Optimizing breathability and protection of a collarbone protector

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Abstract

The number of cyclists ending up in the hospital after a cycling accident increases each year. In 2014, 5100 cyclists ended up in the hospital, of whom 13.5% broke their collarbone. Many of them do not wear any protection besides a helmet. The protection that is available on the market is not comfortable enough.

Last year, a collarbone protector was designed for Comfortable bv, a company best known for its hip protectors. Although this design was protective enough for crashes, cyclists give high value to breathability and this design was not breathable enough. The aim of this research was to make the prototype more breathable.

Perforations were made into the material that performed best in last year's study. The upright cup method was used to determine the breathability and the lab test was used to determine the maximum acceleration. Obtained was that the protector will not be breathable enough for recreational cyclists by implementing perforations. By implementing perforations the water vapour permeability did not increase to an acceptable water vapour permeability value and the cushioning characteristics decreased. Further research has to be done for different material. Either by using completely different material or by implementing material to the current material.

Contents

1. Introduction

1.1 The research

In this research, which is performed at the university of Groningen in collaboration with Comfortable bv, a prototype of a collarbone protector is being improved for cyclists. Last year, a prototype of a collarbone protector is made by Laurens Schumacher. This prototype was not breathable enough for the end user. In order to sell the product a new design is required. We will try to develop this new design within this research. In this chapter the research method will be explained and also how the search will be done is discussed.

1.2. Research method

In this research, the regulative cycle is used to determine the research structure. The regulative cycle is an ongoing process which consists of six phases. First phase is the problem definition, which in this research is the problem analysis. In the problem analysis, the main problem is defined, and a research question is chosen to solve this main problem. In the problem definition phase, mostly literature search is done. Interaction with Comfortable is needed in this phase as well to define their requirements and goals. Following, is the analysis phase, during which the problem will be analysed and methods will be set up. In this analyse phase, literature research is required again. Google scholar and Smartcat are used to do the literature research. Especially material science journals will be used. Methods for measuring breathability should be found. Later the methods will be executed and the tests will simulate an actual situation. A physical set-up will be used for testing breathability and protection. Besides the physical set-up, materials for the collarbone protector and Matlab are required for the test and simulation phase. Testing and simulating will eventually lead to a redesign of the collarbone protector. Due to the limiting time span of this research, the redesign will probably not be implemented in this research. However, it might be possible to do the implementation on small scale. After this the cycle will start over again. It is important to note that the evaluation of all steps will be done separately before starting the next step.

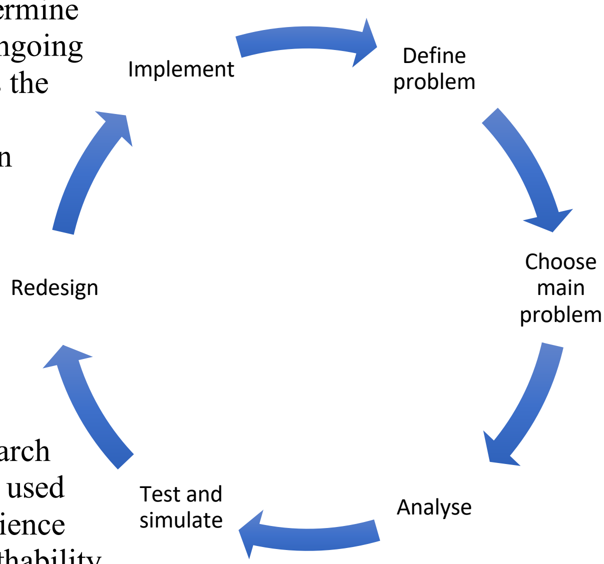


Figure 1. Regulative Cycle

2. Problem analysis

In this chapter the problem of this research is identified and analysed. Stakeholders and problem holders are discussed and a description of the system will be given. This problem analysis will lead to a main research question with its sub questions.

2.1. Problem Description

The number of cyclists ending up in the hospital after a cycling accident each year increases. In the Netherlands, the number of cyclists in the hospital has more than doubled in four years' time [1]. In 2014, 5100 cyclists ended up in the hospital. The most common failures are: collarbone fracture, brain damage and collapsed lungs. Of all cycling injuries, 13.5% of the cyclists breaks their collarbone [2]. The treatment of a cyclist is the most expensive treatment of all sports injuries. The average cost of all treatments is €2900, this is a huge amount of money that has to be paid. A helmet can prevent a cyclist from brain damage, but there is not a good wearable protector yet to prevent collarbone fracture.

Last year a prototype was designed for Comfortable bv, by Laurens Schumacher, student of the University of Groningen [3]. Cyclists do see the need to wear shoulder protection now, but the protection on the market is not comfortable enough. Laurens Schumacher did a survey in his research among 83 cyclists to find the aspects cyclists value most in protection. Cyclist value the breathability, comfort, lightweight, good aerodynamics and low visibility of a shoulder protector. Breathability is rather important for the cyclists, but this is not yet included in the prototype that is already made. Cyclists choose comfort over safety, thus they do not wear protection for the collarbone and shoulder [3]. At the end of Laurens' research, the prototype of the collarbone protector was tested. Outcome of this test was that the prototype was not breathable and had no ventilation. Perspiration arose under the protector and could not evaporate. A collarbone protector is placed over the shoulder, as impact on the shoulder can cause a collarbone fracture. The collarbone fracture almost never arise from immediate contact with the collarbone itself, but from a force on the shoulder.

2.2. Problem Statement

The current collarbone protector prototype experiences low breathability, while cyclists give high value to breathable sportswear.

2.3. Problem Holder Analysis

In this research the problem owner is Comfortable bv. This company gave the order to redesign the collarbone protector prototype to improve the breathability of the protector. Comfortable bv is a Dutch company that produces health care related products and recently started to produce sports products, but not yet protective sports products. The company designs multiple protectors for medical services. Comfortable bv wants to develop a competitive product on the market and they desire to satisfy their customer. They have the patented material that can be used for the protector. In this manner, they do not have to do big investments to produce this product. A requirement is that the company does not want to give in on protection. In Laurens' research it was investigated that the protection of the prototype is 21%, with respect to no protection. Materials they own are flexible and easy to fabricate. Its breathability must be optimized without decreasing the level of protection. In order to sell the product, good knowledge of the breathability and protection have to be known. The problem focuses on improving the breathability and retaining the protection in the current design, this is not something the cyclists can produce.

2.4. Stakeholder analysis

There are multiple stakeholders in the redesign of the collarbone protector. Comfortable is a stakeholder, which is already discussed as a problem owner.
The second stakeholder is the user of the collarbone protector. Obviously, the stakes of the user of the collarbone protector are price and quality. The target of the market is the recreational cyclist, who is 45 years old or older. This group values a safer ride and does not care about a few grams more on the shoulders. Recreational cyclists find it important to have comfortable protection of high breathability. The protector should be thin, lightweight, reliable and has to have good aerodynamics.
Lastly, Laurens Schumacher is a stakeholder. He started this project last year and developed a prototype. Laurens also investigated the peak force a collarbone can handle before fracture. It was his idea to do more research on the breathability of the collarbone protector, since he noticed this is a quite important aspect for cyclists. In table 1 an overview is given of the three different stakeholders and their goals and requirements.

Table 1. Stakeholder analysis, with their requirements and goals.

Stakeholder	**Requirements**	**Goal**
Comfortable bv.	- Protection higher or equal to 21% - Flexible materials - Easy production - Use own materials	- Design a product that can be sold and protects/satisfy the user
Recreational cyclists	- Price - Quality - Comfortable - High breathability - Reliable - Good aerodynamics - Thin - Lightweight	- Safer ride with collarbone protector
Laurens Schumacher	- Breathable - Good testing material	- Safe, reliable product

2.5. System Description

A system description is made to obtain a better understanding of the system and can be seen below in figure 2. The entire system is the human body with the protector on the shoulder. A subsystem is the shoulder with the collarbone protector. The prototype of the collarbone protector is the existing sub system, which was produced by Laurens Schumacher last year. The desired system is a breathable and protective collarbone protector. The characteristics of the system are mainly comfort and impact resistant. The comfort depends on different factors, namely the design and material properties. In earlier research for protective sportswear the design issues were stated, this figure can be seen in the appendix A. The design issues listed there are; density, flexibility, injury mechanism, seams, breathable and thickness [14]. However, a comfortable shape and good aerodynamics are important as well. The material properties are namely high breathability and protection. Aspects of impact resistance are acceleration and mass. A good impact resistant protector is dependent on the mass and acceleration. In the modelled system the material will get influenced by a mass and the acceleration is measured by a sensor. Breathability is measured by performing a breathability test in a simulated environment.

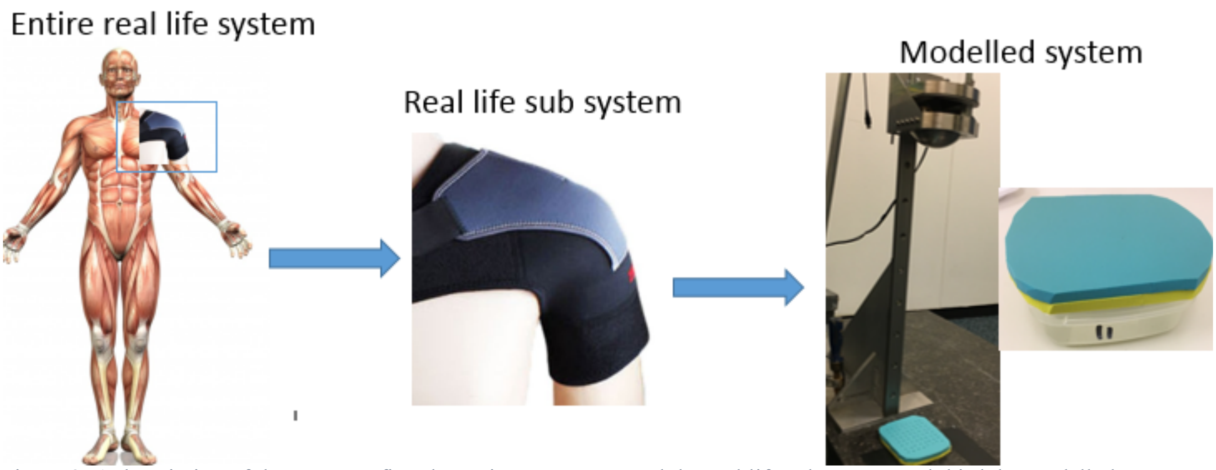


Figure 2. A description of the systems, first the entire system, second the real life sub system and third the modelled system which is to be tested.

2.6. Research goal

The research goal of this research is to find a way to make a material breathable and protective enough for cyclists.

2.7. Design goal

The design goal of this research is to redesign a collarbone protector, which is optimized in the field of breathability and protection.

2.8. Research question

2.8.1. Main research question

- How to obtain the most optimal redesign for the collarbone/shoulder protector, where trade-off between breathability and protection is best for a recreational cyclist?

2.8.2. Sub question

- What is a good value for breathability?
- How can an existing material be made breathable?
- Which tool can be used to measure the breathability of a material?

The aim of the study is clear and as from now thorough literature research will be executed in the next chapter.

3. Literature Research

In this chapter literature research on different breathability test methods will be discussed. Literature search will also be done on how to make the existing material breathable. Easy production and price should be taken into account with making the existing material breathable. The patented material used by Comfortable bv. is discussed and the fracture force needed to break a collarbone is discussed. Literature research is done by using SmartCat and Google Scholar and Google Scholar patents for making the existing material breathable. Some terms that are used are: 'Breathability tests', 'Breathable protective sportswear', 'breathable sports material', 'breathable material', 'make existing material breathable', 'breathable sports pads', 'make material permeable', and 'permeable materials for sportswear'. Information about the material properties is given by Comfortable bv.

3.1. Breathability test

3.1.1. Sweating guarded hot plate method

Multiple methods for determining the water vapour permeability have been compared [4,5]. Four methods will be discussed. The first method is the Sweating guarded hot plate test, whereby the evaporative resistance of the fabrics was measured. This measuring setup consists of a measuring unit and a water supply unit. The fabric that needs to be measured is placed above a metal plate. The plate is heated up to 35°C, to simulate the human skin temperature and kept at a constant temperature. Water flows onto the metal plate from the water supply. Water vapour will pass through the fabric. This causes evaporative heat loss and to keep the plate at 35°C more energy is needed. Then the total evaporative resistance of the fabric can be calculated by using the following formula:

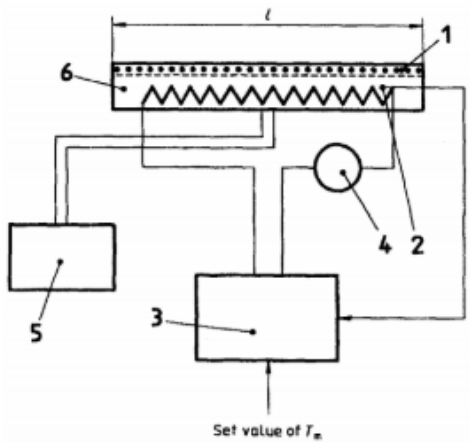
$$R_{et} = \frac{A(P_s - P_a)}{H - \Delta H_e}$$

where:

R_{et}= the total evaporative resistance by the fabric, m^2.Pa/W.
A = the test area in m^2
P_S= the water vapor pressure at the plate surface, Pa
P_a= the water vapor pressure of the air, Pa
H = the heating power in Watt
ΔH_e= the correction term for heating power in Watt.

The measuring setup, which can be seen in figure 3, is placed in a chamber where temperature, air velocity and humidity are constant.

The less resistance to transfer water vapor, the higher the breathability. This can also be seen in table 2, where the water vapour resistance values are linked to a suggested performance [6].



1. Metal plate; 2. Temperature sensor; 3. Temperature controller; 4. Heating power measuring device; 5. Water-dosing device; 6. Metal block with heating element.

Figure 3. A schematic view of the sweating guarded hot plate method

Table 2. The suggested performance for the water vapour resistance values for the Sweating guarded hot plate method

Water Vapour Resistance value (m^2 Pa/W)	Suggested performance
0-6	Very good or extremely breathable. Comfortable at higher activity rate.
6-13	Good or very breathable. Comfortable at moderate activity rate
13-20	Satisfactory or breathable. Uncomfortable at high activity rate.
20-30	Unsatisfactory or slightly breathable. Moderate comfort at low activity rate
30+	Unsatisfactory or mot breathable. Uncomfortable and short tolerance time.

3.1.2. Upright cup method

The second method, which is shown in figure 4, is the upright cup method. In the upright cup method, a material will be placed over a test cup. This test dish contains a predetermined quantity of water, between the water and the material is a layer of air. At first a reference material should be tested and after the to be tested material will be tested. After the tests the water vapour permeability can be calculated by using the following equation:

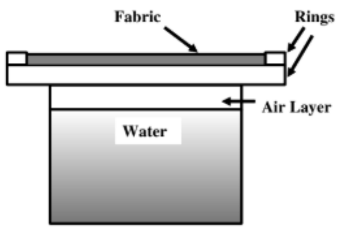


Figure 4. Upright cup method to test breathability

$$WVP = \frac{24 * M}{A * t}$$

where:
WVP = water vapour permeability, $g/m^2/day$
M = the loss in mass of the dish, g
t = the time between the start and the moment the dish is weighed again, h
A = the area of the material and this is equal to the area of the cup, m^2.
The temperature is kept at room temperature, humidity and air velocity are kept constant as well. The outcome can be compared to the reference material by using the following formula:

$$I = \frac{WVP_{test}}{WVP_{ref}} * 100$$

this gives a percentage related to the reference water vapour permeability.

3.1.3. Inverted cup method

The third method, which is displayed in figure 5, is the inverted cup method. The calculations of the inverted cup are the same as the upright cup. The test conditions are the same as those for the upright cup method. The cups were placed in the inverted position.

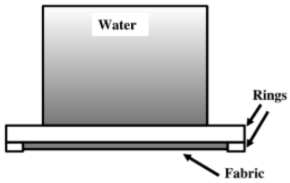


Figure 5. Inverted cup method to test breathability

3.1.4. Alternative method

A last method is a cheaper alternative for the sweating guarded hot plate method. A schematic diagram is given in figure 6. A piece of cotton fabric is placed on the hot plate, with a hole in the middle. Above the cotton fabric an impermeable membrane was placed. Another piece of cotton was placed on the hot plate to cover the hole. This piece of cotton was connected to a water supply container. This simulates the skin with sweat. A waterproof but vapor permeable PTFE membrane is placed upon the cotton layer. A thermocouple is placed between the PTFE membrane and the cotton, to measure the temperature of the cotton fibre. Again, the hot plate was set to a temperature of 35°C. The material that is tested is place upon the PTFE membrane.

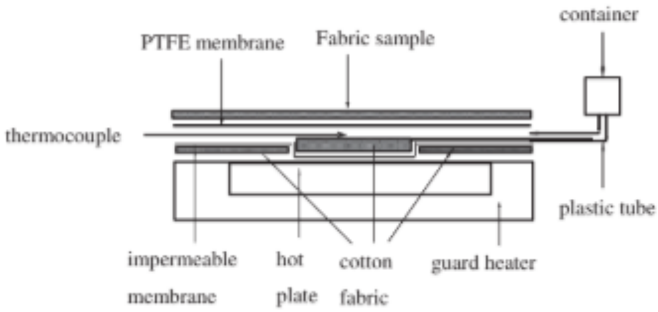


Figure 6. The alternate guarded hot plate method

3.2. Increase breathability of material

On the internet is searched for methods to make material breathable. Information for making existing material breathable is limited. Implementation of perforations is the only method found on the internet. Protective gear has been analysed on the internet. A couple of athletic protective pads are found on google patents [7,8,9]. Perforations are applied to the material to make it more breathable. The purpose of these perforations is ventilation and cooling the user. The amount and the shape of the perforations differ among the different products. An example of perforations applied to a material can be seen in figure 7 [9]. In an article of firefighters clothing the intervals between adjacent perforations range from 3.2 mm and 13 mm [7]. Densities of the perforations range from 1 to 5.5 per cm^2. Perforations are also applied to gear which protects the chest, shoulder and rib, as can be seen in figure 8 [8]. A pair of protective sports pants includes spaced apart perforations to the pads for protection [9]. The perforations are applied in straight lines. In most patents no dimensions are mentioned. However, another invention did mention dimensions, which were 0.5mm to 1.3mm and a spacing between adjacent perforations of 3 to 5 mm and at least a density of 9.3 perforations per cm^2 [10].

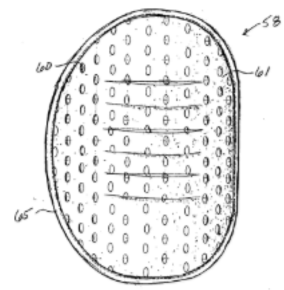


Figure 7. An example of a Protective pad

Fig. 2

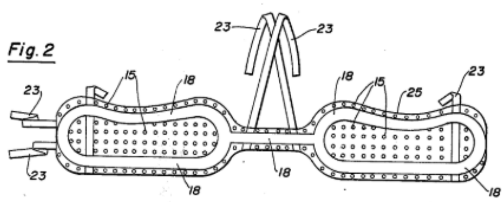


Figure 8. Protective Shoulder pad with perforations

3.3. Material

The material that will be used for the redesign of the collarbone protector is equal to the material of the previous prototype. The material that has the highest protection is 6mm of the green Poron X2-medium Patrol on top and 6mm of the yellow Poron XRD Absorb Yellow on the bottom [3]. It is also stated as G6Y6, which means 6mm of green material and 6mm of the yellow material. The X2-medium Patrol material is stiffer than the XRD Absorb material. A softer material, PX Absorb, deforms more under pressure. This means that the material deaccelerates the object at a slower rate, which results in a lower impact force and more energy absorption. After testing the Poron XRD, it is confirmed that Poron XRD material absorbs more than ninety percent of energy upon repeated impact [11]. The material not only absorbs more energy than alternatives, it is soft, lightweight and contouring. Both Poron materials are made of polyurethane and are open cell structured, which means that every cell contains an opening. The effect of an open cell structure is that when you squeeze it, the air goes out of the cell but the air can go back in afterwards. The advantage of an open cell structure is that the material is long lasting and the performance will not break down after multiple impacts. Both materials are flexible, soft and easy to fabricate. The combination of poron XRD and X2 experienced a maximum peak impact force of 5.0kN. A protector of this material can lower the peak force on a collarbone with 21%. The material properties are listed in the appendix B and C.

Figure 9. Yellow Poron XRD and Maroon Poron X2

3.4. Fracture Force

In Laurens Schumacher's integration project, the maximum impact force is determined. With the aid of post mortal objects, he measured the force that should be applied before fracture. This maximum force is around 2.6kN [3]. In research of Ianotti et al. the force has been determined by doing a static setup. The collarbone was fixated with a plate behind it. In this situation, the fracture force was between 1.3 and 1.5kN [12].

3.5. Risk analysis and contingency plan

The collarbone protector will be redesigned for better breathability by implementing perforations. However, it might be possible that the protection is not enough to withstand a crash when holes are implemented or the perforations will not provide enough breathability. Another method must be obtained by doing more literature research. Perhaps another material should be tested or other material should be implemented in consultation with Comfortable bv.

From this literature research the method for measuring the breathability can be obtained, which will be discussed in the next chapter. Increasing the breathability will be done by implementing perforations to the material. No more literature is found to make an existing material breathable in an inexpensive manner. In literature the method of implementing perforations is found effective, thus this will be done in this research.

4. Methods

In this chapter the methods for the acceleration test, breathability test and how to implement the perforations will be discussed. The acceleration test is called the lab test and will be explained in this chapter. Breathability will be examined using the upright cup method. The upright cup method will be used due to the time frame. This is the cheapest and easiest method to use and has a good correlation with the sweating guarded hot plate method.

4.1. Lab tests

In the first tests the material is first adjusted to do the tests. Adjustments will be made by implementing perforations. If this is done, the actual test can start. This test is similar to the one Laurens Schumacher did with the first research on the collarbone protector. The test setup is shown in figure 10. The length of the slider is 200cm and a cart with a weight of 4kg will fall along the slider. The cart will be released on a height of 52cm. An acceleration sensor was applied to the cart and material was put on the bottom plate with a granite plate below to absorb the remaining energy. The data of the acceleration sensor was connected to the data acquisition tool. This tool translated analog input to digital output. The data was sent to the computer and using Matlab, Data Translation graphs were displayed of each situation. All different situations were tested three times, with a pause of twenty second between every try.
With the use of a stick the cart stays on top, by pulling out the stick the cart falls down. The graphs that are obtained display an acceleration, although it actually is deceleration since the granite plate and the material decelerates the cart.

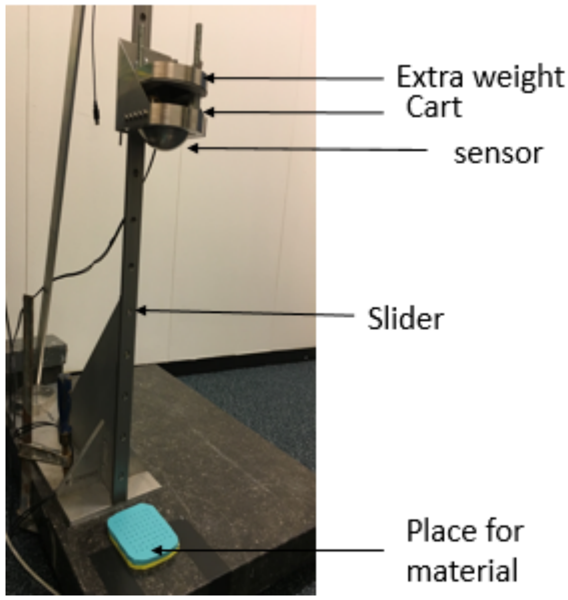


Figure 10. A schematic view of the Lab test

4.2. Breathability test

The breathability test is done by using the upright cup method. All the different material situations will be tested. The reference material is the material without any perforations and one without material on the cup. The different material situations are all tested at the same time to account for temperature and humidity changes. A cup of 0.45L is used and is filled to 10mm from the top. The yellow material should be placed on top of the cup with the green material placed on the yellow layer. Both layers are glued together.
The acceptable value for breathability will be set from 0-13m^{2}Pa/W of the water vapour resistance of the sweating guarded hot plate method. This value can be seen in table two and stands for good to extremely breathable. The acceptable value of the breathability of the upright cup method will be set higher than 845g/m^2/day. This is obtained by comparing it to the water vapor resistance value in the article of Huang [5]. The tests correlate with each other, hence the values can be compared. The correlation between the upright cup method and the sweating guarded hot plate method is 0.8.

Table 3. Comparison of WVR and WVP [5].

ISO 11092	E 96-B
R_{ef} (m^2 Pa/W)	*WVT* (g/m^2/day)
2.6 (±0.38)	1,355 (±101)
3.9 (±0.78)	1,649 (±116)
13.4 (±0.48)	845 (±12.7)
15.1 (±0.99)	882 (±65.4)
275.5 (±13.4)	295 (±48)
363.9 (±10.4)	149 (±29.8)

4.3. Application of perforations

The perforations are applied using a punch. Multiple punches are available in the workshop of the university of Groningen with different diameters. Diameters between 3 and 30mm are available at the workshop, which can be seen in figure 11. The punch is pressed onto the material and then a hole is obtained in both layers. The area that is exposed to the water in the breathability test and thus perforated is equal to $8 \cdot 8 = 64cm^2$.

Figure 11. All of the punches in possession of the university of Groningen

Methods that are discussed in this chapter will be used in the following chapter for testing and simulating the material samples.

5. Testing

In this chapter the testing and simulation of the material will be discussed. The material samples are first tested on their breathability and thereafter they are tested on their maximum acceleration. The mean maximum acceleration is the acceleration that is being measured by the sensor of the measuring set-up. The higher acceleration, the lower the performance. Needs for the methods are discussed. First a pilot study is done for getting used to the set-ups and to find faults within the set-ups if there are. Results of the follow-up study are more accurate since the methods are clear to the researcher.

5.1. Pilot study

A pilot study was done to get used to the measuring setups and to obtain first findings in breathability and protection. In this pilot study, four different samples are tested which can be seen in figure 12. In table 4 the amount of perforations per sample are displayed. The first sample is a layer of material without any perforations. The second sample that is tested contains 1 perforation per 20cm^2, thus 8 perforations. The third sample contained 1 perforation per 10cm^2 and the last sample contained 1 perforation per 5 cm^2. All perforations have a diameter of 3mm.The breathability is tested by using the upright cup method and the protection is tested using the method described under lab test. Since the production of the final product should be easy, the perforations are all in line with each other.

Table 4. Dimensions of the samples, with the amount of perforations and the diameter of the perforations.

Sample	Perforations	Diameter (mm)
D0Q0	0	0
D3Q8	8	3
D3Q32	32	3
D3Q64	64	3

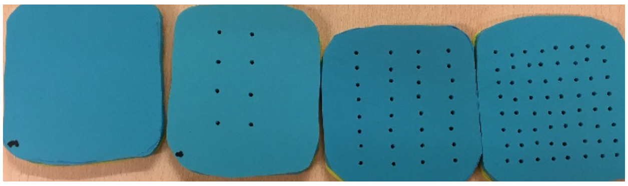


Figure 12. All four samples used in the pilot study

All four samples were first tested on their breathability and hereafter the protection was tested using the acceleration test. The samples consist of a 6mm yellow layer and a 6mm green layer, which are glued together.

A list of necessities for the breathability test is listed below:

- Four cups
- Water
- Punch
- Measuring cup
- Thermometer and hygrometer
- Scale
- Four material samples

The thermometer and hygrometer were used to measure the humidity and the temperature at the beginning of the test and at the end of the test. All samples were tested at the same time to control for temperature and humidity changes.

Below the necessities for the acceleration test are listed:

- Measuring setup
- Weights
- Clamp
- Laptop with matlab
- Four material samples

The weights and clamp were used for stability of the test. On the cart, one more weight was adjusted to a final weight of 4kg. The test is repeated three times to obtain a mean maximum acceleration.

At the start of the test the temperature was 21.3°C and the humidity was 39%. After 20 hours the temperature was 21.1°C and the humidity was 36%.

During the breathability test the yellow material is facing downwards, to the water and the green material is facing up. During the lab test the green material if facing up and the yellow material is facing down. The reason of this is that the yellow material is placed on the body and the green material will first catch the load. The breathability test is done first, which is comparable to a real life situation, where a cyclist will probably first sweat and then crash.

5.2. Follow-up study

Following the pilot study, the effect on breathability and protection of the diameter and quantity was determined. A percentage of the entire area is taken to apply the perforations to. Four different diameters are determined and three different percentages. The percentages are 5, 15 and 30% of the entire area. The quantity is derived with the following formula:

$$Amount\ of\ perforations = \frac{A_{perforation} * percentage}{A_{total}}$$

Where $A_{perforation}$ is the area of one perforation, which is determined by the following formula: $A_{perforation} = d^2 * \frac{\pi}{4}$, percentage is the percentage of the total area that should be perforated and A_{total} is the total area of the material that is exposed to the water. In table 5 the values of each situation are given.

Table 5. Number of perforations for each percentage of area covered and for each diameter

Diameter (mm)	Area of one perforation(mm^2)	Number of perforations at 5%	Number of perforations at 15%	Number of perforations at 30%
3	7	45	136	272
4	13	25	76	153
6	28	11	34	68
8	50	6	19	38

At the start of the breathability test the temperature was 21.9°C and the humidity was 41%. After 24 hours the temperature was 22.2°C and the humidity was 40%.

Acceptable standard deviation during the lab test was discovered by measuring one try for seven samples. Differences between materials were measured by doing the breathability test for only yellow and only green material. A cup without any material is also investigated to find the maximum WVP.

In this chapter the methods are clear and results are obtained, which will be discussed in chapter 6.

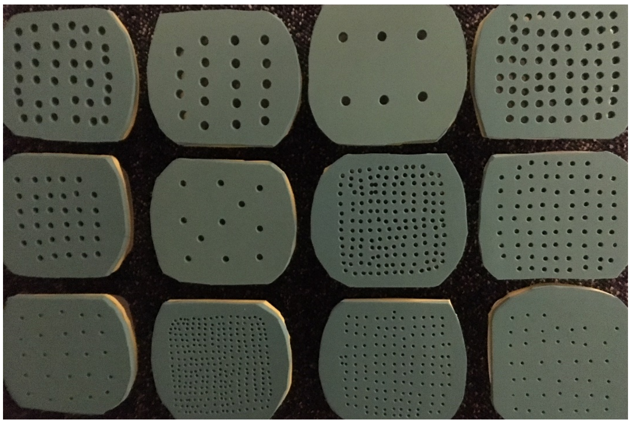


Figure 13. All twelve different samples used during the follow-up study

6. Results

In this chapter the results of the breathability and lab test will be given. First the results of the pilot study are given and afterwards the results of the follow-up study.

6.1. Pilot study

The results of the breathability test are listed below. From the name in the table the tested material can be deduced. For example, D3Q8 means perforations with a diameter of 3 mm and the quantity of perforations is 8. A recap of the water vapour permeability formula is given below:

$$WVP = \frac{24 * M}{A * t}$$

Where m is the weight loss in grams, A is the area of material that is exposed to the water in m^2 and t is the time in hours between first weigh moment and second weigh moment, which was equal to 20 hours. The area of the cup is $0.0064m^2$ and equal at all times. The results of the breathability test are given below in table 6.

Table 6. Results pilot study for the breathability and lab test. Effect of the amount of perforations on the water vapour permeability and on the maximum acceleration. The performance is relative to the non-perforated sample.

Sample	WVP (g/m^2/day)	Max acceleration (m/s^2)	stand dev	Performance (%)
D0Q0	525	1438	122	100
D3Q8	506	1459	121	99
D3Q32	525	1485	104	97
D3Q64	544	1467	-	98

It can be seen that there are no remarkable differences between the four samples. The largest difference is between D3Q8 and D3Q64 and is $38g/m^2$/day. However, the difference in grams is only 0.2g. The water vapour permeability is not high enough to cause good breathability. A value for acceptable breathability is at least higher than $845g/m^2$/day. Either the amount of perforations or the size of the perforations should be increased to obtain a better result.

The results of the lab test are also displayed in table 6. The height from where the cart felt on the material was 64cm and the weight was 2.85kg. The maximum acceleration and standard deviations are obtained using the lab test setup. The mean maximum acceleration is measured and displayed in table 6. The standard deviation of the three tries is also displayed in table 6. For D3Q64 the standard deviation is not reliable, since one of the three tries was zero. This zero was obtained because there was a fault in the signal that the sensor measured.

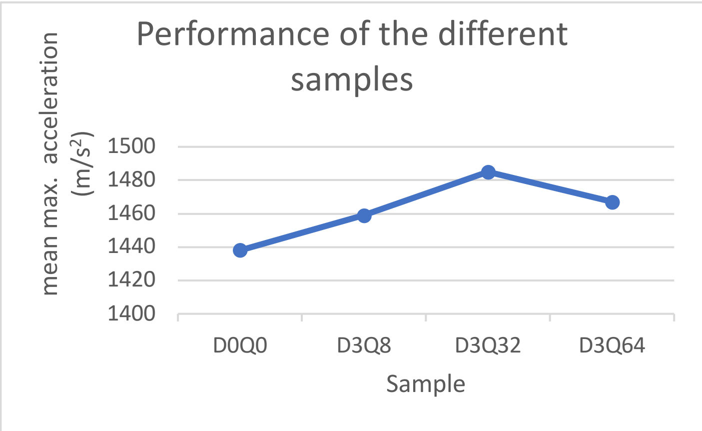


Figure 15. The effect of the amount of area perforated on the mean maximum acceleration.

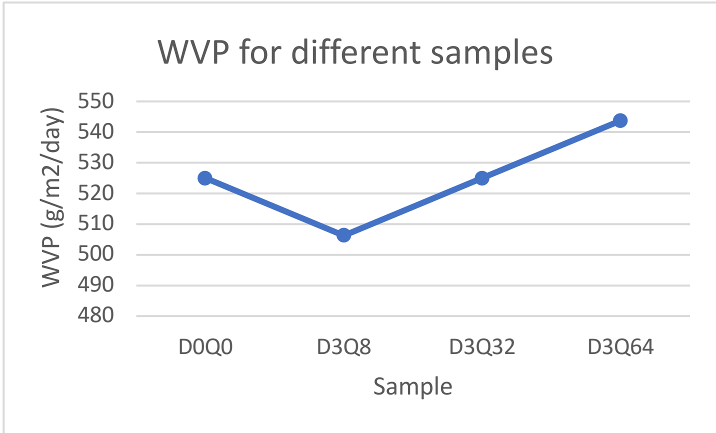


Figure 14. The effect of the amount of area perforated on the water vapour permeability.

In the two figures above the maximum acceleration and water vapour permeability can be seen respectively. From these graphs can be obtained that the acceleration increases at first and then decreases slightly with more perforations. The increase in this case means less cushioning, since the acceleration is higher so the material absorbs less energy. The differences are not significant.

In figure 16 a graph obtained by Matlab is illustrated. In this graph six lines can be distinguished, three straight parabolas and three squiggly parabolas. Straight parabolas are a results of Matlab transforming the squiggly parabolas into straight parabolas. The green, red and orange lines are the straight parabolas. These parabolas give the acceleration curve of one try over time. The value that is given, is the mean maximum acceleration of all three tries with a standard deviation. On top of the graph the tested sample is displayed. From the lab test results, no significant differences can be seen either. The standard deviation of sample D3Q64 is extremely high since one measurement stated 0 m/s^2. When this happens there is a failure in the system. Thus, the outcome of the standard deviation is not reliable. The measurement cannot be done once more, since the performance of the material decreases every try. Both, the 32 and 64 sample, went wrong the first try, since the yellow material was facing up. The second try is displayed in the table. With use of SPSS, a statistics program, the results are compared on the 5% significance level. If the probability falls within the significance level of 0.05 the null hypothesis has to be rejected. The null hypothesis in this case is the maximum

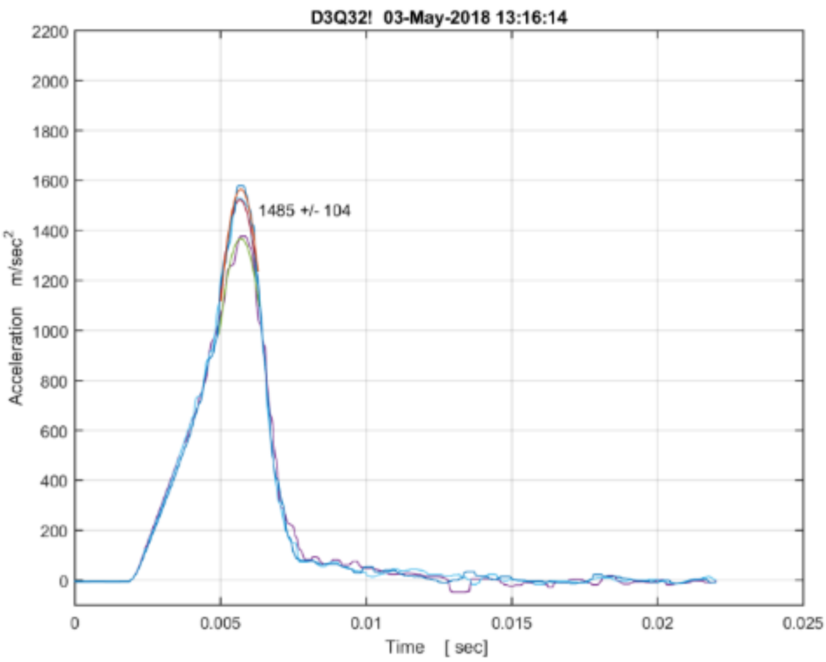


Figure 16. Example of a graph of the lab test with sample 3mm and 32 perforations. The maximum acceleration is displayed with respect to the time.

acceleration value of two different samples is the same. When the null hypothesis is rejected it means that the values are significantly different from each other. In this case only D0Q0 and D3Q8 are significantly different.

6.2. Follow-up Study

Again from the sample name the consistency of the sample can be deduced. For example. P15D6 had a perforated area of 15%, all perforations with a diameter of 6mm. In table 7 can be seen that the water vapour permeability increases as the area of perforations increases. The highest WVP is for the 30% area of perforations with a diameter of 8mm. However, this value of 641g/m^2/day is not higher or equal to 845g/m^2/day and thus not breathable.

Table 7. Results of the breathability and lab test with water vapour permeability, mean maximum acceleration, standard deviation and the percentage of the performance for all samples. P0D0 is without perforations and for example P5D3 is with perforations with diameter of 3mm and five percent of the area is perforated.

Sample	WVP (g/m^2/day)	Mean max. Acceleration (m/s^2)	Stand dev. (m/s^2)	Performance (%)
P0D0	500	1333	118	100
P5D3	500	1462	136	91
P15D3	578	1710	184	78
P30D3	609	1958	156	68
P5D4	500	1580	209	84
P15D4	547	1986	70	67
P30D4	594	1970	179	68
P5D6	469	1852	203	72
P15D6	547	1901	178	70
P30D6	594	1972	76	68
P5D8	484	1682	166	79
P15D8	594	1824	196	73
P30D8	641	1989	97	67

The cart was released at a height of 52 cm and its weight was 4kg. The maximum acceleration of the material without any perforations was 1333m/s^2. This sample has the highest energy absorption, none of the other materials was as protective as the sample without perforations. In the fifth column the percentage of the decrease in performance relative to the P0D0 was given, which is the sample without any perforations. The sample with the highest WVP has the lowest performance in protection, which is sample P30D8. This material reduces to a performance of 67% relative to the P0D0 sample.

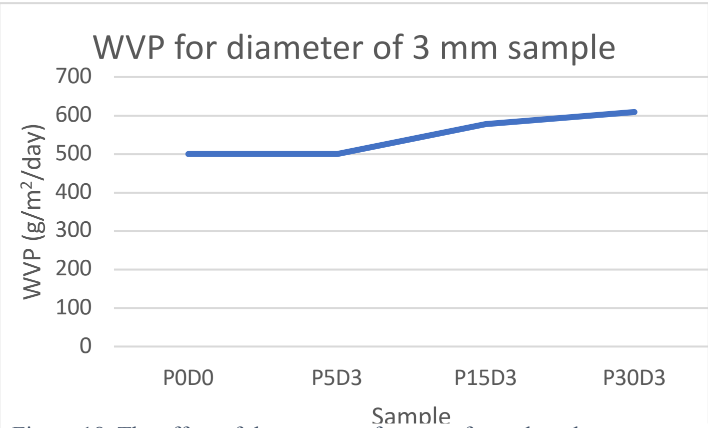


Figure 18. The effect of the amount of area perforated on the water vapour permeability during the follow-up test

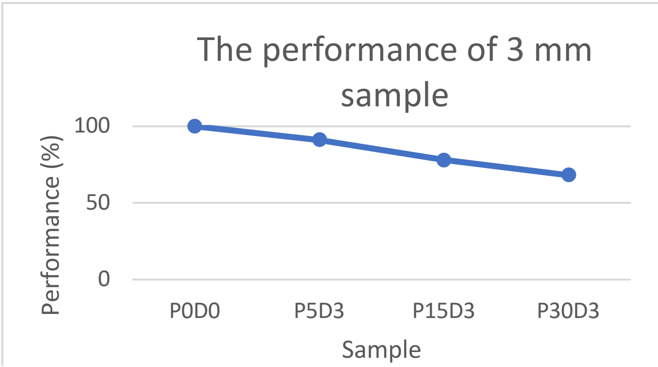


Figure 17. The effect of the amount of area perforated on the performance of the material samples during the follow-up test

In figure 18 and 19 the water vapour permeability and the performance are displayed respectively. The WVP increases slightly as the area being perforated increases. Furthermore, the performance decreases rapidly as the area being perforated increases.

The acceptable standard deviation is measured by performing first tries on seven different samples. This was done to find an acceptable standard deviation between different samples, since the maximum acceleration is never exactly the same. Standard deviation of these results was 120 m/s^2.

Following, the effect of the thickness was analysed. The results are listed in table 8, as well as the result of no material on the cup at all. At the beginning of this test the temperature was 23.6°C and the humidity was 41%. After 24 hours the temperature was 24°C and the humidity was 40%.

Table 8. Water vapour permeability in g/m^2/day for various samples. The yellow and green material are tested independently, the reference WVP is tested with no material.

Sample	WVP (g/m^2/day)
No material	1422
P0D0	500
Yellow material P5D3	797
Green material P5D3	641
Yellow material P5D4	719
Green material P5D4	656

The water vapour permeability for no material on the cup is 1422g/m^2/day and thus higher than 845g/m^2/day. As expected, this implies that the sample is highly breathable for this situation. Remarkable is that for the yellow material P5D3 the WVP is almost 845g/m^2/day, which means good breathability. The thickness of this sample is half the thickness of previous samples, where yellow and green are glued together.

Table 9. The standard deviation in m/s^2 of three trials with varying times in hours in between trials.

Time between trials	Standard deviation (m/s^2)
0.5h	54
1h	175
2h	41
24h	167

In table 9 the standard deviation of the three maximum accelerations is given for all the different samples. The four different samples were tested with varying times between the three trials. The standard deviation after 0.5h is 54 m/s^2, which is acceptable since the acceptable measured standard deviation is 120m/s^2.

Table 10. Maximum acceleration in m/s^2 for four different samples at two different temperatures (26°C and 21°C) and humidities (60 and 40%).

Sample	Acceleration(m/s^2) at 26°C, 60%	Acceleration (m/s^2) at 21°C, 40%
P0D0	1942	1205
P5D3	2096	1319
P15D3	2109	1517
P30D3	2107	1779

In table 10 the comparison between two different temperatures and humidities is made during the lab test. As can be seen, the samples at 26°C and 60% humidity perform worse than the samples at lower temperature and humidity. As well at higher humidity and temperature, the WVP is lower.

7. Discussion

In this chapter first the results will be discussed, then some limitations and their solutions will be considered and at last recommendations for future research will be discussed and explained.

7.1. Results discussion

In this research the objective was to find a solution to make the existing material breathable. The effect of perforations in the green and yellow material was investigated. It was observed from the study that the breathability did not increase enough to obtain a good breathability of the material. Furthermore, the material performance decreased during the lab tests when the density of perforations increased. It can be concluded that with applying perforation to the material the performance reduces and the breathability does not increase for this particular material combination.

The WVP does increase when more perforations are applied. Nonetheless, this increase is not enough to make the material breathable. The increase is also relatively small, since the water vapour permeability value for the non-perforated material is 500 g/m^2/day and the highest values are around 600 g/m^2/day. The decrease of the cushioning effect is remarkable. A decrease of more than thirty percent is recorded for applying perforations on 30% of the area. The requirement of the stakeholder was to not decrease the protective performance of the material. To guarantee this requirement, none of the perforated samples are suitable for the collarbone protector. In figure 17 and 18 the effect of the WVP and performance are displayed. In these figures it can be easily seen that the increase in WVP is little and the decrease in protection is larger.

In this study the effect of the diameter on the WVP and mean maximum acceleration is also investigated. Four different diameters are tested on the same amount of perforated area. Results show that the diameter does not have an impact on the WVP and neither on the mean maximum acceleration. The reason for this is probably that the water molecules have a diameter of approximately 0.275nm [13]. Therefore, the size of the diameter of the perforations is not relevant.
Besides, the WVP of a sample without perforations is relatively high with respect to a perforated sample. The water molecules are small enough to penetrate through the non-perforated material.

It can be derived from the results that the yellow material is more breathable than the green material. Both materials were 6mm thick. The yellow material had a WVP of 797g/m^2/day, where 845g/m^2/day was an acceptable breathability value.

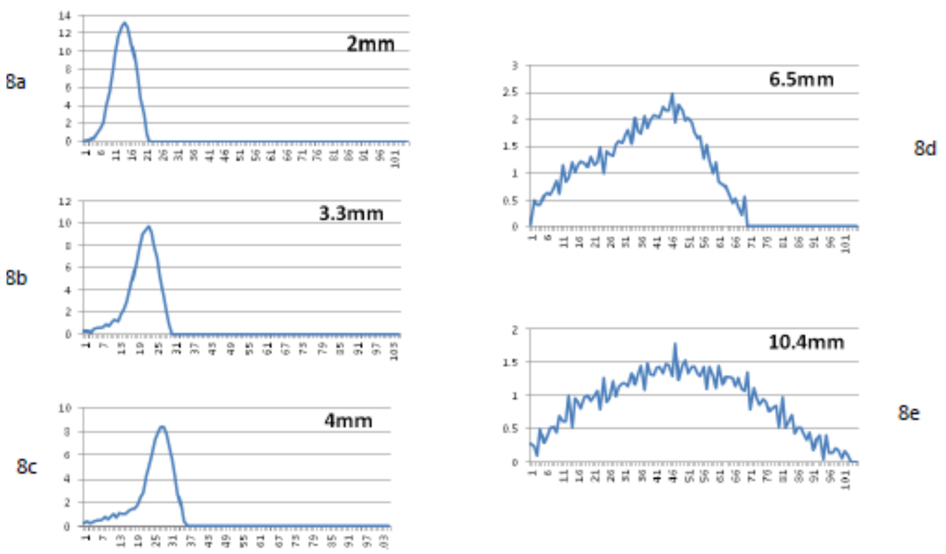


Figure 19. illustration of the peak force at various material thicknesses.

However, the material is only 6 mm thick and thus not protective enough. From earlier research is obtained that the maximum peak force is highly dependent on the thickness of a material [14]. This effect can be seen in figure 19. When the thickness increases a factor five, the maximum peak force decreases a factor seven. The impact load broadens over time and the maximum peak force decreases. In previous research the peak force of different breathable materials was tested for varying thicknesses [14], these results can be seen in figure 20. Leather is used as a reference material, visible as the light blue line in the graph. Obtained from the figure is that the Deflexion TP-Range has the lowest peak force for the thinnest size. The D3O fabric has a limited peak force as well. The Poron XRD sample, which is the yellow material in this study and the green line in figure 20, has the smallest peak force for a thickness of 12.5 mm. The samples tested in this research are 12 mm thick, thus the best material for this thickness would be the yellow material assuming that the research of the article is accurate. However, in Laurens' research, the green and yellow combination was better than 12 mm of yellow material sample. Research has to be done to obtain a better understanding of the different materials and in future research the 12mm of yellow material could be tested.

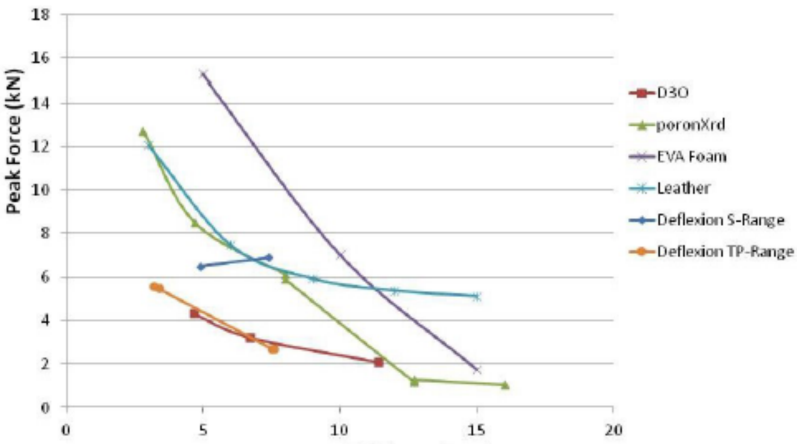


Figure 20. The peak force for various materials and varying thicknesses.

7.2. Limitations

Some aspects of the tests can be discussed. First of all, every single sign was detected by the sensor during the lab test. At first a screw was used to release the cart from the slide, but sometimes the sensor measured this rough release and the fall was not detected anymore. This was a problem for the test, since the material performance decreases every try. However, this only happened for a few tries and the average outcome did not change remarkably.

Secondly, the material is tested at room temperature. However, when the protector is being used, the material is placed on the human body, which is 37°C. In further research the material performance should be tested at 37°C, since this is the real life situation. From earlier research it is obtained that the mechanical properties of foam materials are dependent on the temperature [15]. The temperature influences the energy return efficiency and cushioning characteristics. Poron material was highly effected by the temperature, the poron x2 material experienced less effect of a temperature change than other materials of poron in earlier research. However, the results of poron XRD are not mentioned in the article. On the contrary, in the material properties given by Comfortable bv it is mentioned that poron x2 is temperature resistant to 70°C with a constant use of the material. Unfortunately, it is not known for poron XRD to which degree it is resistant. All tests are performed at room temperature, the temperature was not controlled. During earlier tests the temperature was around 21°C, while at tests later on the temperature was around 26°C, the humidity changed from 40 to 60%. It seemed like the performance decreased when the temperature and humidity increased, these results can be seen in the results section. Actually, the material should perform at a temperature close to the human body temperature. The variation in body temperature can cause the materials to behave different compared to the material properties given by the suppliers. Secondly, the humidity can have an effect on the cushioning characteristics as well. At this moment, it is not possible to distinguish between the effect of the humidity and temperature.

Thirdly, for the small diameter perforations, the perforations were not accurate. After measuring the perforations when punched, it was clear that on one side of the material the perforations was 1 mm larger than on the other side of the material. Nevertheless, this would not make a difference to the overall results.
Furthermore, tests are executed with too little time in between tries. In this research the pause between two lab tests was twenty seconds, although the material had to recover from the first load. Investigated was the time needed for the material to recover from the load. In half an hour the material was recovered, but after an hour in between, the material was not recovered. This could be a consequence of the temperature and humidity increase. The material did not perform as it did with lower temperature and humidity. In the future, the time between two tries should be increased from twenty seconds to at least half an hour. The foam should have the time to fill their open cell structure again.
The differences in amount of grams is small. The scale only measures with one decimal, thus if the difference is 0.2g it might be a measuring fault.

Moreover, the airflow is of importance in the measurements since the airflow is high when cycling in the open air. With more airflow the cyclists sweats less than when cycling inside. In this research the airflow is neglected, but this should not be neglected. In further research this should be included in the tests.

Finally, there is a possibility that the results from the upright cup test are not accurate. The upright cup test was determined correlating with the sweating guarded hot plate test [5]. Water vapour permeability was compared to the water vapour resistance. However, the results cannot be compared linearly, since the temperature and humidity play an important role. During the research in the article the temperature and humidity were kept constant [5]. In this research it was not possible to keep the temperature and humidity constant. In the material properties of Poron XRD in the appendix B is listed that the WVP is between 3100 and 4150g/m^2/day, these results were obtained when the temperature was at 37°C and the relative humidity was 0%. It is evident that the results are higher than in the current research, since the temperature was lower and humidity higher in this research. Therefore, the results cannot be compared. In future research another breathability method, for example the alternative sweating guarded hot plate method, can be done to investigate the inaccuracy of the upright cup method. In the material properties in the appendix, both materials are considered to be breathable. However, this does not appear from the test results. The reason for this could be that the test is not accurate enough or the material properties are not valid.

Nonetheless, looking at the test setup, a similar test setup has been used for comparing new material to an existing rugby shoulder pad [16]. In this research four different samples are tested on the depth of impact and on the water vapour resistance. The depth of impact can be compared to the maximum acceleration, since it also measures the cushioning of the material. In this research the sweating guarded hot plate method was used. For future research it might be relevant to use this method in order to receive more accurate results. The results of this research are listed in appendix F.

7.3. Future research

New research can be done on applying breathable material to the existing material or using different materials than the yellow and green material. The first solution would be best, since

Comfortable bv. explicitly asked to use the material Laurens already tested. The existing material has the best performance of all materials they have. However, this might not be the best material when taking breathability in consideration. Since a requirement of one of the stakeholders was to use the material they deliver, no further research on other materials was done before the tests. After the company heard about the results, they were convinced that other steps had to be taken. They agreed to look for new materials to be tested.

Foams

Foams are known for their energy dissipation properties and have low apparent density [17]. It would be practical to produce microscopic or electro microscopic photographs of both material samples to obtain an insight of the structure. To obtain an optimal energy-absorbing material, the kinetic energy of the impact should be dissipated, while the force should be below some limit. In this way the deceleration on the object is acceptable. The limit is hard to actually know, since there is no hard data for the fracture force of a collarbone or shoulder. A typical stress-strain curve for polyurethane foam consists of a linear elasticity phase, plateau phase and a densification phase. When the load increases, the foam cells start to collapse by elastic buckling, this leads to the plateau phase. Then cells meet and touch, this means that densification takes place. The stress-strain curve can be seen in figure 21. The area under the curve is the absorbed energy. Density of a foam material should be optimised. Lower density foams are able to absorb enough energy with large deformations and lower stresses. Higher density foams are able to absorb the same amount of energy with low deformations and higher stresses. Ideal foams have an intermediate density. For strength higher densities are optimal. However, for breathable, flexible and lightweight foams lower densities are optimal. To obtain the most optimal material for a collarbone protector, the density of the foam should be idealised. The structure of the material is of high importance for the material properties. Factors that affect the air permeability are the fabric structure, fineness of yarns in the fabric and the porosity of the fabric [18].

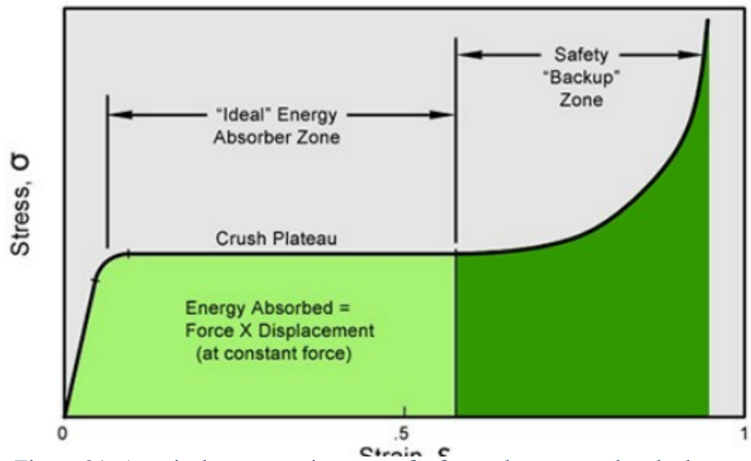


Figure 21. A typical stress-strain curve of a foam, the energy absorbed area and safety 'backup' zone are included [17].

Evaporation layer

In previous research the composition of active sportswear is discussed [19] and consists of layered fabrics. The performance of layered fabrics is better than a single layer structure. The first layer that is in direct contact to the skin wicks away the perspiration rapidly to the outer layer, the wicking layer. The outer layer absorbs and dissipates the perspiration rapidly to the atmosphere by evaporation, the evaporation layer. The wicking layer consists of polyester or other wicking fibers and the evaporation layer consists of cellulosic or other hydrophilic fibers. It might be possible to have the existing materials for the collarbone protector in between the wicking and evaporation layer. To enhance comfort, faster evaporation and higher wicking are required for active sportswear. Moisture management of the material is important and depends on the chemical structure of the surface. A better understanding of the chemical structure should be obtained. Wicking away the perspiration could be done by Coolmax [20]. Coolmax assumes excellent moisture management and wicking performance.

Air permeability of coolmax is excellent, thus this could be used as a wicking layer for the current material. Further research should be done to investigate if there is an evaporation layer and if this is applicable for the current material combination.

Absorbing materials

Another solution for future research could be to add material. In an article on thermos-physiological comfort properties of firefighters' protective clothing super absorbent materials are investigated as a layer in between two existing layers [21]. Super absorbent materials were incorporated into the internal layer of the protective clothing. This layer consist of five different materials, these can be seen in the appendix G. In this research the air permeability, water sorption and evaporation, thermal resistance and water vapour resistance were investigated. It is possible to improve the comfort properties of the protective clothing, by incorporating super absorbent materials into the internal layer. The results indicate that it is likely that the materials can help in the absorption of sweat. The materials can not only help keeping the skin dry, but as well increase the breathability. The values for WVR are highly breathable and comfortable at higher activity rates.

8. Conclusion

Goal of this study was to obtain the most optimal redesign for the collarbone/shoulder protector, where trade-off between breathability and protection is best for a recreational cyclist. After discussing the results of this study, no optimal collarbone/shoulder protector could be made at this moment. Increasing the number of perforations resulted in a decrease of the protection and not enough increase in breathability. More research has to be done to be able to optimize the collarbone protector.
A good value for breathability had to be determined. Determined was that a water vapour permeability of at least 845g/m^2/day was sufficient for breathable protection. This result was obtained by comparing the water vapour permeability to the water vapour resistance. In this research the way to make existing material breathable was by implementing perforations onto the material. A tool to measure the breathability of a material was the upright cup method, which is used. From the results can be obtained that implementing perforations is not sufficient for acceptable breathability of the material.
In this research the redesign and implementation phase are not included, since the results were not positive enough to develop a redesign. Thus making a redesign and implementing it is not relevant for this study.

9. References

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10. Appendix

Throughout the report references to the appendix are given. The appendix in given in chronological order.

10.1. Appendix A-Design Issues

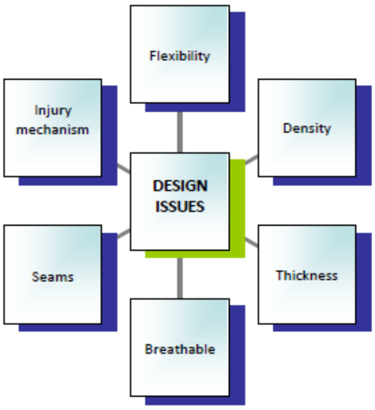

Figure 22. Design issues for a shoulder pad

10.2. Appendix B-Material properties (yellow material)

ROGERS CORPORATION

PORON® Performance Cushioning

Rogers Corporation
High Performance Foams Division
www.poroncushioning.com
www.poronxrd.com

PORON® XRD™ Extreme Impact Protection – Physical Properties

PROPERTY	TEST METHOD	PRODUCT				
*Density, lb/ft³	ASTM D 3574-95 Test A	9	12	15	20	25
Specific Gravity		0.14	0.19	0.24	0.32	0.40
Tolerance, %		± 10				
*Standard Thickness		See Product Availability				
Tolerance, %		± 10				
Standard Color		65 - Vivid Yellow				
Air Permeability	Internal using Gurley Densometer	Open Cell - Breathable				
*Compression Set, % max.	ASTM D 3574 Test D @ 158°F (70°C)	< 10				
*Compression Force Deflection, psi, kPa)	0.2"/min. Strain Rate Force Measured @ 25% Deflection	1.1 - 3.4 (8 - 23)	1.5 – 5.5 (10 - 38)	4 – 9 (28 – 62)	5 – 12 (34 – 83)	10 – 20 (69 – 138)
Hardness, Durometer	Shore "O"	10	19	32	**	
Hydrolysis Resistance, Compression Set, % Max	ASTM D 3574 Test J / Test D after autoclaved 5 hrs @ 250°F (121°C)	**				
Resilience, Shore Instrument Resiliometer, avg (Ball Rebound Tester)	ASTM D 2632-96, Vertical Rebound	**				
Water Vapor Transfer, Typical g/ft²/24hrs (g/m²/24hrs)	Sample Thickness, inches (mm)	0.158 (4.0)	0.118 (3.0)	0.118 (3.0)	**	
	Based on ASTM E96-00 Upright / 37°C / 0% RH	4150	3400	3100	**	
	Leakage – Inverted	Yes	Yes	Yes	**	
Water Absorption, % Wt Gain	Based on ASTM D 570 – 2hr water immersion @ room temperature	Typical Value 10				
Skin Contact	Primary Skin Irritation – FHSA. Based on ISO 10993-10 (2002), ISO 10993-12 (2007), ISO/IEC 17025 (2005)	Negligible Irritant. Primary Irritation Index = 0				
Tear Strength, pli, min. (kN/m)	ASTM D 624 Die C	4.5 (0.8)	5 (0.9)	5 (0.9)	10 (1.8)	14 (2.5)
*Tensile Elongation, % min.	ASTM D 3574 Test E	> 145				
*Tensile Strength, psi, min. (kPa)	ASTM D 3574 Test E	30 (207)	45 (310)	70 (483)	100 (689)	140 (965)
Restricted Substances Compliance	Based on Adidas-Salomon policy for control and monitoring of hazardous substances.	Pass				
Chemical Resistance		*PORON Cushioning Materials are unaffected by mild organic acids and bases. They show modest swelling with oils and greases and other linear hydrocarbons. Strongly polar solvents will greatly swell PORON Materials. In most cases, physical properties recover to a great extent as the solvents evaporate.*				

Notes:
1. All metric conversions are approximate.
2. Additional technical services are available.
3. Information listed based on typical physical properties.
4. * Standard testing property: Certificate of Compliance available per lot.
5. ** Indicates testing in progress to confirm reported results.

The information contained in this Data Sheet is intended to assist you in designing with Rogers' PORON XRD Extreme Impact Protection and should not be used to create a specification. The data expressed is not intended to and does not create any warranties, express or implied, including any warranty of merchantability or fitness for a particular purpose or that the results described or shown on the Data Sheet will be achieved by a user for a particular purpose. Each user must develop its own design and should determine the suitability of Rogers' products for that design.

WARNING: No impact absorbing material can prevent all injuries that may occur when the body is subjected to impact. Rogers makes no representation or warranty that PORON XRD Extreme Impact Protection will prevent such injuries. The user of protective gear containing Rogers' materials should be aware of the limitations of the gear and should exercise reasonable care and caution in the undertaking of activities that may result in impact to the body.

The world runs better with Rogers.®

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1209-PDF, Publication #15C-067

10.3. Appendix C- Material properties (green material)

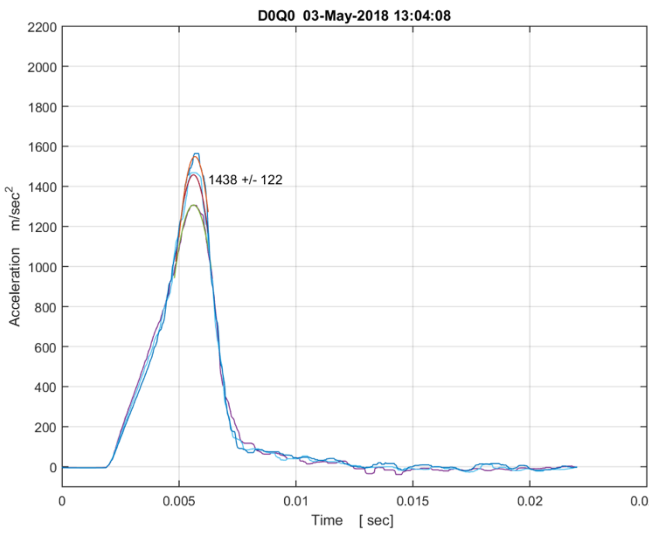
poron® | performance cushioning

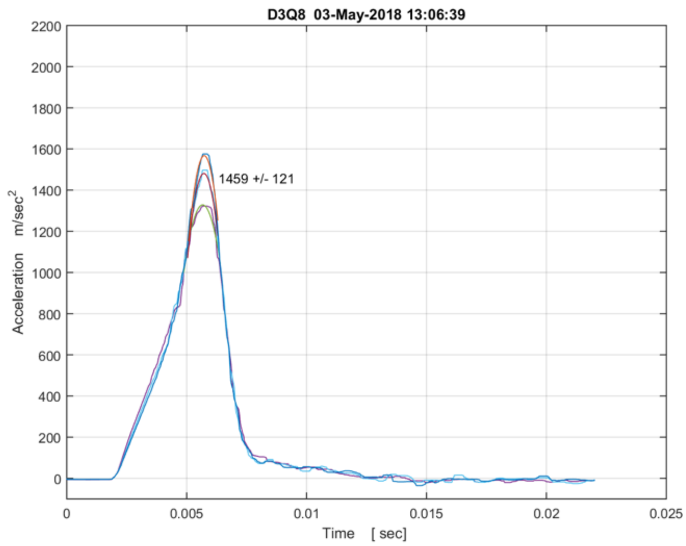
PORON® Slow Rebound Cushioning Series - Typical Physical Properties

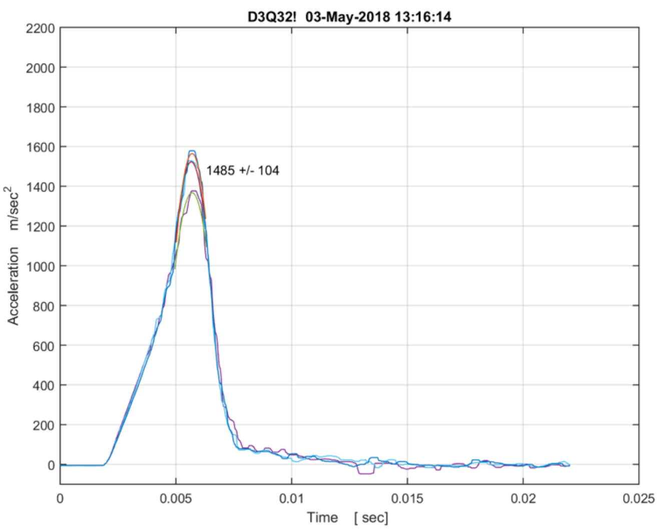
PROPERTY	TEST METHOD	PRODUCT			
FORMULATION		PORON SR Very Soft	PORON SR Soft	PORON SR Firm	PORON SR Very Firm
*DENSITY, lb. / ft3	ASTM D3574-95 Test A	15	15	15	15
Specific Gravity		0.24	0.24	0.24	0.24
Tolerance, %		± 10			
*STANDARD THICKNESS		See Product Availability			
Tolerance, %		± 10			
STANDARD COLOR		Red (84)	Salmon (55) Black (04)	Lambda Red (51)	Cayenne Red (42)
AIR PERMEABILITY	Gurley Densometer	Open Cell - Breathable			
*COMPRESSION SET, % max.	ASTM D3574 Test D @ 158°F (70°C)	10			
*COMPRESSION FORCE DEFLECTION, psi	0.2"/min. Strain Rate Force Measured @ 25% Deflection	0.3 – 3.5	1.5 – 6.5	3 – 18	4 – 22
kPa		2 – 24	10 – 45	21 – 97	48 – 124
HARDNESS, Durometer	Shore "O"	12	18	22	30
HYDROLYSIS RESISTANCE	ASTM D3574 Test J / Test D after autoclaved 5 hrs @ 250°F (121°C)	Good Resistance			
Compression Set, % Max		5			
RESILIENCE, Shore Instrument Resiliometer, avg (Ball Rebound Tester)	ASTM D 2632-96, Vertical Rebound	4	4	7	8
WATER VAPOR TRANSFER, Typical g/ft2/24hrs (g/m2/24hrs)	Based on ASTM E96-00	>37 (400)			
WATER ABSORPTION, % Wt Gain	Based on ASTM D570	< 30%			
ANTIMICROBIAL, Fungal Resistance	ASTM G21	Does not promote fungal growth			
SKIN CONTACT	Primary Skin Irritation – FHSA	Pass			
TEAR STRENGTH, pli, min.	ASTM D624 Die C	4	5	10	12
kN/m		0.7	0.9	1.7	2.1
*TENSILE ELONGATION, % min.	ASTM D3574 Test E	120	120	100	100
*TENSILE STRENGTH, psi, min.**	ASTM D3574 Test E	15	40	80	100
kPa		104	276	552	689
TEMPERATURE RESISTANCE, max	ASTM D746-98				
Recommended Constant Use		70°C (158°F)			
Recommended Intermittent Use		121°C (250°F)			
CHEMICAL RESISTANCE		PORON Urethanes are unaffected by mild organic acids and bases. They show modest swelling with oils and greases and other linear hydrocarbons. Strong polar solvents will greatly swell PORON Urethanes. In most cases, physical properties recover to a great extent as the solvents evaporate.			
ANTIMICROBIAL PROTECTION	AATCC TM90 JIS Z 2801 AATCC TM30(iii)	PASS			

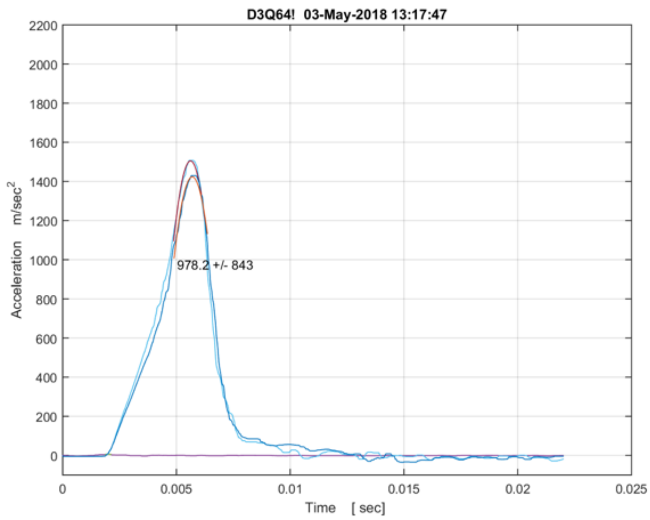
Notes: 1. All metric conversions are approximate. 2. Additional technical services are available. 3. Information listed based on typical physical properties. 4. *Standard testing property; Certificate of Compliance available per lot. 5. **If used in tight radii, care should be used not to exceed tensile strength. We recommend to pair the material with a fabric or film to augment the tensile strength in such cases. Please contact a Rogers Customer Service Representative for additional information.

10.4. Appendix D– Pilot study (acceleration graphs)

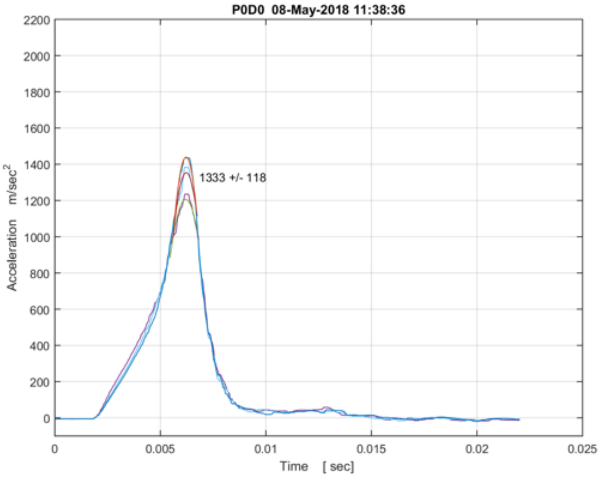


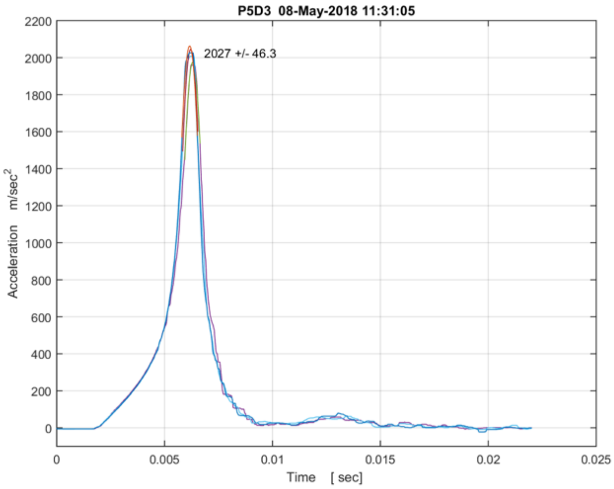


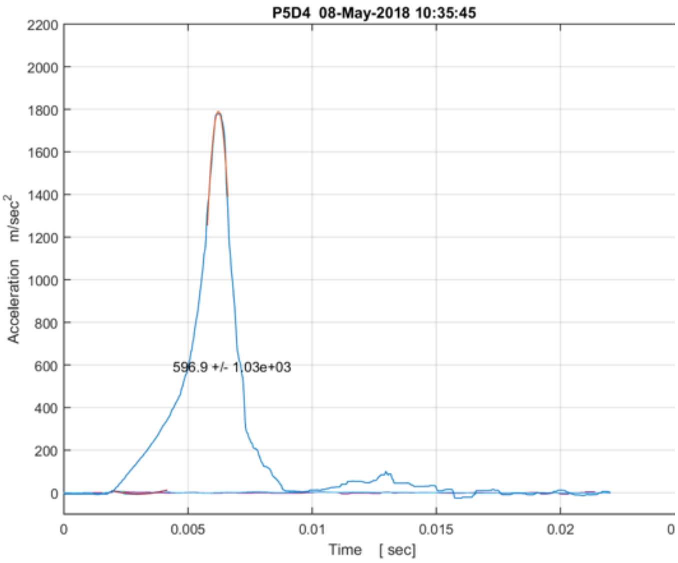


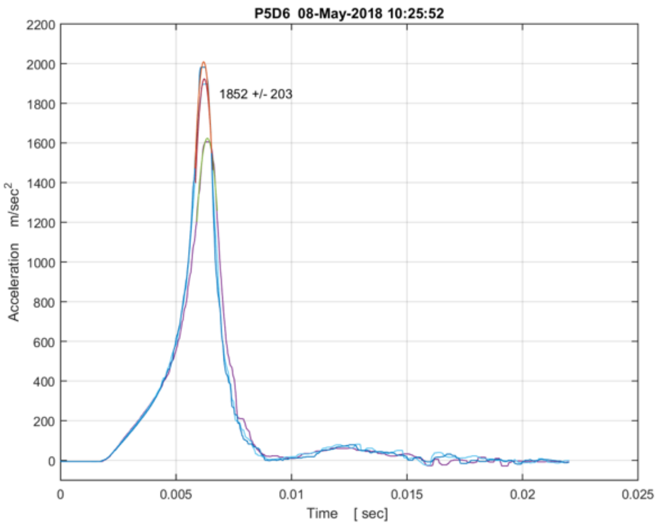


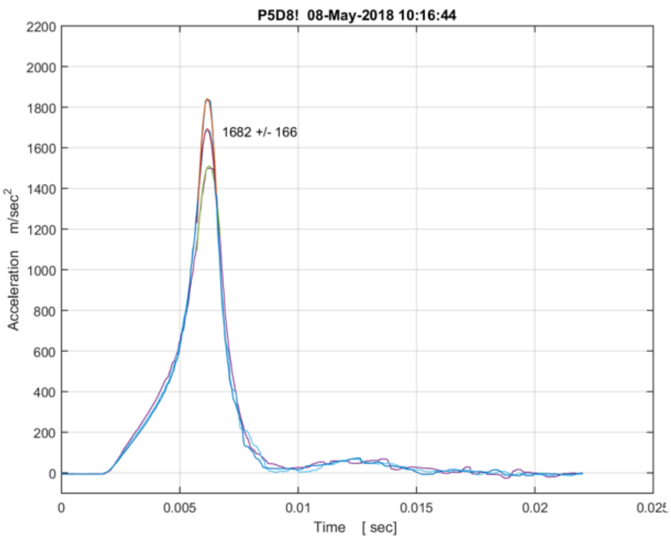
10.5. Appendix E- Follow-up study (acceleration graphs)

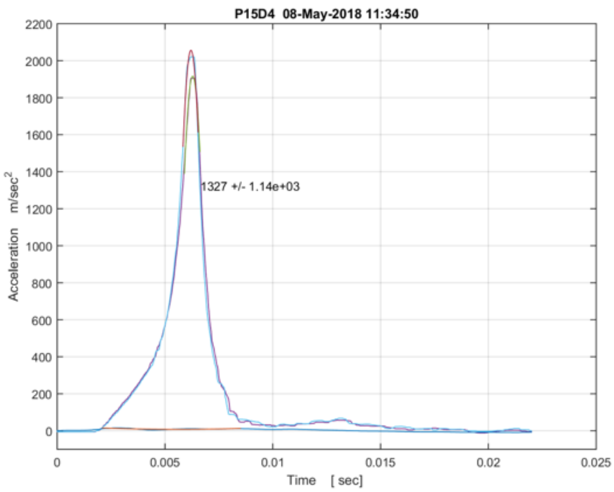


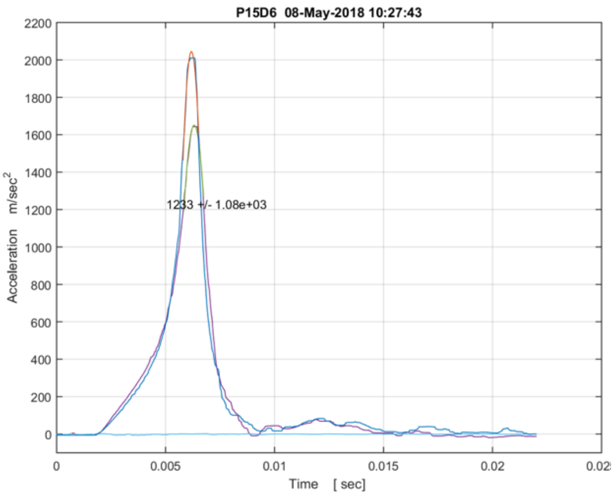








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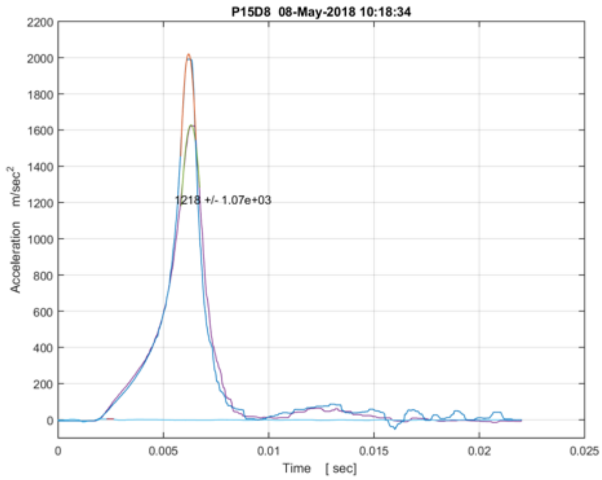
Acceleration m/sec^2
Time [sec]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1218 +/- 1.07e+03
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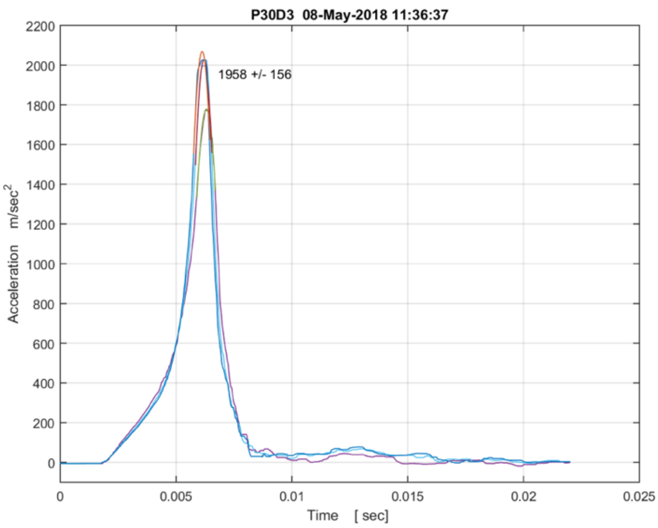
Time [sec]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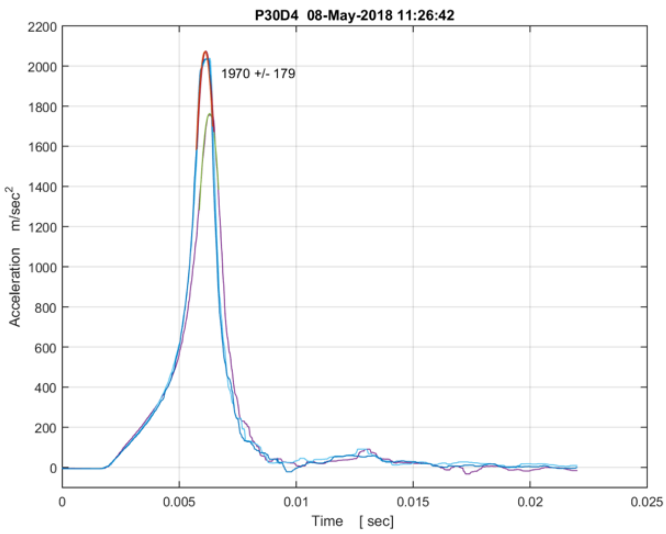
1958 +/- 156
Acceleration m/sec^2
Time [sec]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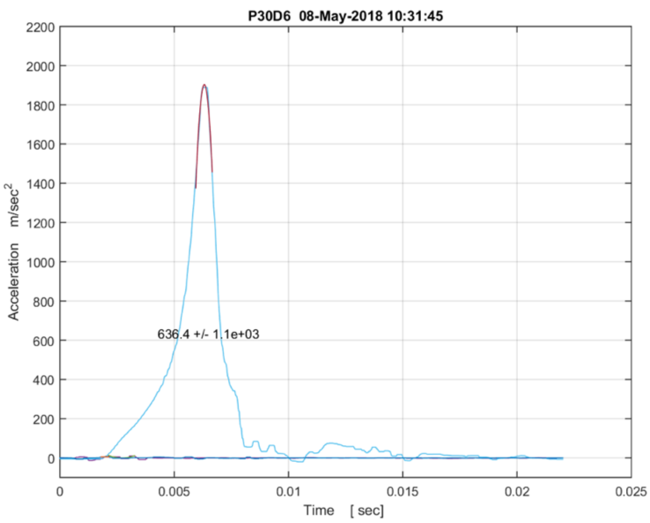
1970 +/- 179
Acceleration m/sec^2
Time [sec]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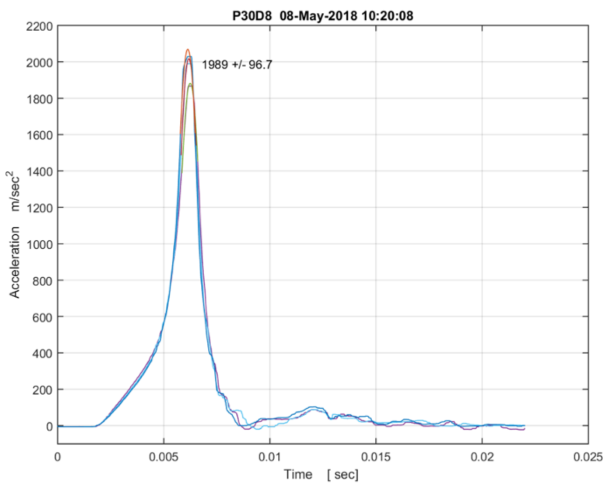
Acceleration m/sec^2
Time [sec]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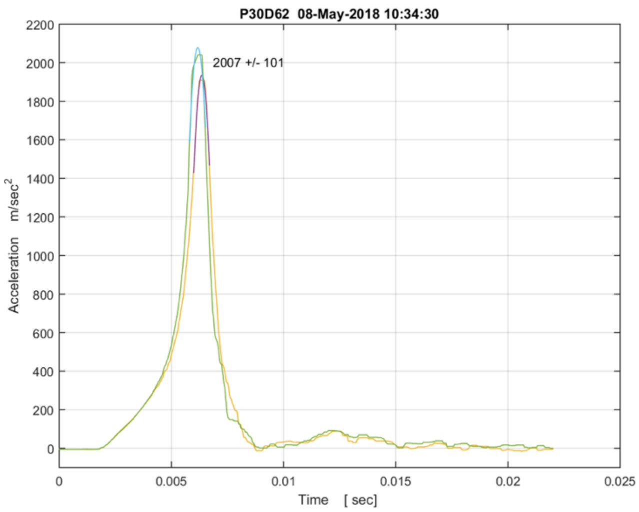
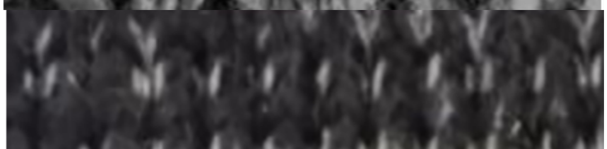
1989 +/- 96.7
Acceleration m/sec^2
Time [sec]



10.6. Appendix F- More literature research

This article discusses the importance to wear shoulder pads for rugby players [16]. It is rather important to wear this protection against injuries. Shoulder pads for rugby are against collarbone injuries as well. However, the commercial shoulder pads are not comfortable. In this research they investigated three new fabrics on its strength and comfort and compared these to the existing commercial padding sample. The three new fabrics are selected for their exceptional high strength and improved comfort. Comfort is obtained from the cotton yarns used. In the figure below all four fabrics are given with their codes, materials, thicknesses and densities.

Table 8. Different fabric layers with its dimensions

Fabric code	Layers 1/2/3	Fabric thickness (mm)	Areal density (g/m^2)	Microscopic images (20X)
A	Cotton-Elastic yarn/ Ballistic Nylon/ Cotton-Elastic yarn	14.4	3477	
B	Dyneema (untwisted)-Elastane/ Dyneema (untwisted)/ Dyneema (untwisted)-Elastane	6.8	1586	
C	Dyneema (untwisted)-Elastane/ Dyneema (untwisted)/ Dyneema (untwisted)-Elastane	7.8	2194	
D	Commercial foam sample	15.3	582	

Tests were done to investigate the performance of the shoulder pads and the comfort of the shoulder pads. The test that was done to investigate the performance measured the depth of impact of the fabric. Results of this test are shown in figure 23. The depth of impact of the new fabrics A, B and C are almost similar to the commercial foam D. Fabric C has a lower impact at all different heights than D. Fabrics A and B have a lower depth of impact at all different heights than D except for 0.5m. A lower depth of impact means a higher performance, since deformation is linearly related to the impact energy.

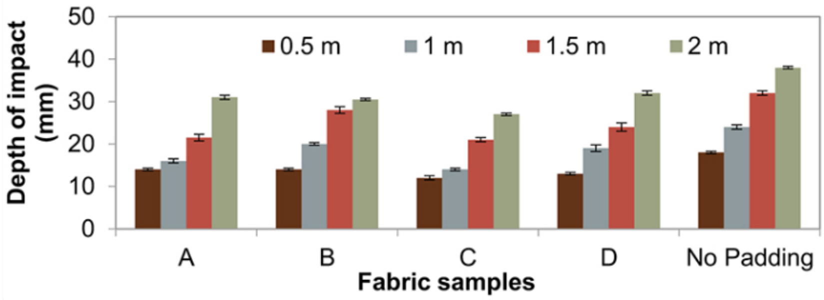
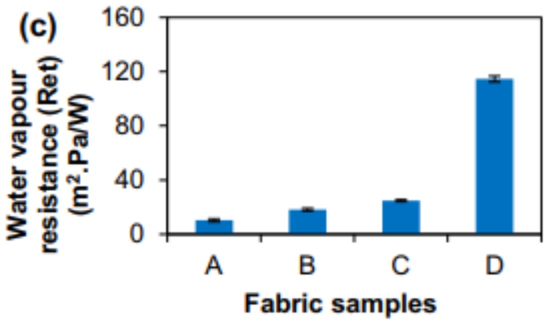


Figure 23. The depth of impact for various fabric samples at varying heights.

The factors that affect the air permeability are the fabric structure, fineness of yarns in the fabric and the porosity of the fabric. The air permeability of the three new fabrics are higher than D, where fabric A has the highest. The water vapour resistance is the highest for D and A has the lowest WVR. The lower the WVR, the higher the breathability. The new fabrics have a satisfactory to moderate level of comfort. Fabric A has a water vapour resistance of 10, which is comfortable at moderate activity rate.



10.7. Appendix G- Materials used in article

Table 9. Different layers to make material more breathable.

Sample	Construction	Thickness (mm)	GSM (g/m^2)	Fibre composition (%)	Microscopic image
First layer (next to skin, to keep the skin dry)					
S[@]	Woven	0.27	129	Nomex (100%)	
Second layer (to improve the comfort)					
A[#]	Nonwoven (laminated, air-laid)	0.80		Coolmax/SAF/polyolefin (75/15/10%)	
B[#]	Nonwoven (laminated, needle punched)	1.40		Coolmax/SAF/polyolefin (65/25/10%)	
C[*]	Woven (plain weave)	1.00		Warp: polyester (100%); Weft: polyester/SAF (75/25%)	
D[@]	Nonwoven	0.23		Nomex® (DuPont ™ Nomex® E89, 100%) (Existing one in use now)