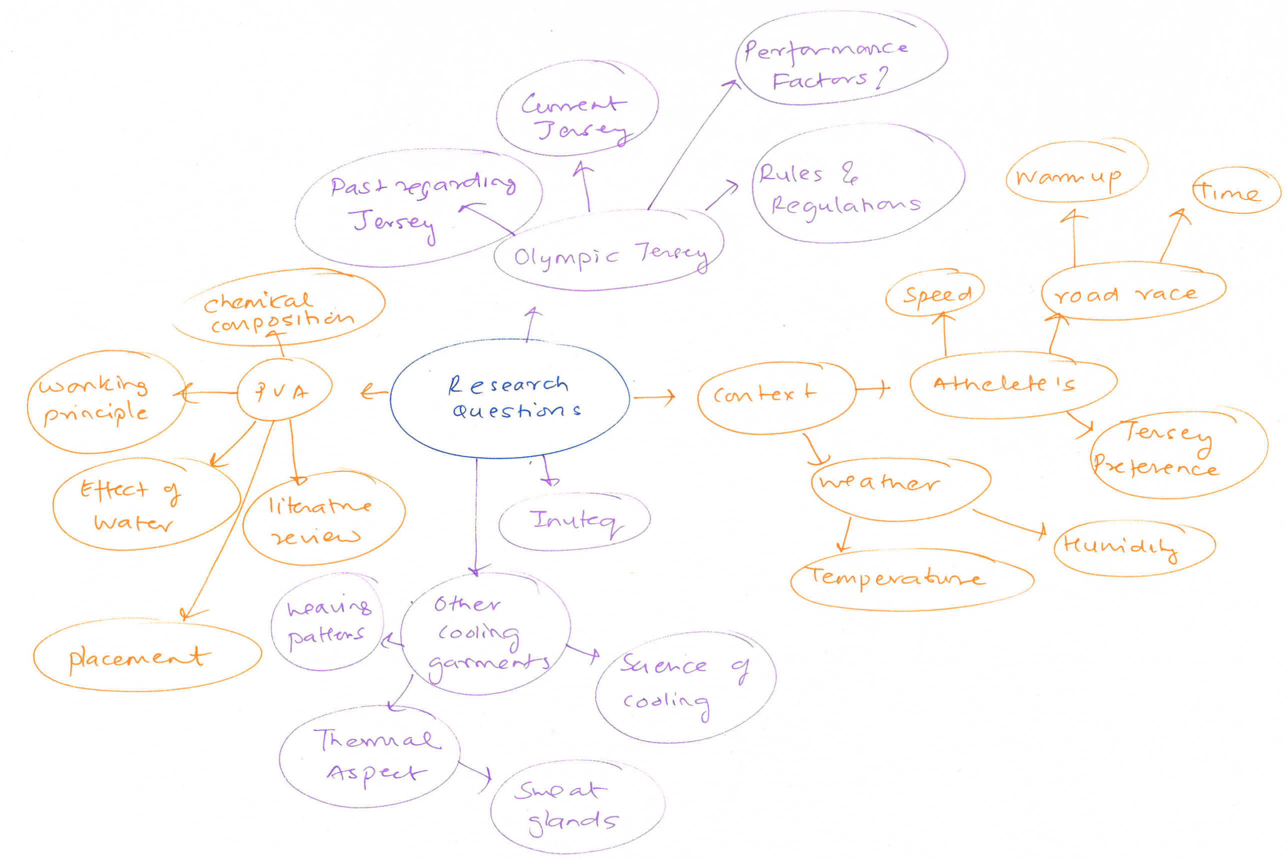


Figure 3. Mind-map for research section

2.1 Heat Impact

Human body temperature can be divided into the core and the shell temperature. The skin is the largest organ in the human body. It protects the body from the sun's rays. It also keeps body temperature normal (37 °C). Skin temperature depends on air temperature and time spent in that environment. The thermal core has been defined as "Those inner tissues of the body whose temperatures are not changed in their relationship to each other by circulatory adjustments and changes in heat dissipation to the environment that affect the thermal shell of the body" (The Commission for Thermal Physiology of the International Union of Physiological Sciences). A single core temperature does not exist as the even inner tissues may be subject to slightly different temperatures and different responses to temperature changes (Moran et al., 2002 & Eichna et al., 1951). Usually, core temperature stays within its normal thermic range of 36.1-37.8°C (Weller, 2005).

Body temperature can rise beyond the normal thermic range while exercising. Exercise in heat can results into heat stress. Heat stress comprises any change in the thermal relation between a temperature regulator and its environment which, if uncompensated by temperature regulation, would result in hyperthermia. Heat stress is dependent on four factors, climate (temperature, humidity, wind, radiation) clothing (insulation, breathability) exercise and individual factors (fitness, acclimatation, disability etc) Intense exercise like the road race for cycling could result in heat stress which can evolve into heat disorders such as heat cramps, heat exhaustion or heat stroke. The details of which can be found in the following table.

Type	Cause	Effect
Heat cramps	Profound sweating causes loss of minerals and fluid	Severe cramping of skeletal muscles (heavily used)
Heat exhaustion	Failure of cardiovascular system to meet the demands of the active muscles	Fatigue, dizziness, breathlessness, a pale and cool or hot and dry skin, weak rapid pulse
Heat stroke	Complete failure of the thermoregulatory system.	Cessation of sweating, warm and dry skin, rapid pulse and respiration, confusion and unconsciousness. May result in death.

Table 2. Cause and effect of various heat disorder.

Heat disorder could be avoided by few ways.

1. By adjusting the pacing while exercising so as to prevent a high rate of heat storage at a premature stage.
2. Helmets, caps and sunscreen can help from protecting against radiation
3. By wearing lightweight, airy, breathable and easy to take out (during breaks) clothing.
4. Individuals fitness can also be beneficial.
5. Acclimatization attenuates heat stress.

In the next section information regarding human body's heat loss mechanism can be found.

2.2 Heat loss mechanism

The ability to sense and regulate body temperature is a key feature for survival of warm blooded species. Physical exercise is one of the environments where human thermoregulatory functions are critical for survival and sustenance of physical work. During intense prolonged physical exertion (e.g., endurance races), body temperature can increase from about 37°C at rest to 40-41°C, where cellular cytoskeleton can be damaged and the functions of organs and central nervous system can be impaired (Morseley PL, 1993). An essential requirement for continued normal body function is that the body core temperature is maintained within a narrow limit of ± 1 °C around the resting body core temperature of 37 °C (Epstein & Moran, 2006) during rest. There are six primary factors that directly affect thermal balance of the body, which can be grouped in two categories namely personal factors and environmental factors. The personal factors are metabolic rate and clothing level, the environmental factors are air temperature, mean radiant temperature, air speed and humidity. In the following section detailed analysis of personal factors and environmental factors can be found.

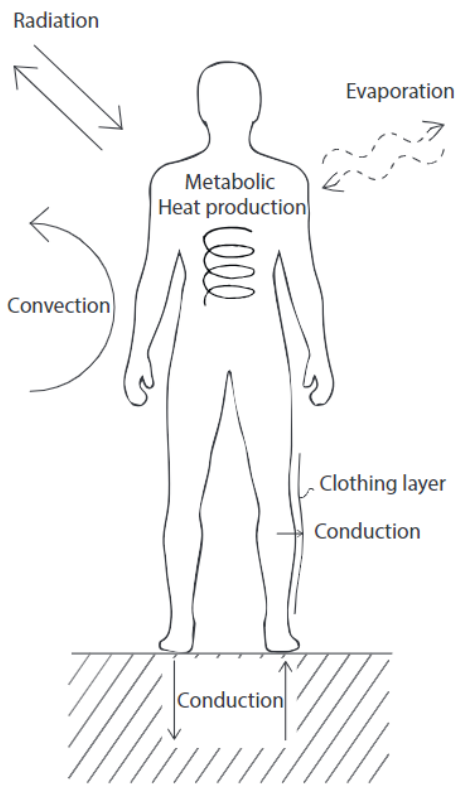


Figure 4. Heat balance factors

Body core temperature is determined by the balance between heat production and heat loss. This heat balance can be captured into the following equation (1):

$$M \pm C \pm R - E = S \qquad \text{(eq 1)}$$

Metabolic rate (M)

Metabolism is the amount of energy that a human produces by bodily processes, and includes processes like food digestion, physical work. During physical exercise, metabolic heat production can increase by 10- to 20-fold, but less than 20% of the heat generated is converted to mechanical energy. Conversely, more than 80% of metabolic heat generated has to be transported from the central to the peripheral compartments of the body (to the skin) to be dissipated to the environment. Heat starts to accumulate in the body when the heat dissipating mechanisms are unable to cope with metabolic heat production, leading to an increase in body temperature..

Storage (S)

S represents net heat storage. When the body heat content remains stable, S will be zero. However, positive or negative heat storage means an increase or decrease in core and/or skin temperature.

Radiation (R)

Radiation is defined as a transfer of heat between two bodies through electromagnetic waves. For instance between the sun and the human body and it is described by the following equation:

$$q = é \bullet \mu \bullet A\,(T1^4 - T2^4) \qquad \text{(eq 2)}$$

Heat flow q (W) is expressed as a function of é (the emissivity between two bodies), μ (the Stefan-Boltzmann constant: 5.6703 10^{-8} (W/m^2K^4)), A is the area of the emitting body (m2), T1 is the temperature (K) of the radiating surface and T2 is the absorbing surface temperature (K).

Conduction and Convection is represented by C

Conduction

Conduction is defined as a the transfer of heat through direct contact among solid materials. For a constant surface area A and distance x, conduction is described with the following equation:

$$q = (k/x) \bullet A \bullet \Delta T \qquad \text{(eq 3)}$$

Where,
q = heat flow (W);
k = thermal conductivity of a material (W/m1K1);
x = the distance between the two surfaces (m^2);
A = the cross sectional area of the surface (m^2);
ΔT = the temperature difference between the two surfaces (K).

Convection

Convective heat transfer occurs when a fluid that is liquid or gaseous flows along a surface and a difference in temperature occurs between the surface and the fluid. This happens for instance between the skin and the outside airflow.
Convection is described with the following equation:

$$q = hc \cdot A \cdot (Ts - Tf) \qquad \text{(eq 4)}$$

Where heat flow q (W) is a function of the convective heat transfer coefficient hc ($W/(m^2 \bullet K)$), the convective surface area A (m^2) and the temperature difference between the surface temperature Ts (K) and the fluid temperature Tf (K).

Evaporation (E)

During exercise, the primary way for a human body to dissipate heat is by the evaporation of sweat. Water, the principal constituent of sweat, has a high heat capacity. 2.43 kJ of heat energy can be removed from the body for every gram of sweat evaporated. During rest in room temperature, evaporation accounts for only 20% of body heat loss. However, evaporation becomes increasingly important (80-100%) when the body temperature rises and/or when the ambient temperature is close to the body's skin temperature. The extent to which evaporation occurs depends on the relevant vapour pressure gradients (of the skin. air. clothing, and ambient environment), and decreases as the relative humidity increases. If the humidity of the air is such that evaporation cannot occur, the body continues to store heat and body core temperature rises

Evaporative heat loss from the skin (Esk), depends on the amount of moisture on the skin and the difference between the water vapour pressure at the skin surface and that in the ambient environment.

$$E_{sk} = w(p_{sk,s} - p_a)/(R_{e,cl} + 1/(F_{cl} h_e)) \qquad \text{(eq 5)}$$

Where,
w = skin wettedness (dimensionless);
$p_{sk,s}$ = water vapor pressure at skin, normally assumed to be that of saturated water vapor at tsk (psi);
p_a = water vapor pressure in ambient air (psi);
$R_{e,cl}$ = evaporative heat transfer resistance of clothing layer ($ft^2 \cdot psi \cdot h/Btu$);
F_{cl} = clothing area factor, dimensionless.
h_e = evaporative heat transfer coefficient ($Btu/h \cdot ft^2 \cdot psi$).

Heat loss is not uniform over the body, there are regional differences which will be discussed hereafter.

2.3 Body Sweat Map

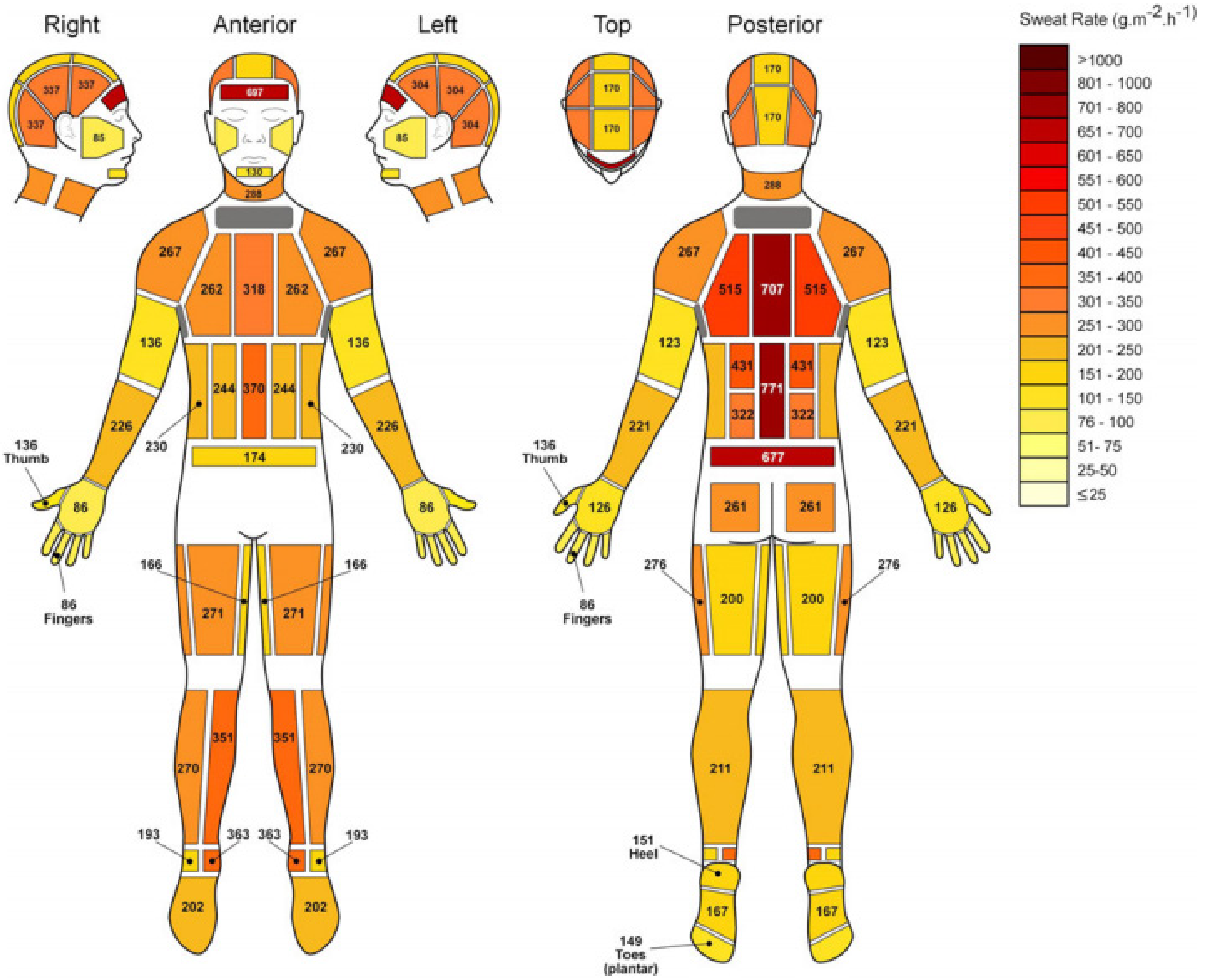


Figure 5. Absolute regional median sweat rates of male athletes at exercise intensity of 55% of VO2 max (Smith & Havenith, 2011)

Heat exchange between the environment and the human body differs per surface area on the human body and per individual. It varies whether the person is male or female. Some areas have a higher heat exchange rate than others, both for heat absorption as well as heat dissipation. Heat exchange rates depend on the structure of a body tissue, the layer configuration of the skin and the underlying tissue.

In relation to sweating, Smith & Havenith (2011) identified areas of high sweat production on the human body (Figure 5) The areas with highest sweat rate(red in colour) are located at posterior dorsal and lumbar followed by chest and the upper arms. (orange in colour). The curvature of the body between anterior and posterior position have less sweat rate (light orange or yellow). Mean Sweat loss values for the different sessions were 524 ± 98,445 ± 98, and 499 ± 121 gm.m^{-2}h^{-1} for the torso/upper body which suggests that there could be almost 20% inter-athlete differences.

2.4 Clothing

The most obvious function of clothing is to improve the comfort of the wearer, by protecting the wearer. In hot climates, clothing provides protection from sunburn while in cold climates its thermal insulation properties are generally more important. . The primary function of clothing for cyclists is protection but wearing of any clothing adds to metabolic heat generated since it has the effect of both adding weight and restricting movement. (Teitlebaum & Goldman,1972) Clothing creates a microenvironment between the skin and clothing. Depending upon the ambient environment, the microenvironment of the clothing is generally hotter and more humid than the ambient environment. Convective air movement in the microclimate may decrease, particularly when thick or impermeable clothing layers or multiple layers are present Clothing also reduces evaporation of sweat by increasing the saturation of the air layer next to the skin (the microclimate) and. if impermeable, the clothing itself may also inhibit vaporization of sweat. In recent years new fabrics are designed to keep the athlete drier, cooler and more comfortable. This is accomplished by wicking sweat away from the skin and through the clothing for evaporation. Natural fibers such as wool and cotton have high water absorbing capacity and less wicking properties but synthetic fiber such as polyester has a diminished capacity for absorbing moisture but is purported to have superior transport properties for water vapor, thus helping clothing to remain drier. Wicking property depend on fabric structure and porosity, both of which are influenced by factors such as fibre type. fibre crimp, smoothness, yam type, and fabric construction. Other garment factors which may affect the exchange of heat include the extent and location of closures, yarn construction (e.g. staple, filament), fabric structure (e.g. woven, knitted), finishes (e.g. waterproof, reflective) and the moisture retained in the garment itself (e.g. due to artificial wetting or sweat production. The closer the fit of the garment, the more important the fibre content is claimed to be. while for looser-fitting garments, fabric construction becomes the more important variable (Pascoe et al.). In the next section, information regarding cyclist clothing is given in detail.

2.5 Aerodynamics & Clothing

A variety of internal and external factors interact to determine cycling velocity. Chief among those are physiological factors which influence mechanical power production (internal factors), and mechanical and environmental factors that affect power demand (external factors). The internal factors are training and nutrition. The external factors include body weight, body composition, body position, clothing, bicycle and wheels. (Jeukendrup & Martin, 2001). Many of these factors are influenced by aerodynamics. In many cases, athletes check which body position has the least drag by testing various positions in a wind tunnel test. Nowadays bicycles and wheels are also designed for least possible drag. Hence the influence of aerodynamics on cyclist clothing is crucial and has to be studied in detail. In this section the influence of aerodynamics on clothing is discussed.

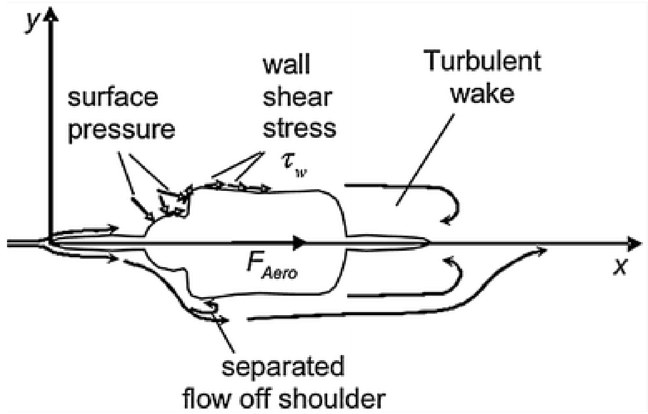


Figure 6. Top view of simplified diagram of the flow field around a cyclist (Martin et al.) highlighting the high-pressure leading surface regions and the low-pressure turbulent wake.

Flows around a cyclist exhibit large regions of separation and, therefore, fall into the category of bluff bodies. Basic of aerodynamic teaches that streamlined bodies such as aerofoils, which have rounded leading edges and a gradual reduction in body width and cross-sectional area from the widest point of the body to the trailing edge, a bluff body has sharp edges or a much more dramatic reduction in body width towards the trailing surfaces. This type of geometry results in large adverse pressure gradients imposed on the boundary layer that are too large to sustain attached flow. As a result, bluff body flows are characterised by large regions of separated flow that may or may not reattach to the surface.

Unlike streamlined bodies, where the viscous tangential wall shear stress forces contribute the largest proportion to aerodynamic drag, the aerodynamic resistance in cycling is mainly from pressure drag. Flow separation around cyclists results in the formation of a turbulent wake and large-scale low-pressure vortices as depicted in figure. 7. The magnitude of the pressure drag is proportional to the pressure differential generated between the low-pressure wake areas and the high-pressure stagnation regions located on the leading surfaces of the rider. The resultant pressure force is found by integrating the surface pressure distribution, which acts normal to the body surface, over its entire surface.

Basic of aerodynamic teaches that the drag can be reduced by minimising the frontal area, increasing the pressure on rearward facing surfaces and in the wake, or by reducing the magnitude of the high-pressure stagnation regions on the leading surfaces of the body..

The size of the wake can be reduced by maintaining the attached flow and controlling the location at which the flow separation occurs. Reduced size of the wake results in increased in wake pressures and reductions in the pressure drag component of the aerodynamic resistance.

Using the textured fabrics near the separation point results in formation of turbulent air pockets (Crouch et al,. 2017). These air pockets have higher momentum and will follow the cyclist past the old separation point (f smooth fabrics were used) Hence textured fabrics delays the separation point towards the back of the body.

The relative texture of fabrics is dependent on a number of parameters, such as yarn type and material, stitch pattern and density, thickness, cover factor, porosity, seam positioning, coatings, and fabric tension. All of these variables have been shown to be important when considering the aerodynamic performance of skin suits. (Underwood & Jermy 2011), (Oggiano et al., 2009).

2.6 UCI Clothing Rules

In Nike Swift Skin project, an aerodynamic jersey was designed for cyclist. (Brownlie et al., 2009) The paper documented the development of aerodynamic apparel and the results from the paper will be used to design an aerodynamic jersey in this project. The main finding from their research are given below-

1. In zones of attached airflow, such as the torso, smoother fabric textures were utilized to minimize skin friction.
2. Appropriate fabric textures were carefully placed in crossflow zones to induce boundary layer transition from laminar to turbulent, and thereby reduce the low-pressure wake behind the segment.
3. The development of a garment pattern that produces the fewest wrinkles when the suit is worn in the TT position
4. In regions of attached flow, the use of flat seams aligned parallel to the flow direction.
5. Placement of the majority of seams towards the rear or in regions of separated flow, where they have no impact on drag
6. Placement of necessary cooling panels in shielded regions out of the air stream.
7. The upper arms, thighs, and calves encounter cross-flow where appropriate surface textures of fabric were found to provide less air drag than bare skin.
8. Custom fitting of each suit to the cyclist to minimize wrinkles or areas of loose fabric.
9. The use of lightweight stretch fabrics to allow adequate thermoregulation during extended periods of exercise

In the following paragraph, information regarding UCI clothing rule can be found.

Items of clothing may not modify the morphology of the rider and any non-essential element or device, of which the purpose is not exclusively that of clothing or protection, is forbidden. This shall also apply regarding any material or substance applied onto the skin or clothing and which is not itself an item of clothing.

Modifications to the surface roughness of clothing are authorised but may only be the result of threading, weaving or assembling of the fabric. Surface roughness modifications shall be limited to a profile difference of 1mm at most.

The measure of surface roughness modification shall be made without pressure or traction on the clothing.

All clothing must maintain the original texture of the textile and may not be adapted in a manner to integrate form constraints. Therefore, when not worn, clothing may in no case contain any self-supporting element or rigid parts.

2.7 Present Day Clothing

Castelli produces Giro d'Italia leaders' jerseys and is famous in the cycling industry for its sports garments. To study the clothing presently used by the Castelli company was selected. As seen from the timeline (Appendix B), after 2006 importance has been given on developing skinsuits and jerseys which are aerodynamic in design. Castelli designed Aero 1 in 2006. The latest version is the Aero Race 6.0 jersey. The features of the jersey is as followed

- CFD-based fabric placement and seam construction
- Engineered for aero efficiency at 30 to 55 km/h
- 3D mesh back for breathability
- Weight:159gm

In 2010 first aerodynamic Body Paint bib shorts were produced which had only one seam whereas bibshort 2 were produced using no seams. Aero dimples are employed in the material which makes this the most aerodynamic bib short on the market. The dimples into the fabric to induce flow separation and reduce aerodynamic drag. The latest version available in the market is the body paint 4.0. The features of the jersey are as followed.

- Boundary Layer engineering to reduce drag over every portion of the suit.
- Longer legs than the shorts for smoother airflow around the legs.
- Seat pad for good protection but minimum bulk
- Weight:315gm

Speed suit designed by Castelli are branded under the Sanremo name. The features of Sanremo 2.0 Speed suits are combination of Aero jerseys and body paint bib shorts. It weighs 259gm

Figure 7. Clothing options available for cyclist, retrieved from www.castelli-cycling.com From the top to bottom, jersey, bib shorts and skin suit

2.8 Understanding Polyvinyl Alcohol

Poly(vinyl alcohol) (PVOH, PVA, or PVAl) is a water-soluble synthetic polymer. It has the idealized formula [CH2CH(OH)]n. Polyvinyl alcohol (PVA) is a semi-crystalline, thermoplastic and biodegradable synthetic polymer having good chemical resistance. It is obtained by the hydrolysis of poly (vinyl acetate), with a large number of hydroxyl groups forming inter and intra chain of H-bonds.

It finds application as thickener (modifier) in polyvinyl acetate, textile sizing agent, emulsifier and membrane material. It is also used in vinylon fiber production and support structure for 3D printing. However, moisture sensitivity and high water absorption rate of PVA, leads to reduction in mechanical properties and hence limits its applicability. However, water absorption can be reduced by crosslinking the PVA chains. Crosslinking is a process of bonding the polymer chains with each other to improve its properties. Before crosslinking, PVA is soluble in water, after crosslinking, PVA swells in water. This crosslinked PVA are used in the fabric which are used for this project.

Once the chains are crosslinked, they have little mobility relative to each other and hence the incoming water cannot make space for itself thereby restricting the number of water molecules absorbing into the PVA films. Crosslinking also decreases the number of hydroxyl groups hence less water molecules are attracted to the PVA. Crosslinking hence performs dual role in controlling water absorption: it reduces the number of hydroxyl groups and limits the movement of chains. Both of these results in the reduction of water absorption and hence reduction in swelling.

According to Prof.dr. S.J. Picken the PVA used in the cooling towels provided by Inuteq, is an open cell foam. First patent to make PVA foam was filled in 1952 (U.S. Patent No. 2609347 A). Nowadays various ways to make the PVA foam can be found.

Why does PVA becomes flexible after absorbing water?

PVA has to be reactivated after every three to four hours with water so that it remains flexible. When all the water is evaporated from the PVA, the PVA becomes rigid. This prevents it from being used in cases where reactivating the PVA frequently with water is not possible. Water acts like a plasticiser. Plasticiser are the substances which are added in order to alter their physical properties. These are either liquids with low volatility or solids. They decrease the attraction between polymer chains to make them more flexible. Absorbed water reduces its tensile strength, but increase its elongation and tear strength.

How does PVA cools the body?

PVA cools the body through evaporative cooling. The advantage of evaporative cooling garment is that it employs the large latent heat of water evaporation, which is around 2430 KJ/Kg at 30^{0}C, more than seven times the heat of ice fusion. There is a heat transfer through conduction from the skin to the PVA fabric which heats up the fabric. Simultaneously the fabric is cooled down by evaporation of the water in it. Therefore there is a transfer of heat away from the skin.

2.9 Possible Outcomes

Cooling from PVA material is dependent on the evaporation rate of water from it. In the next section experiments are performed to find the rate and compare with the sweating rate and evaporation rate from the skin. In this section all possible outcomes of the experiments are discussed. For this project, understanding the relationship between them is critical so as to make correct design decisions.

Sweating Rate (Sr) and Rate of evaporation from PVA (Ep)

PVA is superabsorbent fabric which means it will absorb all the water which is in contact with it. If the PVA fabric is in contact with the skin of the athlete, the sweat coming out from the body will be absorbed by PVA fabric. The sweat which is absorbed by the PVA fabric will evaporate, taking away the heat from the athlete's body. Depending on the rate of sweating and evaporation, three possible scenarios could be described

1. Sweating rate is less than evaporation rate in PVA

In this situation, the PVA fabric will not get enough water (from sweat) to remain flexible during all the duration of the race. Therefore It becomes necessary to reactivate the PVA fabric with water frequently, to keep it flexible.

2. Sweating rate is equal to the evaporation rate in PVA

In this situation, the PVA fabric will absorb sweat at the same rate as it will evaporate sweat. The fabric will neither become rigid nor absorb too much water. The weight of the shirt will not increase. There will not be any sweat accumulating on the skin.

3. Sweating rate is higher than evaporation rate in PVA

In this situation, the PVA will have more than enough water to remain flexible. After some time, the PVA will get saturated with water and will not have more capacity to absorb water. Then the sweat will start accumulating on the skin, resulting in skin wetness. The weight of the fabric will be high because of the absorbed water.

The following table summarises the discussion given above.

Relationship	Reactivating PVA with water	Skin Wetness
Sr < Ep	Necessary	Negligible
Sr = Ep	Not Necessary	Negligible
Sr > Ep	Not Necessary	Significant

Table 3. Possible relationship between Sr and Ep and its consequences.

Rate of evaporation from PVA (Ep) and Rate of evaporation from skin (Es)

There are two possible scenarios possible

- Rate of evaporation from skin exposed to the environment is higher than the rate of evaporation from PVA

  Then skin should be exposed to the environment.

- Rate of evaporation from PVA is higher than the rate of evaporation from skin

  Then the PVA is more efficient in cooling

The following table summarises the discussion given above.

Relationship	Remarks
Ep < Es	Sweating is efficient
Ep > Es	Cooling with PVA is efficient

Table 4. Possible relationship between Es and Ep and its consequences.

Experiment were performed by Tam, et al. to find the evaporation rate of sweat at 30^{0}C and 25 ± 5 % RH at 0.1m/sec wind speed. The rate was found to be equal to 220.2 $gm.m^{-2}.hr^{-1}$. In the second experiment the evaporation rate from PVA is found.

Relationship between the sweating rate (Sr) and the evaporation rate from skin can be found in Appendix F

2.10 Experimenting with PVA

To clearly understand the cooling properties of PVA an exploratory research was conducted with the aim to acquire new insight into cooling properties of PVA foam.

Experiment 1.

Experimental Setup

A temperature and humidity chamber, SH-661 from ESPEC is used n this experiment. The PVA sample use in the experiment were 20cm*20cm size.

Description

The chamber is used to find the evapoartion rate from a PVA sample which is kept inside the chamber.

Following steps have been taken to find the evaporation rate

1. The test sample is immersed in water so that is absorbs water. Then it is taken out of water and excess water is removed.
2. Weight of the sample is measured (M1)
3. Temperature and humidity of the chamber was set to the required setting (which depends on the test scenario). Power is turned on.
4. Sample is kept in the chamber
5. Sample is taken out after test duration is over (T). Duration of the test depends on the type of the test which can be found in the results section
6. Weight of the sample is measured again (M2)
7. Evaporation rate is then calculated

Calculated data-

Rate of evaporation(E)= (M1-M2)/A*T) (eq 6)

where

A is the surface area of cloth

Results

The following table shows various settings used in the chamber and the corresponding evaporation rate. Raw data containing the tests results can be found in Appendix C .

Sample	Time (min)	Temper-ature (^0C)	Hu-midity (%)	Evaporation Rate (gm. $hr^{-1}.m^{-2}$)
PVA foam	30	30	0	322.5
PVA foam	30	30	85	147
PVA foam	30	30	100	80
PVA foam	30	20	85	142.5
PVA foam	30	40	85	167.5
PVA foam	30	30	85	147
PVA foam	60	30	85	147.5
PVA foam	90	30	85	187.5

Table 5. Evaporation rate from PVA at different temperature and humidity settings

Conclusion

From the second test it can be concluded that:

1. As the humidity in the air increases, the PVA towel loses less water, for the same duration.
2. The rate of evaporation increases with increase in temperature..
3. The rate, for first one hour is approximately constant after which it increases. After 90min the edges of the fabric starts to become rigid. Therefore the fabric should not be used for more than that time without reactivating it with water.

Figure 8. Temperature & Humidity Chamber

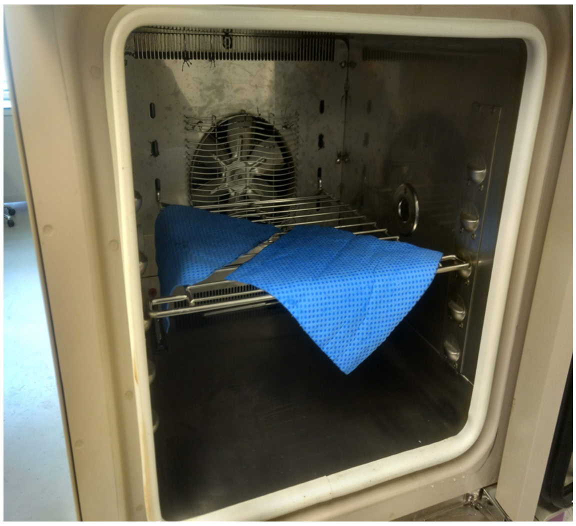


Figure 9. Placement of PVA inside the chamber

Interpretation of the results

Sweating Rate (Sr) and Rate of evaporation from PVA (Ep)

The minimum sweating rate, in the area of interest (that means the body parts on which the shirt is worn) is 230 $gm.m^{-2}.hr^{-1}$ (figure 5) and the rate of evaporation absorbed with PVA is 147 $gm.m^{-2}.hr^{-1}$ therefore condition three will occur.

Relationship	Reactivating PVA with water	Skin Wetness
Sr < Ep	Necessary	Negligible
Sr = Ep	Not Necessary	Negligible
Sr > Ep	Not Necessary	Significant

Table 6. Outcome of experiment 1 highlighted in dark colour background

Experiment 2.

Experiment were performed by Tam, et al. to find the evaporation rate of sweat at 30⁰C and 25 ± 5 % RH at 0.1m/sec wind speed. The rate was found to be equal to 220.2 $gm.m^{-2}.hr^{-1}$. The humidity chamber could not be used to perform the experiment as the wind speed in the chamber cannot be controlled. The aim of the experiment is to find the evaporation rate from PVA at similar conditions as that as found by Tam, et.al.

Experimental Setup

The PVA sample use in the experiment were 20cm*20cm size. It was kept in the Applied Science room at 32.5% RH and 20ºC for 30 min with no wind speed.

Description

Following steps have been taken to find the evaporation rate

1. The test sample is immersed in water so that is absorbs water. Then it is taken out of water and excess water is removed.
2. Weight of the sample is measured (M1)
3. It is kept on a rack immediately.
4. Weight of the sample is measured again after 30 min. (M2)
5. Evaporation rate is then calculated

Calculated data-

Rate of evaporation(E)= (M1-M2)/A*T) (eq 6)

where

A is the surface area of cloth

Results

The evaporation rate from PVA was found to be 117 $gm.m^{-2}.hr^{-1}$. Raw data containing the tests results can be found in Appendix C .

Conclsion

The rate of evaporation from PVA is found to be almost half of the rate of evaporation from skin.

Interpretation of the results

Evaporation rate from sweating is higher than PVA so the cooling from the sweat will be more efficient. Therefore condition one will take place.

Relationship	Remarks
Ep < Es	Sweating is efficient
Ep > Es	Cooling with PVA is efficient

Table 7. Outcome of experiment 2 highlighted in dark colour background

Experiment 3.

In this experiment, instead of using PVA to find the evaporation rate lycra is used. The experiment setup and description is same as that of experiment 1.

Results

At 30ºC and 85% RH the rate of evaporation from lycra was 147 $gm.hr^{-1}.m^{-2}$

Conclsion

The rate of evaporation from lycra and PVA is same at similar temperature and humidity setting in the climatic chamber.

Interpretation of the results

The evaporation rate is found to be the same for lycra and PVA, therefore the cooling power should also be the same.

. **Experiment 4.**

The aim of this experiment is to compare the cooling power obtained using present conditions i.e. using lycra and with PVA.

Experimental Setup

A hot plate was used to find the cooling power. The hot plate was custom made at the Applied Labs. Top plate of the hot plate is maintained at constant temperature of 35^0C . Test samples of 20cm*20cm size are kept on the top plate for a duration of 15min.

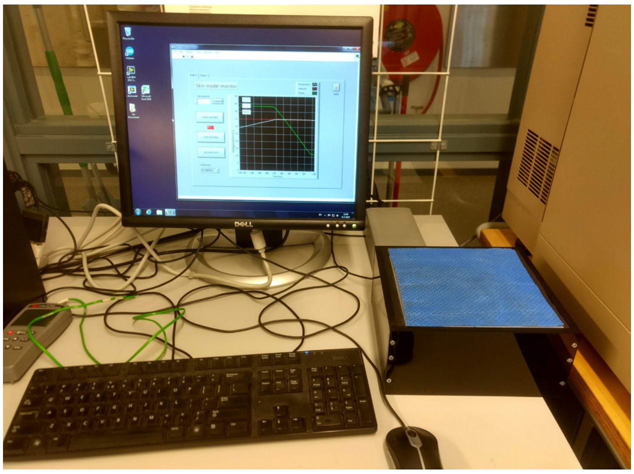
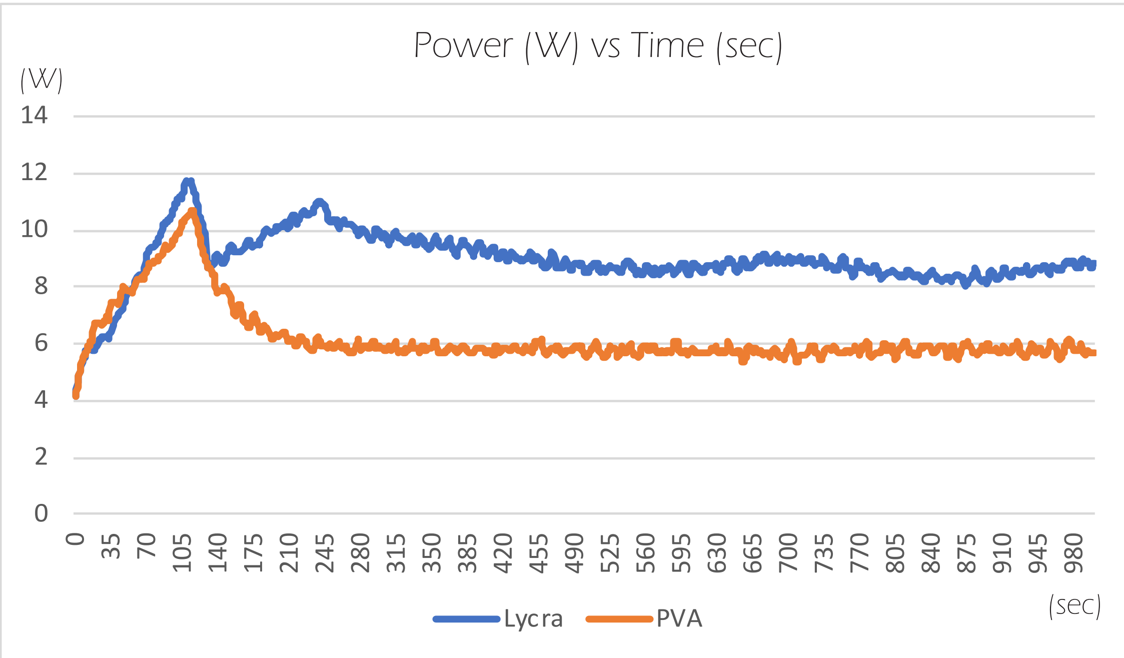


Figure 10. Skin model and computer

Description

Following steps have been taken to find the cooling power from the test sample

1. The test sample is immersed in water so that is absorbs water. Then it is taken out of water and excess water is removed.
2. The test sample is kept on the hot plate.
3. The test is performed for 15 min
4. Sample is taken out from the hot plate



Graph 1. Power results for lycra and PVA

Results

The results obtained from the experiment is shown in the following graph. Raw data containing the tests results can be found in Appendix C.

Conclusion

From the first test it can be concluded that:the cooling with lycra (with water in it) is more beneficial than cooling with PVA foam.

nterpretation of the results

The cooling power from lycra is higher than PVA even when the evaporation rate is same. This could be associated to the less thickness of the fabric. Lower is the thickness of the fabric, greater will be its ability to absorb heat from the surface of the hot plate rather than absorbing heat from the surrounding environment.

2.11 Alternative use of PVA

In the previous section it was found that:

- The sweating was more efficient in cooling the body than cooling with PVA.
- Cooling with wet lycra is also more efficient than with PVA

In the following section another application of PVA for cyclist clothing is presented

PVA could be useful for cyclist clothing by preventing the skin from becoming wet. Alber-Wallerstrom & Holmer (1985), found the relationship between skin wetness and sweating efficiency. Sweating efficiency was between 87% and 51%, and the corresponding skin wettedness was from 0.56 to 1.0. The sweating efficiency fell below 51% for fully wet skin. In this project PVA is used to improve the sweating efficiency of the cyclist. If the rate of sweat generation is higher than the rate of sweat evaporation, sweat may get accumulated in clothing leading to hydromeosis. a mechanical blockage of sweat glands through the swelling of the epidermis. Hydromeosis decreases sweat rate and can lead to increased rate of heat storage.(Candas et al., 1983) .

PVA can also be used as a buffer or a reservoir. When sweat rate is very high and there is a lot of drippage (dripped sweat does not contribute to cooling as no heat is absorbed from the body), PVA can absorb the excess sweat. While climbing, cyclist have lower velocities and sweat is not evaporated quicker. During that phase sweat can be stored in the PVA fabric and while descending the stored sweat can evaporate quicker due to higher cycling speed.

Evaporation rate from pva must be increased so as to decrease the skin wetness. In the next chapters, efforts are taken to do the same.

2.12 Summary

Here a short summary will be given of the complete discover chapter with the most important findings and conclusions.

Context
The clothing will be designed for Dutch Olympic cyclist participating in Tokyo Olympics 2020. The race will take place in July and the expected weather conditions are 30^{O}C and 85% RH. This weather conditions are difficult for sports, which can result in excessive rise of the core body temperature. Clothing with cooling ability will help to cool the skin temperature which will help to reduce the rate of increase of core body temperature. The project is done with a company, Inuteq. Cooling material, PVA fabric is provided by them

Clothing.
In the clothing section, factors related to cyclist clothing such as aerodynamics, performance material, UCI rules and regulations, development of cyclist clothing and present day clothing has been discussed.

Thermal aspects
In heat storage in the body is given by the heat balance equation and is dependent on four factors, Metabolic rate (M), conduction & convection (C), radiation (R) and evaporation (E). During exercise the majority of heat loss from the body will be due to evaporation. According to Smith & Havenith (2011) sweating rate is non uniformly distributed over the body, there are regional differences as well as individual differences. Heat balance of the body is dependent on four factors, climate (temperature, humidity, wind, radiation) clothing (insulation, breathability) exercise and individual factors (fitness, acclimatation, disability etc) Intense exercise like the road race for cycling could result in heat stress which can evolve into heat disorder which can result in heat cramps, heat exhaustion or heat stroke. In order to avoid it, the athlete either has to reduce his/her performance level or have to be cooled. Wearing clothing which cools the cyclist is therefore very important.

PVA
PVA is water soluble, PVA has a strong affinity towards water as it can form hydrogen bonds with it. Cross linking it prevents it from dissolving completely with water. The cross linked chain are attached to each other with a chemical bond therefore water cannot separate those bonds but is now stuck in between them, which makes PVA a superabsorbent material. Water also acts as a plasticiser and therefore the addition of water in PVA makes it flexible. The PVA fabric is used as the cooling material in the clothing. The absorbed water evaporates by taking the heat from the body and environment therefore providing cooling.

Application of PVA in cyclist clothing
In the previous section it was found that: one the sweating was more efficient in cooling the body than cooling with PVA, second, cooling power with wet lycra is more than with PVA therefore it was concluded that PVA should not be used for cooling but for preventing the skin from becoming wet by absorbing excess sweat.

03 DEFINE

After spending a significant amount of time working on experimentation, research papers and the internet, develop phase of the design process could be started. In this section, problem definition using the method found inN.F.M. Roozenburg and J. Enkels is used to thoroughly understand the problem and list of requirements using the checklist found in Delft Design Guide is used to set the requirements which the final design must have.

3.1 Problem Definition

For defining the problem N.F.M. Roozenburg uses list of questions. By asking the following questions the full scope of the problem becomes clear. Answer to those questions can be found below.

What is the problem?
The cyclists during the Tokyo Olympic road race will be exposed to the hot and humid environment. Exercise performed in these conditions can lead to an increase in body temperature and attainment of a critically high body temperature which can cause hyperthermia. Cyclists have to reduce the performance output to reduce the heat storage in the body which would reduce their chances of winning the race.

Who has the problem?
The cyclist cycling in the Tokyo Olympics would have the problem.

What are the goals?
The goal is to improve the performance of cyclist by optimum use of PVA fabric. In this project, the PVA is used for sweat management applications.

What are the side effects to be avoided?
The jersey should neither absorb too much sweat nor it should absorb too little sweat. Absorbing excess sweat, will make the PVA heavy. While some sweat is necessary for keeping the PVA flexible, too much sweat must be avoided. Absorbing less sweat also has to be avoided so as to prevent the PVA from becoming rigid.

3.2 List of requirements

A list of requirements is a list which contains features which the final design should have. A checklist was used from Delft Design guide to come up with these requirements

Demands

Top Three:
Environment
The clothing should perform well during Tokyo Olympics It should address the "side effects" mentioned in problem definition section.

Function
The clothing should contribute towards improving the performance of the cyclist.

Rules and Regulations
The clothing should follow UCI rules and regulations.

Remaining
Aerodynamic Features
The clothing must have aerodynamic design.(refer to page 10 for more information on aerodynamic design)

Ergonomics
The clothing should be designed for racing position of the athlete.

Sponsors
The clothing should allow for sponsor details.

Wishes

Weight
The weight of the clothing should be as less as possible.

Power
The fabric should provide as much cooling power as possible.

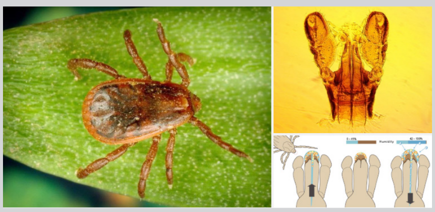
The new cyclist's jersey should comply with all the requirements stated above. The wishes will be used to make decisions in the next phase.

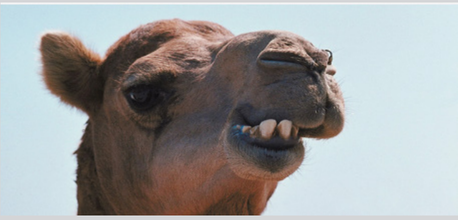
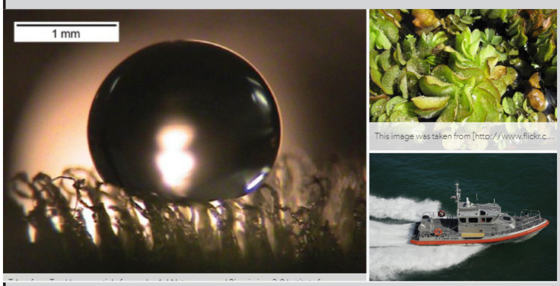
04 DEVELOP

After the define phase, develop phase starts here. The step towards generating ideas can be a hurdle. There are multiple methods and ways to help a designer with the creative process of generating ideas that lead towards problem solving. Methods such as brainstorming, biomimicry, worst possible solutions and how to's are used in this project. After the ideation stage, the most promising ideas will be chosen and used for further iterations. At the end of the ideation phase a final concept will be chosen. This will be the solution that will be developed further in the embodiment phase.

4.1 Biomimicry

During the ideation phase, multiple techniques and tools will be used to generate ideas and solutions. The most promising ideas will be chosen and used for further iterations. In this section biomimicry is used to find new ideas. Biomimetics or biomimicry is the imitation of the models, systems, and elements of nature for the purpose of solving complex human problems. Plants and animals have a diversity of ways to keep cool. Some are well-known, like sweating. Others may be less familiar, such as how ticks pull water from the air. From sweating, panting, to pulling water from air, living systems rely on a number of forms and processes to stay cool and hydrated. In this section various strategies available in the nature are studied, Their application in the context of the project has been explored. Few examples are not related to temperature regulation.

Nature	Strategies
Saharan silver ants (Cataglyphis bombycina) 	The hairs reduce heat absorption by maximizing the amount of light that is reflected off their surface, a process known as total internal reflection (TIR). This is achieved through the unique prism shape of the hairs, which have a flat base that lies against the body of the ant, while the other two sides are grooved (see gallery images). When light enters through one of the grooved sides, it reflects off of the base, and then exits from the other grooved side. A groove concentrates a ray of light onto a certain part of the hair in order to optimize its path of exit and thus maximize TIR
Honey Bees	Honeybees cool the hive by collecting water, spreading it, and fanning to increase evaporation.
Calanoides acutus 	The tiny Antarctic marine crustacean Calanoides acutus hibernates overwinter by descending to great depths. Once it reaches depths below 400 meters (one quarter mile), the cold temperatures cause a large pocket of waxy liquid within its body to transform to a dense solid, causing the organism to sink until it reaches a depth at which it is neutrally buoyant again
Ticks 	The tick rehydrates using a three-stage process. First, it uses its foremost pair of legs to detect micro regions of high humidity, such as those surrounding water droplets. Once a suitable water source is detected, the tick secretes a hydrophilic solution from its mouth. Once it is saturated, the tick draws the now hydrated secretion back into its mouth.
Bromeliad 	The hydrophobic properties of the leaves direct water downward to the plant's center, a pool forms, acting as a water reserve of dissolved nutrients.

Nature	Strategies
Hercules beetle 	The exoskeleton of the Hercules beetle changes from green to black with increasing humidity using thin film interference by reversible modification of layer thickness.
Camel 	During the nighttime, outside temperatures are typically lower than the camel's core body temperature. When the camel inhales, the cool outside air passes through the nasal passages where heat is exchanged: the nasal surfaces are cooled while the incoming air is warmed. Inside the camel's lungs, air is at body temperature and fully saturated with water (100% relative humidity). When the camel exhales, the warm air inside the lungs passes over the cool nasal surfaces and exchanges heat again. This time, the air is cooled as it's exhaled, and as it cools, water vapor in the outgoing air condenses onto the nasal surfaces as liquid water
Salvinia molesta 	Researchers from the Nanoprobe Laboratory for Bio- and Nanotechnology and Biomimetics at Ohio State University are developing a biomimetic coating for use on ships and submersible aquatic vehicles. The purpose of their research is to mimic the air trapping ability of the water fern Salvinia molesta, an aquatic plant that traps air on the surface of its leaves. The research team has demonstrated microfabrication techniques that can be applied in various industries. These techniques can be used to produce materials that reduce drag in water by using a layer of air to repel surrounding water.
Moloch	The Moloch (also known as the Thorny Devil) an Australian desert lizard, has a special skin structure so that it can absorb water from all over its skin and transport it to its mouth by capillary action.

Nature	Strategies
Termites 	Termites use an ingenious ventilation system to cool their nests
Whirligig beetles	Whirligig beetles and other small organisms experience a fluid world differently than larger organisms do. For a small organism moving in a fluid, the viscous forces within the fluid (that make it feel "sticky" and contribute to fluid resistance) play a larger role than inertial forces (that keep a fluid moving). That is, they operate at a relatively low Reynolds number (the ratio of inertial to viscous forces). The result for the whirligig beetle is that when it sweeps its leg through the water to swim forward, little water flows between the tiny hairs. A leg with its hairs extended functions as if it were a solid paddle, generating more thrust than if the hairs weren't there. Upon the leg's return stroke, the hairs collapse against the leg to reduce the "effective area" and help minimize drag.

Table 8. Strategies applied by animals to cool down. and its application in this project. Images in this table are retrieved from https://asknature.org/

Biomimicry was used during the start of the project to generate ideas. The ideas were focused on keeping the PVA foam flexible and improving the cooling properties of PVA foam Following are the list of ideas generated after the ideation session-

1. PVA yarn is knitted with other yarn which can reflect sunlight thereby reducing the heat absorption.
2. Moving the sweat away from high sweat zone to low sweat zone.
3. The PVA changes its property during the race
4. The PVA will absorb water from the environment to keep it flexible
5. Using hydrophobic spray to increase evaporation
6. The PVA changes colour to indicate that it has to be reactivated with water.
7. The surrounding air can be manipulated to improve the evaporation from PVA

This session provided many ideas at the beginning of the develop stage. After understanding the properties of PVA material only a few of these ideas were relevant, which were later tested.

4.2 Worst Ideas

In order to think of creative ideas it was necessary to not just think of sensible ideas but also think of non sensible ones therefore a ideation section was conducted with main focus of not judging the ideas but to think of as much as possible ideas. Many ideas were collected and then they were clustered into several groups. The following list contains the information of all the groups. Sketches of the ideation section can be found in Appendix G. The information of this method can be found on www.interaction-design.org website.

Shape, Size and Density
Patches of PVA material can be used in the clothing with variable shape, size and density.

Hydrophobic & hydrophilic coating
Coating the fabric with hydrophobic or hydrophilic material may be used to increase or decrease water loss through evaporation.

Pumping Action
When PVA is rigid, it shrinks and when PVA is flexible, it elongates. This property of PVA could be used for pumping sweat where the PVA is getting dry.

PVA moving
Using PVA fabric which can be moved on the body so that the PVA absorbs sweat at different rates.

Sweat movement
The sweat itself could be moved by hydrophobic coating or by applying force to push the sweat by force.

Changes in environment
Changing the surrounding air composition so that the evaporation rate could be altered

External source
Using water from ice or water bottle to reactivate the PVA could be a possible solution

Some ideas generated with this method also overlapped with the ideas generated by the biomimicry method however this method provided some new ideas which was crucial as new ideas were hard to find during that stage of the project.

4.3 Brainstorm Session

Brainstorm session was conducted near the end of ideation phase of the project to find new ideas. The participants involved in the session were involved in research undertaken by emerging materials department. Two of them were doing their graduation project using phase change materials for cooling the athletes and another one was the mentor. Therefore they had enough understanding of the problem itself. "How to's" were used for the ideation. Each how to's were written down on paper. Every participant was given one paper and they were asked to write down as much as possible ideas on a post it in 3 min. After every 3 min participant exchanged their paper. The how to's used in the session were:

1. How to reduce water absorption by the PVA fabric?
2. How to reduce water which is already absorbed in the PVA fabric?
3. How to increase the evaporation rate of the water present in PVA?

At the end, all the ideas were collected and clustered into a group. Following list contains the details of the groups-

Airflow
1. To induce dry airflow over the clothing.
2. Using ducts to channel airflow over PVA fabric.

Heating
1. Increasing the temperature to enhance evaporation.
2. Addition of buffer material which heats PVA fabric to release water.

Coating
1. Using hydrophobic coating.

Re-distribution
1. Distribution of sweat to low sweat areas.
2. Distribution of sweat outside fabric.

Force it out
1. Compress PVA
2. Squeeze PVA
3. Fit PVA on the body tightly so that it forces water out

Surface Area
1. Using small fins to increase evaporation

PVA Placement
1. Place PVA at the hottest part
2. Place PVA where sweating is least

Less or no PVA
1. Using PVA with holes
2. Using small patches of PVA
3. Finding new alternatives

In Between layer
1. Using another fabric between skin and PVA

Mix with another liquid

Less thickness

Almost all the ideas obtained after the brainstorm session were already tested. Therefore the session clearly gave a good indication that many options were explored during the ideation phase.

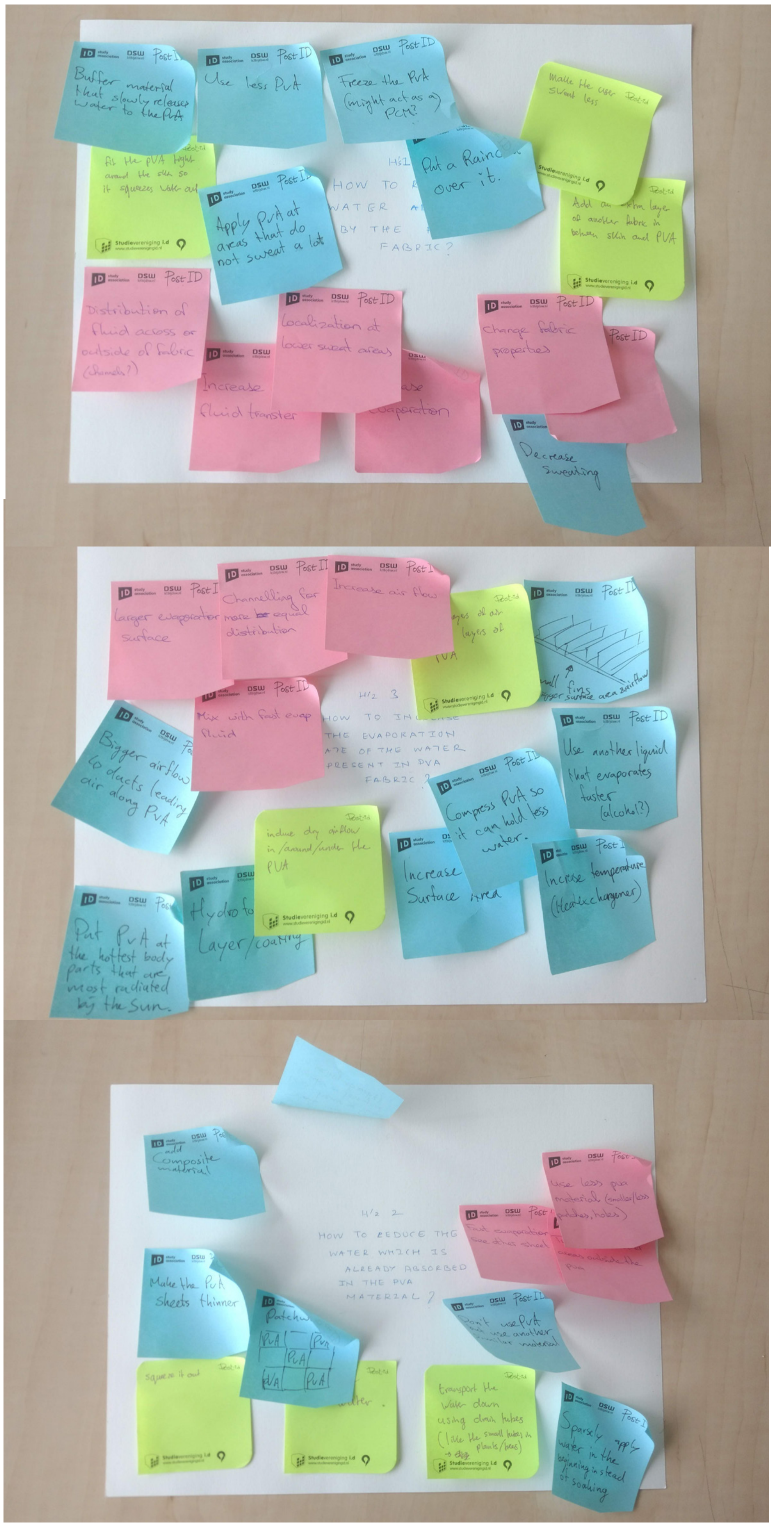


Figure 11. Results from brainstorm session

4.4 Testing various ideas

Different ideas were tested to check which one will be the best possible idea for the project. The higher evaporation rate is the best idea as it will have least weight. Temperature and humidity chamber was used to find the evaporation rate, as done before in the exploratory research. The raw data of the tests can be found in the Appendix C.

Test 1- Various Solutions

Instead of using tap water, various other solutions were tested to check their effect on the evaporation rate. The test duration was 30 min and temperature and humidity was set at 30°C and 85% respectively.

Solutions	Evaporation Rate (gm. $hr^{-1}.m^{-2}$)
Water saturated with sugar	137.5
Water saturated with salt	110
Lemon water	167.5
Dish washing liquid	140
Salt and hydrophobic coating	85

Table 9. Results obtained using different solutions

In salty solution, the rate of evaporation is observed to be less than usual. Possible reasoning for that could be because of hydrogen bond formation between salt and water. The salt settle into the pores of the PVA foam. Now more energy is needed to break that bond. In the remaining solutions, the evaporation rate was almost the same.

Test 2- Three different hydrophobic spray

Three different hydrophobic sprays were used to find the evaporation rate. The hypothesis behind this experiment was that the water in the PVA sample will get repelled by the spray which would increase the evaporation rate.
.

Spray Brand	Time (hr)	Evaporation Rate ($gm.hr^{-1}.m^{-2}$)
Nanolex	0.5	152
	1	127
Gyeon Q2	0.5	166
	1	137
HG Textel	0.5	270
	1	143

Table 10. Results obtained using different hydrophobic spray

The evaporation rate was measured for the first half hour was high but the rate decreased in the next half. The reason is that the hydrophobic spray itself evaporated.

Test 3- Hole with 0.5mm,1mm and 1.5mm diameter.

To increase the evaporation rate, holes 0.5mm, 1mm, 1.5mm were made in the fabric. The results are as followed
-

Hole diameter (mm)	Percentage of area occupied by holes.	Evaporation Rate ($gm.hr^{-1}.m^{-2}$)
1mm	70	305
1mm	30	235
1.5mm	70	270
1.5mm	30	200
0.5mm	30	310

Table 11. Results obtained using different diameter of holes with different densities

The less the diameter of the holes the more evaporation rates were found. The higher the percentage of the holes the higher the evaporation rate was found. However the fabric with 0.5 mm holes cannot be used as the strength of the fabric was found to be less.

Test 4- Hole with different shapes

Holes of different shapes such as square and hexagon were tried but as the laser cutter was used for the cutting of the holes, the edges of these shapes were not sharp but rounded so they looked very similar to a circle.

Test 5- Hot water/ Pan/ Microwave

The PVA fabric was immersed in hot water (70°C and above) for 45 min. It was observed that the fabric partially lost it absorbent properties. Similar observation was found when the fabric was heated in pan and microwave. Therefore it could be concluded that the PVA fabric loses its properties when it is heated.

Test 6- Thickness Reduction.

Attempts were made to reduce the thickness of the fabric using grinding machine and sand paper. Unfortunately the surface finish achieved was not satisfactory and inconsistent.

Test 7- PVA Yarn

Knitting PVA yarn into a cloth and then using it for cooling garment is also possible, To check the feasibility of the PVA yarn and to compare it with PVA foam, couple of PVA yarn were bought from Hong Kong and the United Kingdom. Both of them were water absorbing yarn. Yarn brought from UK was SHC type Solvron yarn with dissolving temperature of 90⁰C. This yarn was a shrinkage yarn which could shrink upto 40-50% when immersed in water at 25⁰C. The yarn brought from Hong Kong was Durafil yarn with dissolving temperature of 80°C without any shrinkage properties. The results are as followed-

PVA Yarn	Specification	Evaporation Rate ($gm.hr^{-1}.m^{-2}$)
Hong Kong	8 ply	238.1
Hong Kong	16 ply	230.6
Hong Kong	24 ply	196.2
Hong Kong	32 ply	147
UK	8 ply	110

Table 12. Results obtained using PVA yarn

PVA yarn from UK cannot be used as it gives very low evaporation rate but the PVA yarn from Hong Kong has some potential to be used for this project

Conclusion

PVA foam with holes and PVA yarn from Hong kong both had high evaporation rate therefore could be used for the project. In the next section, the comparison between both of them can be found.

4.5 Selection of final direction

As mentioned in the previous section, various ideas were tested in the humidity and temperature chamber to check which one has the highest evaporation rate. Out of all of those PVA yarn and PVA foam with holes had the highest evaporation rate and were selected for further investigation. The plan was to choose one direction before heading to the conceptualization phase. In the following section comparison between them can be found

Power
Skin model was used to check the cooling power. In the following table comparison between them can be found The raw data for the power test can be found in Appendix F

PVA Yarn	Power from yarn (W)	Ratio of area covered with holes to the total are of PVA foam	Power from foam (W)
8 ply	5.9	70% holes	6.8
16 ply	5.7	50% holes	6.6
24 ply	5.8	30% holes	6.1
32 ply	5.9	No holes	5.7

Table 13. Power results obtained using PVA yarn and PVA foam. Average value of last 5 min of the test.

From the power testing the PVA foam with holes was found to be better than PVA yarn.

Flexibility
PVA yarn is more flexible than PVA foam (when both of them are dry). If the PVA is placed on areas with sweating rate (Sr) is higher than evaporation rate from PVA (Ep) the PVA should always remain flexible. Therefore flexibility should not be a deciding factor for choosing which one is better.

Water Uptake Capacity
This factor signifies the amount of sweat that can be absorbed by the fabric. PVA yarn can absorb three times its weight whereas PVA foam can absorb six times its weight. Higher the capacity, higher will it absorb the sweat but it cannot be concluded in this stage whether it is better to have higher or lower absorbing capacity. Weight of the jersey increases if it absorbs more sweat, on the other hand if it absorbed sweat evaporates quickly (during a descent), the PVA will be left with less or no water therefore the fabric is not cooling the body.

Weight
The weight depends on ply for PVA yarn and no. of holes for PVA foam. In the following table comparison between them can be found

PVA Yarn	Weight of the knitted fabric (gm)	Ratio of area covered with holes to the total are of PVA foam	Weight of PVA foam sample (gm)
8 ply	13.1	70% hole	13.6
16 ply	23.7	50% holes	14.5
24 ply	31.8	30% holes	15.7
32 ply	32.9	No holes	18.1

Table 14. Weight of PVA yarn and PVA foam

The differences in weight indicates that PVA foam is lighter than PVA yarn.

Conclusion
PVA foam was found to be better than PVA yarn but the differences between PVA foam and PVA yarn were small therefore after discussing with the chair and mentor of the project it was decided to use both of them for conceptualization stage.

4.6 Conceptualization

PVA is used in this project to prevent skin wetness. Therefore it should not be used in places where the skin will not get accumulated by sweat. Conservation of mass principle is used to find the number of holes required in the PVA foam and ply required in PVA yarn. The sweat released from the body can be one, evaporated from the skin, two, absorbed by PVA foam or three evaporate from the PVA foam. Using conservation of mass principle it can be said that-

Mass from sweat = mass evaporated from skin + mass evaporated from PVA (with holes/with ply) + mass absorbed by the PVA

Mass = Time*Surface Area*Rate

Therefore it is necessary to find the sweating rate, the absorption rate and the evaporation rates. Below, details of all the rates can be found

Sweating Rate

From figure 5, the sweat rate is obtained. At the front side of the body the evaporation rate from skin (Es) is higher than the sweating rate (Sr) that means sweat accumulation over here will be negligible. On the back side, the sweating rate (Sr) is higher than evaporation rate from skin (Es) therefore the skin will get wet. At the back side, the area with sweating zones with 515, 677, 701, 771 $gm.m^{-2}.hr^{-1}$ sweat rate, will get accumulated by sweat and therefore should be covered with PVA.

Absorption Rate

PVA is superabsorbent which means it will absorb all the water which is in contact with it. In this case the sweating rate will be equal to the absorption rate of PVA

Evaporation rate of skin.

The evaporation rate from the skin depends on the humidity, temperature and wind speed in the environment. The evaporation rate from skin (Es) was found out to be 427.1$gm.m^{-2}.hr^{-1}$ (back side) and 767.7 $gm.m^{-2}.hr^{-1}$. (Appendix I)

Evaporation rate from PVA

PVA Foam

The evaporation of the water from the pva foam depends on the percentage of the area covered by the holes and the diameter of the holes. The evaporation rate was measured at 0%, 30% 50% and 70% of the area occupied by the holes for 1mm and 1.5 mm diameter. The values can be found in the following graphs.

From the graph the relation between the rate of evaporation (y-axis) and area occupied by the holes (x-axis) were found and given by a straight line equation

For holes with 1.5 mm

Eq $Ep = 1.8026x + 148.84$ (eq7)

Foe holes with 1mm

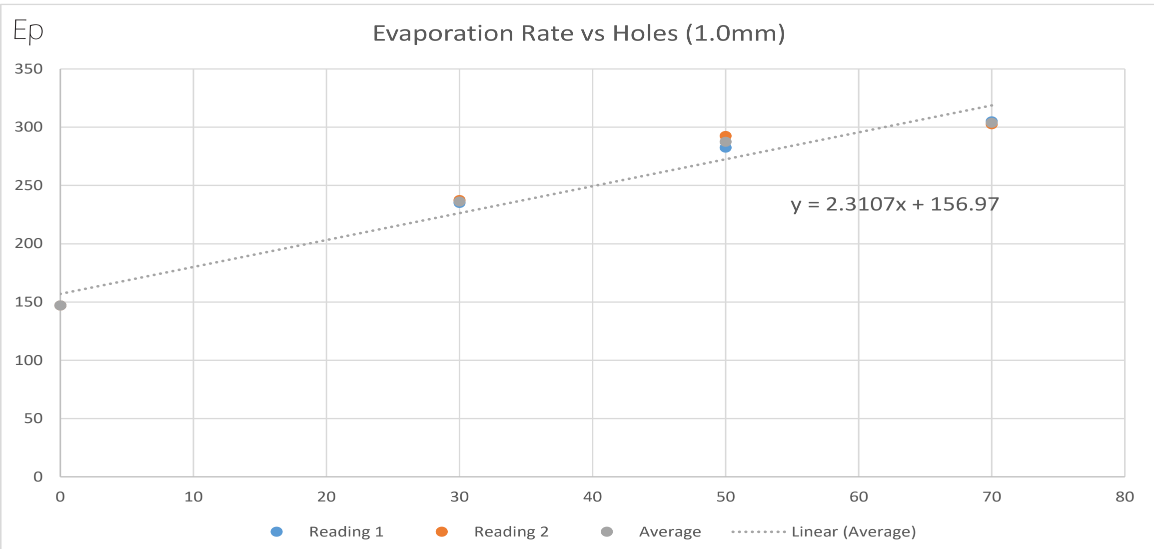
Eq $Ep = 2.3107x + 156.97$ (eq8)

PVA Yarn

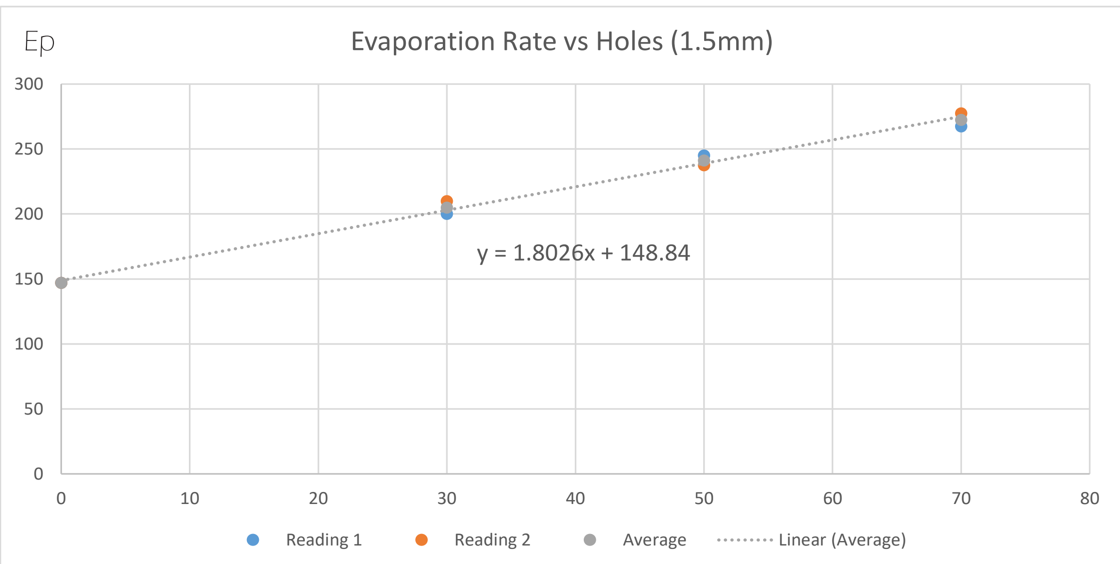
The evaporation rate of PVA with different ply configuration can be found in the table below

PVA Yarn	Specification	Evaporation Rate (gm.hr^{-1}.m^{-2})
Hong Kong	8 ply	238.1
Hong Kong	16 ply	230.6
Hong Kong	24 ply	196.2
Hong Kong	32 ply	147

Table 15. Evaporation Rate from various PVA yarn ply configuration



Graph 2. Evaporation rate (gm.hr^{-1}.m^{-2}) vs Perventage of holes (1mm diameter)



Graph 3. Evaporation rate (gm.hr^{-1}.m^{-2}) vs Perventage of holes (1.5 mm diameter)

Calculations

PVA foam with holes

All the rates are found, the calculations can be found in Appendix E The results of the calculations are given in the table 16

Sweat Zone	Percentage of the area with holes (1mm)	Percentage of the area with holes (1.5 mm)	Evaporation Rate from PVA (Ep) in that zone ($gm.m^{-2}.hr^{-1}$) (obtained by solving eq 7)
515	76.5	79.4	285.6
677	48.6	52.7	234.4
701	45.7	49.8	229.8
771	38.9	42.1	217.2

Table 16. Results after solving equation obtained from conservation of mass

From the table it can be interpreted that on the sweating zone of 515$gm.m^{-2}.h^{r-1}$,76.5% of the PVA foam should have holes of 1mm diameter. Similarly for other sweating zone, the calculation can be found in the table 16. Figure 12, 13 explains the concept

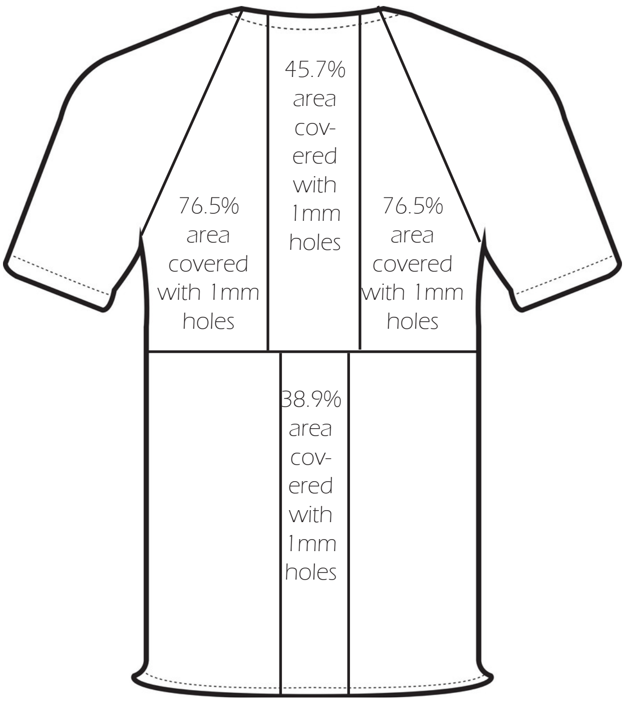


Figure 12. Concept with PVA foam and holes

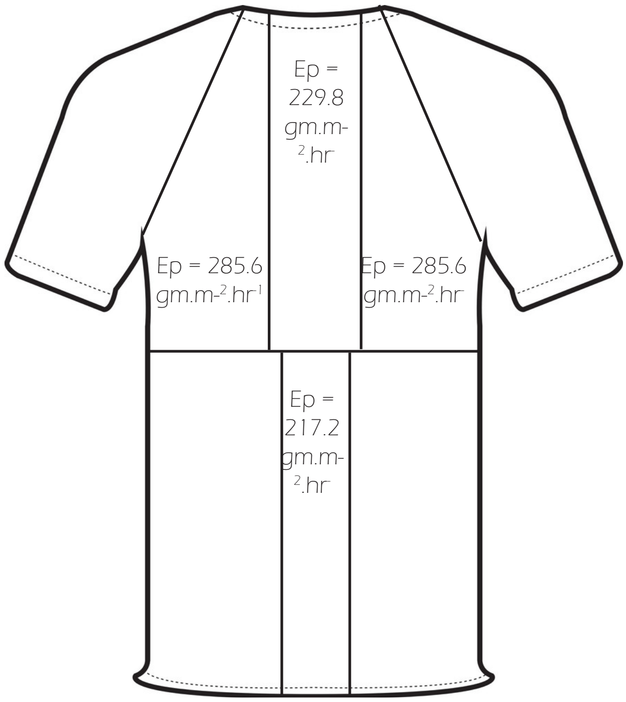


Figure 13. Required evaporation rate at various areas

PVA Yarn

From the conceptualization section from PVA foam, the required evaporation rate is already known figure 32. The PVA ply with the similar evaporation rate will replace the foam in respective places. Figure 14 explains the concept.

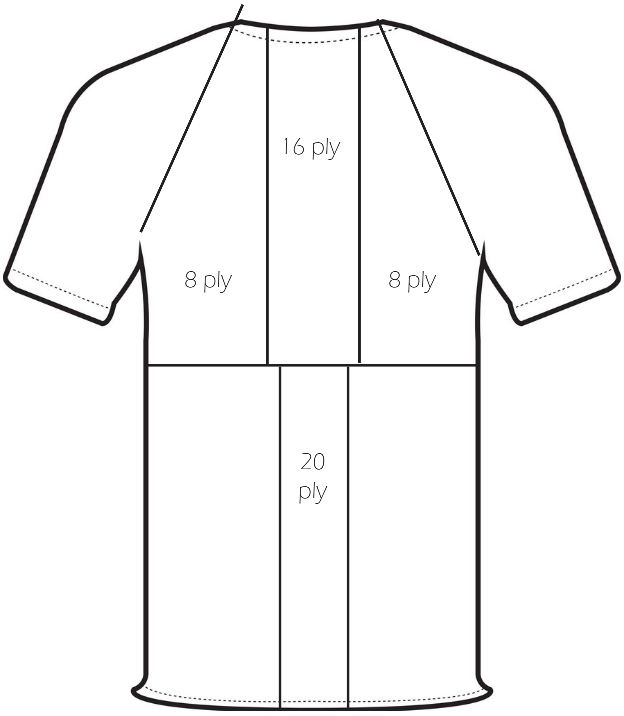


Figure 14. Concept with PVA yarn

Conceptualization stage is completed. In Appendix J, prototyping has been explained in detail.

Limitations of the calculations

The evaporation from the skin should not be calculated but should be measured. The values used in this project may not be accurate.

The wind speed in the humidity chamber varies. It is maximum near the fan and decreases when it is closer to the door. It also varies along the width of the chamber. A constant airflow over the sample is necessary to get accurate results.

The evaporation rate form the PVA with holes is not found at 2.5m/sec wind speed but at lower wind speed (around 1.5m/sec). That means the results will not be accurate.

Multiple iterations will be needed in a climatic chamber to improve the design and finalize it.

Figure 15. Images of the prototypes with PVA foam. From top left to bottom left, front view, right hand side view, back view and left hand side view. On the right side, isometric view.

Figure 15. Images of the prototypes with PVA yarn. From top left to bottom left, front view, right hand side view, back view and left hand side view. On the right side, isometric view.

05 CLOSURE

The final chapter will discuss the results of the project. Validation of the PVA jersey will be done through testing. This will compare the difference of the rise of core and skin temperature as well as perception parameters such as thermal comfort and thermal sensation. The test will also investigate the change in weight of the subject and the jersey, an indication of the evaporation rate.

After the validation, the conclusion will reflect back on the entire project, discussing the goal of the project and which requirements were met and which ones needs further work. Finally, recommendations will be made for the design in order to further optimize the jersey..

5.1 Evaluation

After the final prototype is made (Appendix J), the performance of the jersey has to be tested. In order to do that, experimental trials were performed with participants, cycling in Tokyo climate with the new designed jerseys and the current national Dutch jersey. In this section complete information can be found.

Method

Experimental Protocol

Four participants, two male and two female (represented by LT, LV, ML, KL) participated in the test. The participant attended three experimental trials, performed in a random order wearing either one of the three jerseys: current Dutch national jersey (unaltered), Dutch jersey with pva yarn (as per the new design developed in this project), Dutch jersey with pva foam (as per the new design developed in this project)

Few hours before coming to the test, the participants were asked to ingest temperature pills (MyTemp BV, Nijmegen, The Netherlands) so as to measure the core temperature (Tc) of the body. Before starting the test, each participant wore a belt with a data logger which collected the data form the pills.

Weight of the participants was measured with them only wearing cycling shorts and undergarments. Weight of the shoes and socks was measured separately. The weight of the jersey was also measured separately. All the weight measurements were done before and after the experiment. For the experiment trials with the PVA yarn and PVA foam jersey, 150gm of water was sprayed on the large size jersey and 140gm on the small size jersey before the start of the test.

To determine the local and the mean skin temperature (Tsk) thermal sensors (iButtons (DS1922L, Maxim Integrated Products Inc, Sunnyvale, CA, USA). were taped on four skin sites: the right scapula, right shin, left hand and neck as shown in the figure 16 which recorded the skin temperature. Tsk was measured throughout the trial at a sample frequency of 0.1 Hz Temperature sensor at the scapula was directly placed under the cooling part present in the new jersey which measured the local Tsk changes occurring as a direct result of the cooling garment A weighted average of the iButtons resulted in the mean Tsk, as described by ISO9886 (2004).

5 min before the cycling, the participants wears the jersey. All experimental trials consisted of 30-min cycling on an ergometer (Lode Excalibur bicycle ergometer, Lode, Groningen, The Netherlands) in a climatic chamber at Papendal Sport center. The climatic chamber was maintained at 33ºC and 70% RH. After entering the climatic chamber, participants first rested on a chair for 15 min to familiarize with the environmental conditions in which the exercise protocol would be performed and to allow stabilization of physiological values. 5 min before the test the participants wore the jersey. Then they performed 30 min cycling: first 15-min cycling, at a power rating of 2W per kg body weight.. This was followed by 15-min cycling adjusted to the physical capacity of the participants (3W/kg for one participant, 2.5W/kg for two participants and 2W/kg for one participant). Thermal images of the participants were captured with an infrared camera at the beginning and end of cycling. During the exercise protocol, participants were exposed to a frontal air velocity by a table fan placed at 80cm distance away from the steer of the ergometer.

During the test, participants were asked to rate their thermal sensation (general and back), thermal comfort (general and back), wetness perception of the back and rating of perceived exertion at the 0, 10, 20, and 30 min. For this purpose, four perceptual rating scales were used: a 9-point thermal sensation scale (i.e., −4, very cold −3, cold; −2, slightly cold,-1, cool; 0, neutral; +1,warm, +2 slightly hot, +3 hot, +4, very hot), a 5-point thermal comfort scale (i.e., +1, comfortable, +2 slightly uncomfortable, +3, uncomfortable, +4, very uncomfortable, +5 extreme uncomfortable)., a 9-point wetness perception on the back (i.e., -4, completely dry, -2, dry, -1, nearly dry, 0, neutral, +1, slightly wet, +2, wet, +3, very wet, +4 completely soaked), a 6 to 20-point rate of perceived exertion (RPE) scale (i.e. +7, very very light, +9, very light, +11, fairly light, +13, somewhat hard, +15, hard; +17, very hard, +19 very very hard).

Figure 16. White patches indicating the placement of the skin temperature sensor. Left most,neck and scapula, middle, hand and right most, leg.

Figure 17. Participant cycling during the experiment.

Results

Core Temperature (Tc)

Unfortunately, the temperature pill did not work for 4 out of 12 trials. 3 of these trials included the controlled jersey and remaining one was with PVA yarn jersey. Therefore data regarding those trials are missing. The rise in core temperature for 30 min cycling in case of 3 participants (LT, ML, KL) and 20 min for one participant (LV) for the remaining trial is mentioned in the table 17 below.

Jersey Type	Temperature increase (°C)			
	KL	ML	LT	LV
Controlled			1.72	
Yarn	1.37	1.72		0.91
Foam	2.15	1.47	0.87	1.12

Table 17. Results for rise in core temperature.

The results cannot be used to compare PVA foam and yarn jersey with the controlled jersey due to the missing data. Comparison between PVA yarn jersey and PVA foam jersey is still possible. For two participants (KL, LV) the rise of core temperature was higher with PVA foam jersey than PVA yarn jersey. For one participant (ML), opposite results were observed, the rise of core temperature wearing the PVA yarn jersey was higher than foam one.

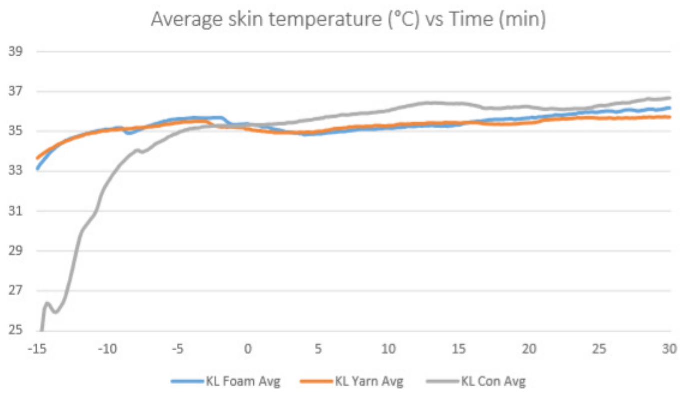
Mean skin temperature

The rise in mean skin temperature for 30 min trials for participants (LT, ML, KL) and 20 min for one participant (LV) for the remaining trial is mentioned in the table 18 below. This is the difference in mean skin temperature at 30 min and 0min.

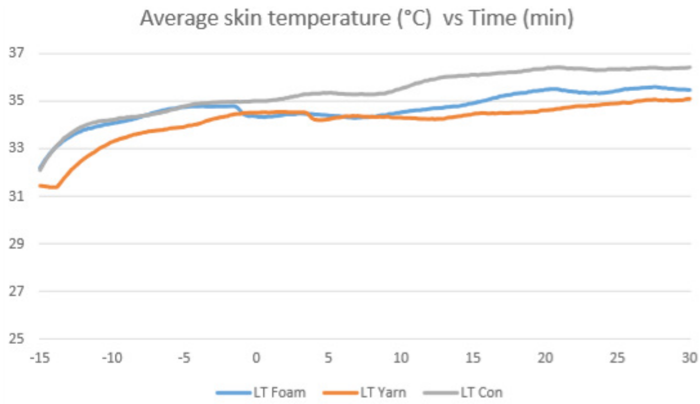
Jersey Type	Temperature increase (°C)			
	KL	ML	LT	LV
Controlled	1.35	2.06	1.42	0.71
Yarn	0.60	1.53	0.98	1.09
Foam	0.80	1.88	1.11	0.38

Table 18. Results for rise in mean skin temperature

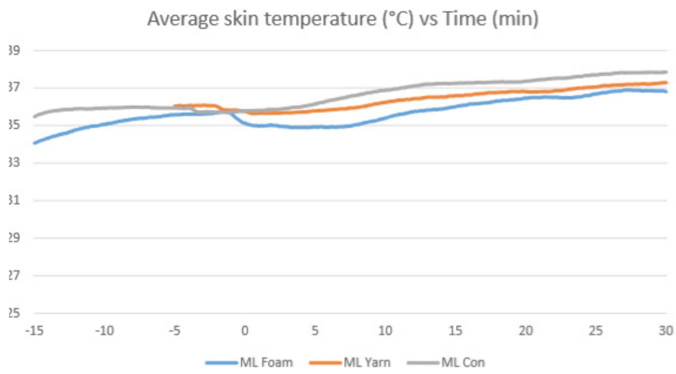
In all the trials PVA foam jersey performed better than controlled jersey as the rise of average skin temperature while wearing PVA foam jersey was less than that obtained while wearing control jersey. The lowest rise of mean skin temperature was found while wearing PVA foam jersey (LV). Eventhough the data has high spread, the mean rise in skin temperature is 1.39°C for controlled jersey, 0.95°C for yarn jersey and 0.99°C with foam.



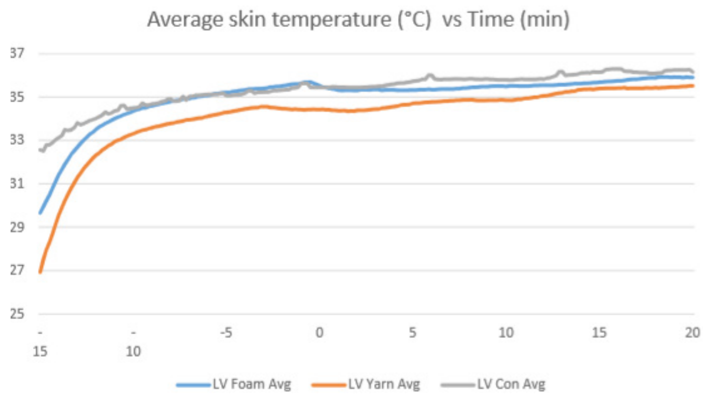
Graph 4. Average skin temperature for KL participant.



Graph 6. Average skin temperature for LT participant.



Graph 5. Average skin temperature for ML participant.



Graph 7. Average skin temperature for LV participant.

Graph 4,5,6,7 represents the average skin temperature from entering the climatic chamber (-15 min till the end of the test (30min). It is observed in few participants that the rate of increase of skin temperature decreases after they wear the yarn and foam jersey. In others, the temperature decreases for some time after which it starts increasing. In all four participants the skin temperature obtained at the end of the trial after wearing the controlled jersey was higher than foam and yarn jersey. In three participants (KL, LT, LV) the lowest temperature at the end of the trial was found while wearing yarn jersey.

Scapula skin temperature

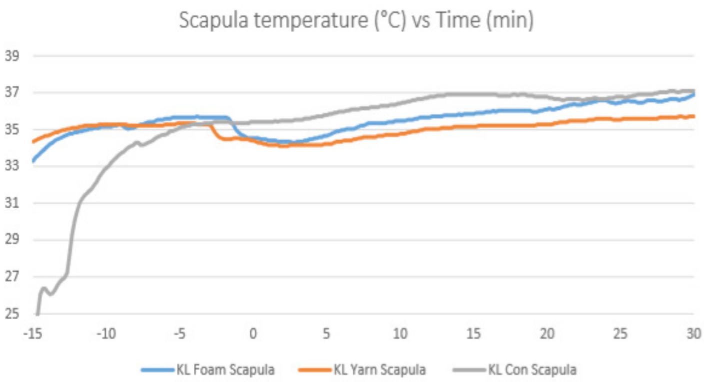
The temperature sensor at the scapula skin site is placed under the cooling portion of the jersey. As seen from the graph 8,9,10,11 there is a drop in the skin temperature soon after wearing the jersey. Table 19 shows the maximum temperature drop observed at the scapula after wearing the PVA yarn and foam jersey

Jersey	Temperature Drop (°C)			
	ML	KL	LT	LV
Yarn	1.17	1.24	1.62	1.61
Foam	2.74	1.43	1.87	2.18

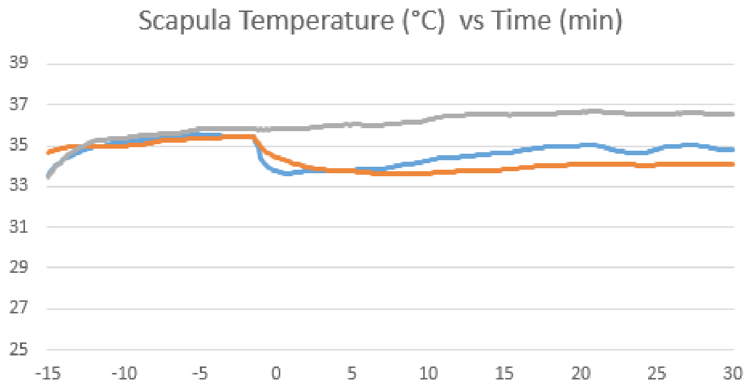
Table 19. Results for drop in scapula skin temperature

The temperature drop is observed in both PVA yarn and foam jersey. Temperature does not drop while wearing control jersey. Maximum temperature drop was observed to be 2.74°C using PVA foam (ML trial) and minimum 1.17°C using PVA yarn (ML trial). The average temperature drop using foam is 2.05°C and yarn is 1.41°C

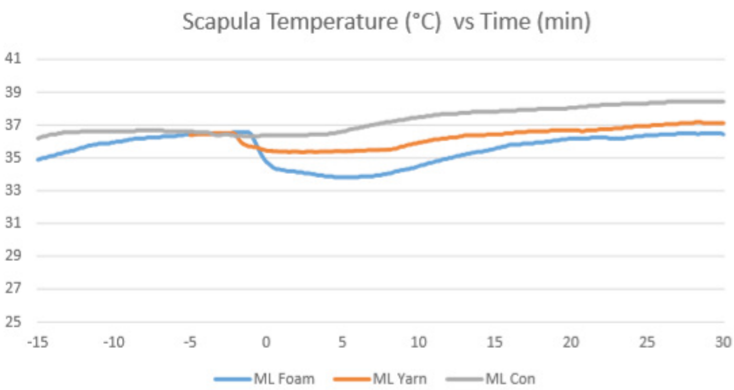
In all four participants the skin temperature obtained at the end of the trial after wearing the control jersey was higher than foam and yarn jersey. In three participants (KL, LT, LV) the lowest temperature at the end of the trial was found while wearing yarn jersey.



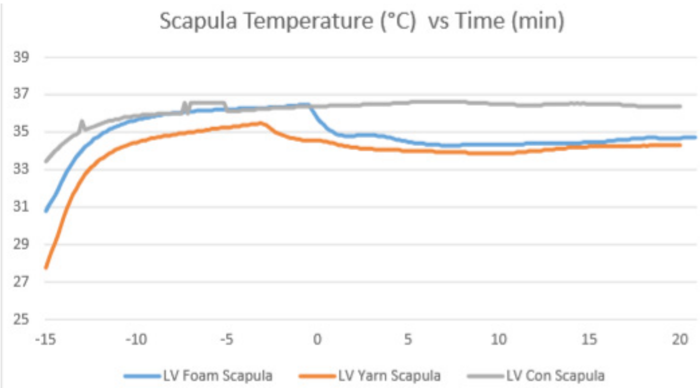
Graph 8. Scapula skin temperature for KL participant.



Graph 10. Scapula skin temperature for LT participant.



Graph 9. Scapula skin temperature for ML participant.



Graph 11. Scapula skin temperature for LV participant.

Fluid loss

In the following table total fluid loss of the body is presented.

Jersey	Fluid loss (gm)			
	ML	KL	LT	LV
Controlled	400	1000	100	400
Yarn	400	700	100	400
Foam	400	800	300	700

Table 20. Results for fluid loss of the body

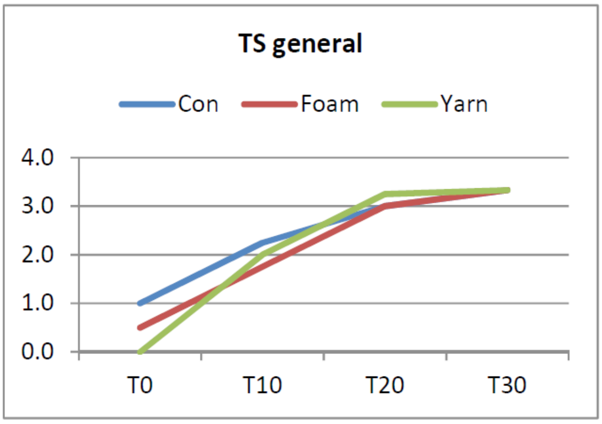
No relationship is found between the fluid loss and the jersey type.

Jersey weight difference.

The average difference in the weight of control, yarn and foam jersey is 59.25 gm, -3.75 (i.e weight of the jersey reduced) and 28 gm respectively. This data indicates that higher evaporation is achieved in yarn jersey followed by foam and than control. This does not necessarily indicate that the sweat evaporation is higher in foam and yarn jersey. Both of these jerseys had water sprayed on it at the beginning of the test which could contribute to higher evaporation. The results indicates that in Tokyo like environment the foam jersey should not become rigid because there is weight increase in the jersey due to the sweat (however the effect of wind speed on evaporation is not studied well in the test).

General thermal sensation

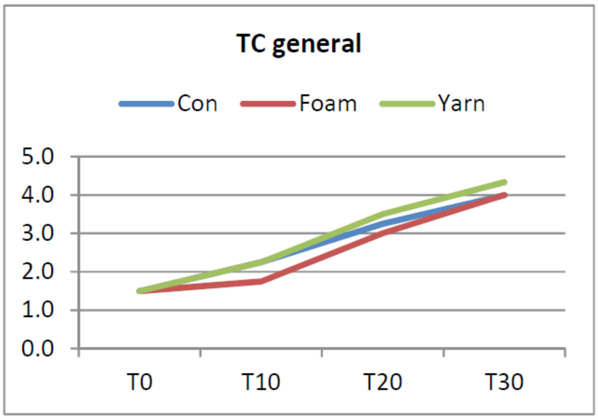
Mean thermal sensation scores for each trial are shown in graph 12. Overall thermal sensation recorded while wearing the controlled jersey, yarn jersey and foam jersey were 2.4 (i.e slightly hot), 2.1(i.e slightly hot), 2.1 (i.e slightly hot) respectively. Differences were observed at the beginning of the test where sensation after wearing the yarn jersey was found to be coolest followed by foam and control. By the end of the trail the sensation obtained wearing all the jerseys was observed to be the same.



Graph 12. Mean general thermal sensation.

Overall thermal comfort

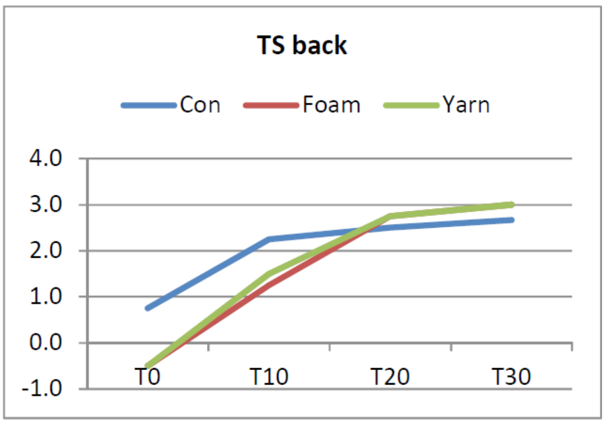
Mean thermal comfort scores for each trial are shown in graph 14 Overall thermal comfort recorded while wearing the control jersey, yarn jersey and foam jersey were 2.8 (i.e uncomfortable), 2.9 (i.e uncomfortable), 2.6 (i.e uncomfortable) respectively.



Graph 14. Mean general thermal comfort

Thermal sensation at the back

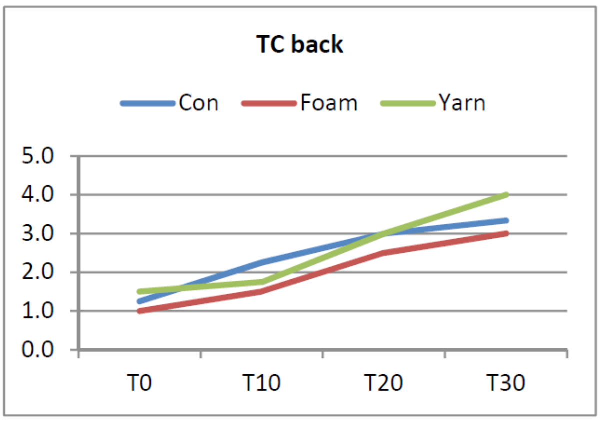
Mean score for thermal sensation at the back for each trial are shown in graph 13. Thermal sensation scores for the back while wearing the controlled jersey, yarn jersey and foam jersey were 2.0 (i.e slightly hot), 1.6(i.e slightly hot), 1.7 (i.e slightly hot) respectively. Differences were observed at the beginning of the test where sensation after wearing the yarn and foam jersey was found to be cooler than the control one.



Graph 13. Mean thermal sensation at the back.

Thermal comfort at the back

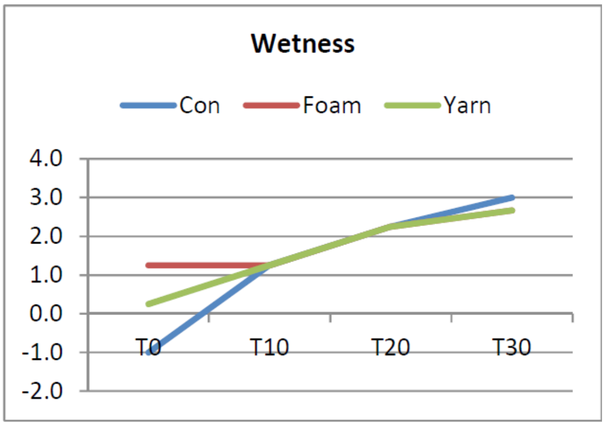
Mean scores for thermal comfort at the back for each trial are shown in graph 15. Thermal comfort recorded while wearing the control jersey, yarn jersey and foam jersey were 2.5 (i.e slightly uncomfortable), 2.6 (i.e uncomfortable), 2.0 (i.e slightly uncomfortable) respectively. Foam jersey is perceived to be more comfortable than yarn and control jersey at the beginning and the end of the trial . The yarn jersey is perceived to be more uncomfortable than foam and control jersey at the beginning and the end of the trial.



Graph 15. Mean thermal comfort at the back

Skin wetness

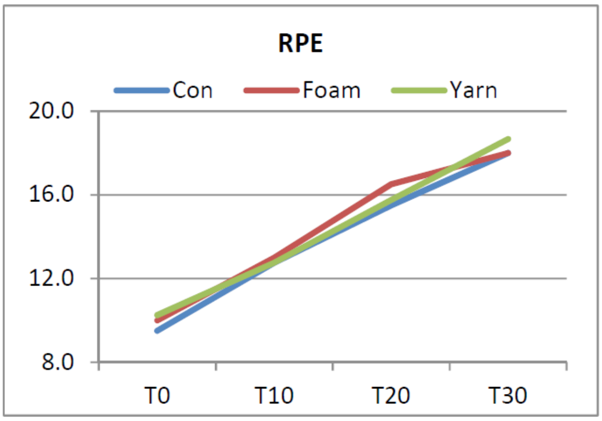
Mean wetness perception score can be seen in the graph 16. The score indicates that the wetness perception was "slightly dry" when the control jersey was worn and by the end of the trial it was "very wet" For the yarn jersey, the wetness perception was "neutral" at the beginning and "very wet" in the end. For the foam jersey he wetness perception was "slightly wet" at the beginning and "very wet" in the end.



Graph 14. Mean skin wetness

Rate of perceived exertion (RPE)

Mean rating for perceived exertion are shown in the graph 17. The average RPE score for control jersey, yarn jersey, and foam jersey were 13.9 (i.e somewhat hard), 14.4 (i.e hard) and 14.4 (i,e hard) respectively. RPE followed similar trend with all the three jerseys. It increased from "very light" to "very very hard" from the beginning of the trial to the end.



Graph 17. Mean RPE.

Discussion

The aims of this study were to investigate the physiological and perceptual effects of new jersey during cycling in hot and humid conditions. The outcome of the study indicates that the PVA yarn and foam jersey significantly lowered the scapula's local temperature. As studied in the "discover" section, this is because of conductive cooling by the PVA foam and the yarn. Local Tsk is instantly cooled by putting on the yarn/foam jersey, providing a cooler sensation for the first part of the trial. Although local Tsk seems to remain somewhat lower than control during the trial, thermal sensation scores become rather equal in the course of the trial. Other perceptual scores only show minor differences throughout the trials. As far as Tc is available, it does not provide a clear pattern regarding differences between conditions. Shirt mass increased less in foam and yarn conditions, probably mainly due to extra initial evaporation of the wetted back panel of the shirt. Total sweat loss not absorbed by clothing, seems higher in the foam condition than in the other two conditions. Unfortunately, the amounts of sweat evaporation and sweat dripped on the floor, could not be measured separately. So a difference in evaporative cooling power remains unclear.

In summary, the outcome of the study indicates that with the new jersey design has main impact on the mean and local skin temperature which is similar to the previous study by Filinger D, et al, .2015 where he testes evaporative cooling jersey (Oxylane, Quecha Aquafreeze, Villeneuve d'Ascq, France) on runners. but the impact on skin wetness, RPE, thermal comfort, and thermal sensation is negligible, opposite of what previous research suggests (Filinger D, et al, .2015). None of the results suggested that the new jersey has a negative influence on the performance of the cyclists therefore it can be concluded that the new jersey could be beneficial for cyclists especially for those participating in the Olympics where small differences usually can make a huge impact on the result of the race.

.The results can be improved by increasing the number of participants. Lack of participants makes it difficult to draw conclusions In this test, professional cyclists did not participate, so the results may vary for them. It was anticipated even before the test that evaporative cooling would be beneficial to reduce the skin temperature because of the cooling properties of the PVA material but it is important to check for how long will it be significant and can it be beneficial for long duration road race. From this test the effect of sweat management on the performance of cyclists is still unclear. Therefore it is recommended to do more comprehensive tests which is out of the scope of this project due to time limitations. In the end it can be concluded that the new jerseys have potential to be used for the Olympics but further work is still needed.

5.2 Conclusion

This section provides the reflection on the design of the jersey developed and improved during this project. For this purpose the list of requirements mentioned previously in the report is referred. It tells about the development achieved in the project and areas where the jersey could be developed even more.

Passed

Function
The clothing contributes towards improving the performance of the cyclist by reducing the skin temperature. This will contribute to cooling of the athlete. Therefore the new design passes this criteria.

Aerodynamic Features
The PVA integrated jersey developed in this project should perform in the same way as the present day jersey because the features which makes the jersey more aerodynamic are not altered. Placing the PVA foam and yarn away from the attached flow region and avoiding altering the vortex generator at the turbulent flow region makes it possible to do so. Therefore the design of the new jersey is aerodynamic.

UCI Rules and Regulations
The jersey neither alters the morphology of the rider nor does it changes the surface roughness and the original texture of the material. Therefore the design of jersey follows the UCI rules and regulation.

Ergonomics
The clothing is designed for racing position of the cyclist. No alterations were made on the size of the jersey. The present day jersey and PVA integrated jersey have the same features. Therefore the design is ergonomical.

Power
The jersey developed in this project has better cooling capability (refer to "discover" section) than the one Inuteq currently sells.

Uncertain

Environment
While testing the jersey at Papendal sport centre, there was no net fluid loss from the jersey during the trial, ensuring that the jersey remains flexible. However, the effect of wind could not be properly simulated therefore it is uncertain whether the jersey passes this criteria. Jersey with PVA yarn passes this criteria as the yarn jersey is always flexible.

Sponsor details
PVA foam is available in different colours and PVA yarn can be dyed. Logos can also be printed on them. Therefore displaying the sponsor details should not be a problem but this way not tried in this project

Weight
PVA will absorb water or sweat and the jersey will become heavier. This is inevitable, it is the property of the material but by making holes, the weight of the jersey is reduced. With the holes there are two advantages first, there is less PVA material therefore less water absorption and second, the evaporation rate of the water or sweat is higher which contributes to lowering the weight of the jersey. The weight of the jersey (in wet state) is lower than the one which Inuteq sells but higher than the present cyclist jersey.

5.3 Recommendations

The section is useful for one who will develop the jersey further. The improvements which could not be implemented in this project but will help in the development of the jersey are mentioned below.

Recommendation for Inuteq

Altering the properties of PVA material (so as to one, absorb less water so as to reduce weight and two, to prevent rigidity) could be a possibility. Consulting an expert in polymer science and technology should be the next step Inuteq should take. If possible Inuteq should also collaborate with the producer of PVA and try to alter its production ways. Then study the effect it has on the cooling properties and then select one or more production techniques. Thickness of the PVA should be reduced to improve cooling efficiency. Inuteq should request the producer of PVA to cut the PVA foam with less thickness

Evaporation rate from PVA fabric is dependent on the weather conditions where it would be used. If Inuteq wishes to sell the cyclist jerseys in The Netherlands, the design has to be modified so as to reduce evaporation from the PVA (as the humidity is lower and wind speed is higher than in Tokyo).This could be achieved by reducing the number of holes or by increasing the number of ply which would prevent the jersey from getting rigid

The wind speed at the back side was taken as half of the front side and the evaporation rate corresponding to that was used but the ratio of wind speed on the back to front is not constant but varies from 0.5 to 1. To improve the design further, the airflow topology studied by Crouch, T. N. et.al. could be used.

The best use of PVA fabric for cooling is when the user is not sweating continuously for a long time. Therefore using PVA for athletes playing sports such as archery, golf, weight lifting, shooting, billiards etc could benefit from it. Inuteq should seriously consider getting into these markets.

The current design of PVA jersey depends on the sweating rate of the athlete. Sweating rate varies and is not constant for every individual. Inuteq should consider making three different alterations of the design suitable for people who sweat less, sweat moderately and sweat a lot.

Recommendations for Thermo Tokyo Project

If the Thermo Tokyo group decide to use the current national jersey for Tokyo, few improvements can be made quickly. The present national Dutch jersey with lycra could also be improved by making small holes in it This ensures that sweat evaporates from the skin (closer to the body) and improves the efficiency of cooling by evaporation. This will prevent the jersey to become heavily soaked with sweat.

The nation Dutch jersey could be kept in a refrigerator or water could be sprayed on it before the start of the race. This would also give the same effect as obtained with PVA jersey but for less duration as the water absorption capacity of lycra is lower than PVA.

5.4 Personal Reflection

One of the personal goals in the graduation project was to get to know myself as a designer. What, So what and what next method found in Delft Design Guide is used to reflect on the project and find answers to the above question.

What?
Double Diamond process was used in this project. Before the discover phase mind map was used, experiments were performed during it. Problem definition and list of requirements were used to define the problem. In the ideation phase, brainstorm, how to's, biomimicry etc was used.

So what?
I have noticed, not just in this project but in previous projects that I like to use mind map at the beginning of a new project. Mind map can be used in an ideation phase too but I prefer to use it here. It is a great method to find the areas which are relevant to the project and questions which are needed to be answered to clearly understand the problem. On the other hand it can also be misused by exploring too many areas which may be irrelevant to the project. In the midterm evaluation, the supervisory team felt the research phase was too broad but I do not have much problem with it as I consider this phase as one of my strengths and I can do with quickly.
Usually gathering information through research papers, interviews, internet etc is sufficient to gain all the information relevant for the project but this time experimentation was needed. I did few internships in my bachelors which were related to similar experimentation which turned out to be useful in this project. Coming from an engineering background is useful for such projects. During this experimentation I understood the importance of getting consistent results every time an experiment is performed.
I agree with the supervisory team remarks list of requirements, it was below par but I tried to improve on it after the midterm. I think it is the most crucial part of the design process and getting it wrong would result in a wrong product but I had a clear understanding about it which helped me a lot.
Ideations usually starts with thinking of ideas which are on top of my mind then when I am exhausted with it I will use a few methods. Methods which can provide some stimulus such as biomimicry are very useful to think beyond the knowledge I have. Brianstorm sections are also useful because it uses someone else's knowledge to come up with ideas. My main motive during ideation stage is to just go wild and free and come up with as many ideas as possible without thinking of the feasibility. With all these methods it is possible to think of new ideas. I did not use any tools for selection of final direction, which makes sense in this project but I prefer to use a weighted objectives method. I like the quantitative aspect of it.

I think all the design methods makes the job of designer easy and that's why I like them but on the other hand, I do not think one has to use them every time. I usually use it less often than many students in our faculty but in the next projects I would like to use it more. I also think I learned a lot in this project to use the methods properly.

The design process used in this project was double diamond but the implementation of the process was not as organised as it can be seen in the structure of the report. The most scary but most interesting part is the first few weeks of the project. It is the chaotic phase where nothing is organised. Multiple stages were carried at the same time. Slowly and steadily the phases could be distincted for each other and after midterm everything looked more organised. This is how it is for most of the projects and is not surprising but it can get intense when one has limited time to complete the project.

Strengths and weakness
I think design and engineering are two different ways of thinking and the differences between them is significant. I studied mechanical engineering in my bachelors for which one needs to have strong analytical mindset. I consider this as my strength which is very helpful in literature review phase. Experimenting with the PVA material was an intuitive step for me because of my engineering background. I enjoy projects which focuses on embodiment. I think I am very good at simulation phase of the product design. It comes very naturally to me and I do not have to forcefully do it. Advance Concept Design (ACD) course is comfortable for students with design bachelors but I am not. Also one of the reasons I avoided those kind of projects for my graduation. I have very practical approach while designing which is not the best way to approach that course. I think coaches for ACD do not appreciate simple ideas. I am sure if this project was ACD course, using PVA and making holes in it as a concept would definitely not help me clear the course. I would like to improve in the conceptualization section but I do not see myself working on such kind of projects in the future.

What next?
It is dependent on the type of project which design process or methods I will use but if the project has similar characteristic I would still use the same process and methods. I will not make the mistakes I made this time and probably make new ones, but it is fine for me. I would still remain open to learn different ways of designing a product. If the project has different characteristics, I would love to explore new methods. I think the methods are really powerful especially when the project is different or outside of comfort zone.

Overall I am very satisfied with all the lessons that I have learned, and the process that I went through. Reading the book from N.F.M. Roozenburg and J.Eekels was crucial to bring the remaining bits and pieces of the design puzzle together. I am happy with the project The design was original.

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