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The Hague Sailing Innovation Centre

MSc Graduation Project Report

Websuit 1

The protective wetsuit for foiling sailors.

Foreword

Welcome to the graduation project report.

Sailing is an Olympic sport, a discipline where athletes express their exceptional physical and mental abilities in challenging weather conditions and complex boat acrobatics. High speeds on sailboats are not a novelty. However, with the recent (2020) announcements of the new foiling classes in the 2024 Summer Olympics, it is vital to study the safety of these athletes and the solutions in place to ensure their collective well-being. Foils have been around for a while now, yet increasing numbers of athletes at foiling regattas make it more apparent how accidents may happen.

It is worth noting that sailing associations, federations, and committees dedicate significant attention to the sport's safety. Numerous rules, equipment design choices, and methods are in place to ensure the safety of sailors at sea both during training and competitions.

Thanks to the input of the Sailing Innovation Centre, who noticed that sailing gear is not advancing at the rate at which these foiling classes are gaining popularity and creating hazardous circumstances. Based on this opportunity, this report describes the work conducted over five months, investigating foil sailors' safety, and proposes a product to protect athletes. The final product is a technical garment, a wetsuit, Websuit 1.

Gratitude is expressed to the project supervisors Dr. ir. Arjen Jansen, lecturer at the Faculty of Industrial Design Engineering, MSc. Lyè Goto, Ph.D. student at the Faculty of Industrial Design Engineering, and MSc. Inge de Zeeuw, Project Manager at the Sailing Innovation Centre, for their distinguished guidance, assistance, and advice throughout the project. Thanks to Linda Plaude, lecturer at the Faculty of Industrial Design Engineering, for the continued support and advice. The project has gained the interest of numerous stakeholders, including *World Sailing* (the governing body for the sport of sailing), who is thanked for the collaboration and for sharing valuable data. The author is grateful to the athletes and coaches who have dedicated their time and resources to support this research. Finally, thanks to Taiana and GRDXKN for providing technical advice and materials for realizing the product.

Graduation project by Matteo Sammarco

Delft, July 2021

Graduation project executred for the MSc. Industrial Product Design (IPD), Master Variant for Engineers (MVE)

Faculty of Industrial Design Engineering, Delft University of Technology

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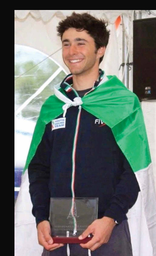

Summary

Bridging innovative textiles with Olympic sailing

This project was carried out with the educational, financial, and technical support of the Sailing Innovation Center and the Delft University of Technology, Faculty of Industrial Design Engineering.

The project focused on improving Olympic foiling classes' sailing athletes' safety: Nacra 17, iQFOiL, and IKA Formula Kite.

The primary objective was to investigate dangerous circumstances with foil sailors to research the mechanisms that cause injuries and develop a design solution to prevent them.

The research performed provides an integrated perspective into the subject of foil sailing safety. The research methods include participatory observational research, one-to-one interviews, multimedia evidence analysis, incident reporting archives study, and explorative retail analysis.

A hydrofoil consists of a winglike structure mounted across the keels of a catamaran or on a board's fin. The highest risks to safety are identified as foil strikes. The Nacra 17 sailors are usually struck by the rudder elevator. The iQFOiL sailors may be struck by another iQFOiL; however, the evidence is not vast. Finally, IKA Formula Kite riders can be struck by hydrofoils at various speeds and at different locations on the body. For the latter, the video evidence is vast.

The mechanics and kinematics of crashes are reported from a qualitative and quantitative standpoint. Further research was conducted on the anatomical effects of crashes on sailors, for example, through the types of injuries and how their recovery period negatively affects their mental health and, consequently, their physical performance.

An overview of current protective wear in sailing, other sports, and disciplines is presented. The manufacturing method of sailing wetsuits is relevant for comparison with the proposed manufacturing method. Many textile technologies suitable for the application are presented and compared with one another.

A list of design requirements for the wetsuit is redacted, and four primary objectives are established. Impact and cut protection on the entirety of the wetsuit's surface, comfort, and aesthetics, which are two factors in attracting the use of such a suit.

The product's name is Websuit 1, which is a protective wetsuit for Olympic foiling sailors. Full-length woven Dyneema lining is stacked with lightweight neoprene and GRDXKN foam— a mix of comfort and unprecedented protection.

Results of several iterations have proven that GRDXKN can be printed on Guard Shield. Furthermore, based on the tests, 100% Dyneema lining can be bound to neoprene rubber thanks to special glues. The proposed manufacturing method is the same as the current one, with the addition of a GRDXKN printing phase.

Under the impact tower, the GRDXKN absorbed 56% of the maximum force applied from an impact. The reinforced neoprene has been shown to distribute the energy over a larger surface, which decreases the stress applied. Furthermore, it did not tear or break under stresses caused by high energy impacts. In contrast, conventional neoprene concentrated the applied force on a smaller area for the same energies and was torn.

This project provided the first steps into connecting innovative textile technologies with the sailing world.

Websuit 1 Project Report

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Section 1 Introduction

Design personal protective equipment for Olympic foiling sailors

Delft University of Technology

The Hague Sailing Innovation Centre

This project was carried out with the educational, financial, and technical support of the Sailing Innovation Center and the Delft University of Technology, Faculty of Industrial Design Engineering.

The Sailing Innovation Centre helps to accelerate innovations in sailing by supporting the sporting ambitions of the Netherlands, promoting interest in sailing, and contributing to economic growth by sustaining companies in realizing new and better products and services.

The Delft University of Technology, Faculty of Industrial Design Engineering, is focused on matching the evolution of society with the revolution of technology by approaching design from the perspective of people, organization, and technology, with sustainability and ethics becoming increasingly important considerations.

Sailing safety is the study and practice of designing and constructing equipment to minimize boat collisions and consequences involving sailboats. The project focuses on improving Olympic foiling classes' sailing athletes' safety: Nacra 17, iQFOiL, and IKA Formula Kite.

With the rise in popularity of new foiling classes, the average sailing speeds have significantly increased, and so have the risks and severity of injuries. In the unlikely event of a crash, an out-of-control foiling sailboat/board and its components become dangerous to sailors and the others around them. An impact with a hydrofoil may cause severe skin lacerations, contusions, and bone fractures.

Personal protective equipment should be the last line of defense against injury. However, due to the imminent dangers that foil sailors are currently exposed to and the lack of reliable personal protection, designers are urged to investigate new cut and impact protection options.

The final result of this project is the design of a novel wetsuit that sets the example for a new level of protection, comfort, and look.

1.1 PRELIMINARY PROBLEM DEFINITION

The sailors' gear, customs, and habits are a delicate "ecosystem", so introducing a new type of protective equipment should minimize its disturbance in exchange for the most significant benefits. The direct benefits of protective clothing are physical and emotional; with increased body protection, sailors are willing to push boundaries, sail faster, and win regattas.

Personal protective equipment should become the optimal configuration that maximizes protection, performance, and comfort through innovation and integration. Excessively trading off one aspect for another is not ideal. For example, knit's armor effectively prevents injuries at the cost of the athlete's freedom of movement.

Sailors consistently put their gear to the test by exposing it to the elements. The brutal wear and tear that sailing gear is put through further constrain the solution space for protective wear.

Hence, a holistic approach to the problem is essential for ensuring safety and creating a product that sailors desire to wear. Different perspectives are required, including engineering, ergonomics, and sailing know-how.

1.2 PRIMARY OBJECTIVE

Investigate dangerous events with foil sailors to research the mechanisms that cause injuries and develop a design solution to prevent them.

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Nacra 17

© Sailing Energy/Engadinwind 2020

iQFOiL

© Jesus Renedo/Sailing Energy/World Sailing

IKA Formula Kite


© Felix Diemer

Sailing Energy/Engadinwind 2020

1.3 What is a sailing hydrofoil?

A sailboat/board with wing-like foils mounted under the hull

Foil sailing is an extreme sport

40kn[1]
Top speeds achievable on the water by foiling hydrofoil crafts

Foil sailing is an Olympic sport

2000+
Number of active athletes in the Olympic world circuit[2]

♀♂
Performed solo and in mixed crews

With the iQFOiL and IKA Formula Kite's recent addition to the Olympics, foils sailing is increasing it's popularity.

[1] Approx. 74km/h
[2] Estimation based on World Sailing data from 2020.

Foiling is a discipline of performance sailing that involves flight mechanics and is characterized by higher speeds than conventional boats. A sailboat moves thanks to its interaction between two fluids of different densities, air, and water. Wind performs work onto a sail by acting an aerodynamic force onto it. Meanwhile, the flow of water onto the centerboard applies a hydrodynamic force. The final result of these forces applied to a boat allows it to move. A sailboat floats thanks to its' hull and the Archimede's principle.

Foiling sailing introduces the flying aspect. The boat's appendices are equipped with hydrofoils, which generate upward lift when moving through the water, raising the hull above sea level. Foil sailors are in control of a sailing machine as well as a flight machine. Consequently, the mental and physical abilities required to sail a foiling boat are significant. The sailors on the Olympic foiling classes are typically experienced in complex and potentially dangerous sailing styles.

The Nacra 17, iQFOiL, and the IKA Formula Kite are the official foil sailing disciplines of the 2024 Olympics. The Nacra 17 catamaran, left, sailed by a mixed-gender crew, has been the Olympic multihull class since the Olympic Games of 2016.

In 2017, the class association decided to change the shape of the daggerboards to allow the catamaran to fly (Graf et al., 2021).

The iQFOiL is a one-person windsurf, a type of board with a sail attached to it, equipped with hydrofoils at the rear fin. In 2020 it was announced to substitute the RS-X class in the 2024 Olympics.

The IKA Formula Kite is a kitesurfing class in which boards are equipped with hydrofoils. Kiteboarding or kitesurfing is an extreme sport where the kiter uses wind power with a large power kite to be pulled on a water, land, or snow surface. It combines aspects of paragliding, surfing, windsurfing, skateboarding, snowboarding, and wakeboarding [15].

World Sailing is the world governing body for sailing recognized by the International Olympic Committee and the International Paralympic Committee.

Section 2
Analysis

from Design Problem to Design Specification

To solve a problem, it is crucial to acknowledge it and understand what it is. A problem has always to do with discontentment about a particular situation, it is directed to the future, and it must be possible to do something about it. As described by the assignment owner, sailors of the Olympic foiling classes are expected to be seriously injured due to foil strikes.

Below is a list of elements, as described by Ackoff and Sasieni [16], to which attention must be paid when defining a problem. Based on research results and conclusions, the following section provides an overview of these elements.

What is the problem? The existing state must be defined, as well as the problematic aspects that are experienced in it. It is also essential to investigate what causes the current situation and how it will develop if nothing is done.

Who has the problem? Often the problem-owner is a group of people. A group may strive for one or the same goal, but it is also possible that different group members pursue other goals.

What are the goals? Discontentment with a situation is not more than a signal. To solve a problem, more desirable situations must be conceived of.

To define a problem is to answer these questions. The activities leading to a problem definition can be summarized as follows: observing and describing, explaining and predicting, and identifying and formulating goals and objectives.

The first four activities also play a central role in empirical research, for which several methods and sources have been employed. Section 2 focuses on presenting the results from the study performed.

In the following chapter, the research questions and methods used for the research are listed and described.

Research strategy for product design

2.1 Research questions

1. What are the characteristics of a hydrofoil?
2. How is a hydrofoil a risk to foil sailors?
3. How strong is a foil strike?
4. What do foil sailors currently wear?
5. How often are foil sailors injured?
6. What are the repercussions of a strike?
7. How is the problem being addressed now?

2.2 Research methods

Participatory observational research was performed in Almere, The Netherlands, with the iQFOiL team of the "Almere-Central" Windsurfing association. Data was gathered in the form of digital media (video, photo, and audio), notes from interviews, and notes from personal impressions. This study aimed to explore the subject, meet foiling athletes, and gather footage for statistical analysis.

In total, more than 70 crash videos have been gathered for the three foiling classes and numerous photographs. The footage has been uncovered from social network profiles of athletes, class organizations, World Sailing, and direct sharing of files from coaches and athletes. This footage was examined to determine the kinematics and mechanics of crashes for each of the Olympic classes. Furthermore, such crashes were analyzed to discover similarities within each class and categorize the types of crashes. Wind and weather conditions in these videos were also considered to estimate their influence on the craft's speeds.

World Sailing requires that an *incident* be reported if it involves a World Sailing organized or recognized event, any training at or before World Sailing recognized events, and any training or racing at events run by a World Sailing Member National Authority (MNA). World Sailing defines an incident as "an unexpected event resulting in death or injury to a person or an unexpected event that is hazardous in nature and has the potential to harm a person or property." Through a survey, World Sailing's incident reporting portal presents detailed and open-ended questions. Respondents are asked to describe the incident, including weather conditions, the cause of injury, the parts of the injured body, and the type of injury (e.g., fractures, sprains, or strains, or contusion). World sailing has granted special access to these reports for this research. The reports were reviewed in detail to: learn the types of injuries that athletes are subject to, confirm the assumptions made in the media analysis and perform a statistical analysis of injuries.

Fifteen one-to-one interviews and many casual conversations have been conducted with foiling sailors and coaches to provide information about an individual's actions and motivations. Among the questions, respondents were asked to discuss their past injuries, which at times tend not to be reported in the World Sailing Incident Reporting Portal. Another part of the interview investigated how sailors currently experience and use sailing clothing. These interviews were conducted by a moderator, phone, or video chat in sessions typically lasting thirty minutes to one hour.

Available sailing safety products have been further observed and reviewed through visits to physical and online shops of watersports equipment. Such activity was performed to assess the options available on the market for specialized sailing protective equipment.

Observational research in Almere, NL

2.3 Hydrofoil characteristics

A lifting surface operating in water

A hydrofoil consists of a winglike structure mounted across the keels of a catamaran or on a board's fin. As a hydrofoil-equipped watercraft increases in speed, the hydrofoil elements below the hull(s) develop enough lift to raise the hull out of the water, significantly reducing hull drag, providing a corresponding increase in speed.

2.1.1 HYDRODYNAMIC MECHANICS

Since similar fluid equations govern air and water—albeit with different levels of viscosity, density, and compressibility—the hydrofoil and airfoil (both types of foil) create lift in identical ways. The foil shape moves smoothly through the water, deflecting the flow downward, which, following the Euler equations, exerts an upward force on the foil. This turning of the water creates higher pressure on the bottom of the foil and reduced pressure on the top. A velocity difference accompanies this pressure difference via Bernoulli's principle. Hence, the resulting flow field about the foil has a higher average velocity on one side than the other.

When used as a lifting element on a hydrofoil boat, this upward force lifts the vessel's body, decreasing drag and increasing speed. The lifting force eventually balances with the craft's weight, reaching a point where the hydrofoil no longer lifts out of the water but remains in equilibrium. Since wave resistance and other impeding forces such as various types of drag on the hull are eliminated as the hull lifts clear, turbulence and drag act increasingly on the much smaller surface area of the hydrofoil and decreasingly on the hull, creating a marked increase in speed.

2.1.2 WHAT CONSITUTES A HYDROFOIL

On the right is the photo of an IKA Formula Kite board. The rider stands on top of the board (1), and his feet are strapped down. A mast (2) is assembled to the bottom rear of the board. By applying a force couple to the board through his feet, the rider controls the yaw of the craft. Furthermore, the mast performs the fundamental role of keeping the board from drifting through the water and allowing it to sail in different directions.

At the end of the mast is the fuselage (3), whose role is to support the front lifting foil (4) and rear stabilizing foil (5).

The lifting foil has a larger surface than the stabilizing foil because it carries the most vertical load. The resultant vertical forces are applied through the rider's feet onto its aerodynamic center. The stabilizing foil facilitates the pitch changes, which are controlled by the forces applied by the rider.

The shapes of the foils are complex due to their high degree of optimization. However, the forms are based on the sweep of conventional airfoil profiles.

The foil of an iQFOiL is nearly identical, except that the lifting foil's surface is larger because it carries more load. The foil of a Nacra 17 is shaped differently, but the hydrodynamic mechanics are applied in the same manner. All of the aforementioned hydrofoils are shown in Chapter 2.4.

A hydrofoil is not a danger in itself; it is the situations surrounding it that can turn it into a threat to an athlete's health. In fact, at high speeds, the physical characteristics of a foil turn it into a blunt object that can strike a person underwater with a high force and cause serious injury.

© Core Kites

Nacra 17 rudder strikes

It was assessed through reported incidents, media evidence, and interviews that accidents are likely to happen during maneuvers, such as mark roundings, tacks, and jibes, where the boat's speed changes. During an upwind mark rounding, sailors bear away, causing the craft to increase speed. If the craft rotates about the yaw axis too fast, sailors hanging by the harness lines may be pulled out of the boat and swung back into it at high speeds. Because of the acceleration, the centrifugal force increases, so sailors have learned not to be extended entirely outward and hold on to the control lines to keep them secure. In 2017, a report described how a sailor had crashed this way. However, while falling back towards the boat, the harness hook failed, causing the sailor to fall overboard and be struck by the incoming rudder elevator, causing a severe injury to the foot.

During tacks and gybes, the sail completely loses power for nearly a second, causing the catamaran to lose speed. Sailors move from one side to the other while adjusting the sails and hooking into the harness on the other tack. Missing the harness hook and losing grip on the ropes has lead sailors to fall overboard and sometimes be hit by the rudder elevator. The rudder's line of fire is directed to the outside of the craft, so aligned to a person's location when falling overboard.

The backside of the legs is usually involved in foil strikes due to how sailors fall in the water. The bowman may fall legs first after accidentally unhooking from the harness. Because the athletes rotate their upper body facing forward while sailing, the bowman may fall facing the direction of motion, therefore exposing the backside of the body to the line of fire of the foil. Furthermore, watersport athletes instinctively keep upright when going in the water, which is evident from the interviews. In nearly all of the reported incidents, foil strikes were caused by the same boat being sailed.

The same evidence describes how foil strikes from other boats seldom happen. No injury from foils of another boat has been reported to World Sailing. An improbable occurrence does not mean it can be overlooked. In fact, by reviewing photo evidence of capsized catamarans, it is clear that a person can crash into another capsized catamaran, therefore producing a foil strike but in reverse: a stopped foil with a fast-moving body.

© Jesus Renedo/Sailing Energy/World Sailing

2.4.1 NACRA 17 FOILS CHARACTERISTICS

The foiling surfaces on a Nacra 17 are configured slightly differently to the board classes and are made entirely out of carbon fiber. There are two daggerboards and two rudders, one of each is placed respectively on the two hulls.

Below is a visualization of the starboard side rudder (1) and daggerboard (2). Both can also be seen coming out of the water in the left photograph.

The rudder is T-shaped, resulting from the assembly of a single hydrofoil with a mast. The daggerboard is L-shaped and is only one piece. Based on the amount of wetted area, the daggerboards generate the lift to raise the catamaran.

The collective workings of all the four lifting surfaces act through the same principles of the previously shown kiteboard foil, where the daggerboards act as front foils and the rudders as stabilizing foils.

The craft's pitch is controlled by moving the crew's weight forward and backward, while the yaw is changed by the rudders rotating about their vertical axis.

SUMMARY

- Both Nacra 17 sailors have a high chance of being struck and injured by the rudder elevator and protruding fuselage.
- The Nacra 17 catamaran remains on course and maintains its speed when a person falls.
- Striking or being struck by a foil of another boat is possible but unlikely.

2.4 Crash dynamics

Out-of-control IKA Formula Kite board

The crash dynamics of the IKA Formula Kite are the most unpredictable of the three. They carry the least mass, which leads to a higher degree of uncertainty in the direction of motion of a rogue board during a crash. As described by the athletes during the interviews and by the video evidence, when crashing, riders lose balance and control of the board, releasing their feet from the straps and pushing it away to fall as far away as possible from it. The board is highly susceptible to human input. When a rider falls forward, the board nosedives and stops. At the same time, the rider slips out of the straps and is carried away with the kite.

When falling backward, the hydrofoil critically increases its incidence angle; the board jerks up into the air and slips out of the straps. The wind catches the board and foils, causing them to move randomly (like a rolling football) into the air for seconds until falling back in the water. Similarly, the board can be shot up into the air whenever the rider falls or steps off the board sideways. Sometimes the board can come up flying and hit another person, and because of the unpredictable orientation of the board, he may even be hit by the trailing edge of the foil (the sharp side at the rear of the wing).

In other cases, a gust of wind may pull up the rider along with his board and may not be in control of the landing location. Riders can fly up into the air, reaching up to 30m. If riding alone, unless the rider falls precisely on top of the board, there should be no foil strike. However, in a group of riders, this event may cause an incident. Video evidence shows how one rider was carried up in the air during the start of a race along with his board. His foil had a near-miss of nearly 25cm from the neck of a nearby rider.

The video evidence of IKA Formula Kite crashes between different riders is vast and ever-increasing.

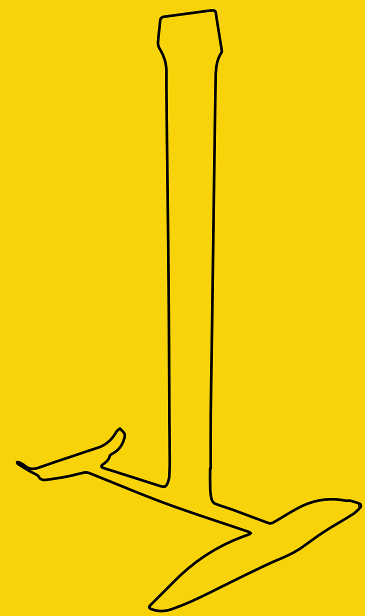
Photo: Alex Schwarz

2.4.2 NACRA 17 FOILS CHARACTERISTICS

The IKA Formula Kite Association approved 13 different foil manufacturers. All of these brands should build foils according to the specifications indicated by the class.

The dimensions of the foils are public domain and have been gathered for this research. The most notable dimensions of these foils are the maximum thicknesses of the mast, front and rear foils, ranging from 15mm down to 5mm. It is essential to mention that, due to the shape of an airfoil, the maximum thickness is not indicative of how sharp it is; at the front and rear edges, the radius of curvature makes the foil even thinner.

The trailing edges of these foils become as thin as 1mm, with some sailors even sanding down the edges to make them sharper.



SUMMARY

- The board's motion is unpredictable during an accident, like a rolling football (American football).
- Evidence proves that serious accidents happen between two or more riders at once.
- Riders can get hit by the trailing edge of the hydrofoil.

2.4 Crash dynamics

iQFOiL multi-party accidents

Foil strikes are not an impending danger to iQFOiLers while riding alone. Based on the gathered footage, riders fall forwards in 61% of the videos, 20% backward, and 19% to the side. In the first case, the wind transfers its inertia to the person, launching him forward while the sail hitting the water causes the board to halt. When falling backward, the athlete transfers its kinetic energy to the board, sending the board flying away from him. Falling sideways results in the sail losing power and the overall speed decreasing. In all cases, the immersed foil does not pose an impending danger.

Athletes agree that the iQFOiL is harder to control the higher the speed of the board. This phenomenon is due to the increase in available lift power from the foil relative to the craft's mass. The lift force is proportional to the incidence angle and the square of the velocity. Therefore, at higher speeds, a slight change in the incidence angle of the foils generates a substantial lift force. The hydrodynamic force can quickly jerk the board in unexpected directions reacting to the slightest input from the rider, causing him to lose balance.

Sailing in groups, however, introduces a new type of risk: a foil strike from a third party. In fact, in a group of eight sailors, of all the recorded crashes, 5% involved a near-miss between two riders. Therefore, if one crashes, his board is less likely to hurt him than his riders. With iQFOiL racing gaining traction, the number of riders sailing at once can easily exceed the hundreds. If a rider hits a person in the water, it would likely become a foil strike. Due to the novelty of the discipline and consequent lack of extensive data, this risk cannot be quantified with certainty. However, after critical evaluation, this dynamic is given special attention in this study.

There is video evidence of a head-on collision between two boards flying simultaneously at the 2020 iQFOiL Europeans in Lake Garda. It left two riders overboard with many high-speed boards going around them. One more case is a crash between two professional iQFOiLers at the iQFOiL International Games Split of 2021. A gust of wind caused a rider to run over the rider in front of him and risking a serious injury. Both parties survived with minor injuries.

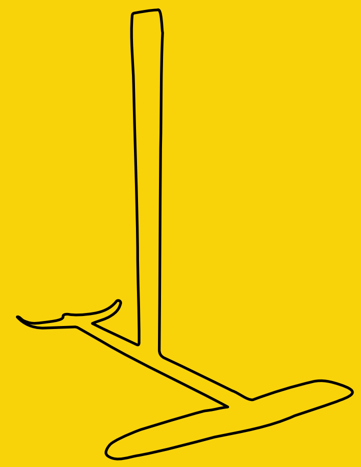
Finally, iQFOiLers are often subject to low energy impacts with equipment during minor wipeouts involving the knees, elbows, and abdomen.

© Severne Croatia

2.4.3 IQFOIL FOILS CHARACTERISTICS

The hydrofoil, shown below, is manufactured by Starboard, which offers a variety of foil configurations. Wings, fuselages, and masts can be interchanged or upgraded to match rider style, budget, foil racing conditions.

The front wingspan ranges from 62cm to 70cm, while the fuselage is nearly 95cm in length, which allows for increased pitch stability at higher racing speeds.



SUMMARY

- During a crash, the board's motion is easily predictable based on the direction of the rider's fall.
- Higher speeds make the board harder to control.
- Other riders pose a greater risk of accidents compared to sailing alone.

2.5 Kinematics and mechanics of impact

Quantifying the collision

A detailed approach describing the kinematics and types of forces at play during a foil strike to the human body is essential for developing the primary objectives. Such description can be replicated with a simplified test setup in a laboratory.

The complexity and the vast number of variables that can significantly influence calculating the magnitude of these forces go beyond the assignment's scope. The problem has been analyzed through the principle of energy conservation and by making informed approximations on significant energy transfer losses from the craft to the body. Furthermore, the final calculations are performed for a scenario with no losses and complete energy transfer (worst case scenario) and repeated for one with losses (best case scenario).

2.5.1 MODEL DESCRIPTION

The previous chapters have described what types of foils strikes and what causes them. The phenomenon of a foil strike itself is common to all situations, as it consists of the human body being impacted by a rigid carbon fiber blunt object.

The accident can be divided into three phases: (1) craft sailing undisturbed, (2) inelastic phase of collision, (3) crash continuation.

Phase 1: After a person falling overboard, the craft is sailing straight with nobody on board in the iQFOiL and IKA Formula Kite case. In the case of the Nacra 17, one person remains on board. This system carries constant kinetic energy as it sails at a constant speed.

Phase 2: The second phase is the most critical, where the rigid mass of the foil hits the soft body. The soft body is subject to an impulse that coincides with the foil mast's maximum deformation phase and temporary cavitation in the human tissue. The craft's energy is transferred to the body, and for a brief moment, the foil and human tissue travel at the same velocity. The body does not start moving yet; the foil is compressing and deforming the human tissue.

Phase 3: After the compression phase, the body is accelerated to a new equilibrium speed. The injury has happened by this stage, so it is only a matter of how the body slips away from the foil's line of fire.

In summary, phase 1 has one mass moving (the craft) and another at rest, not interacting. Phase 2 is the contact phase of the impact, where the craft's energy is lost in the compression of the tissue. Phase 3 has two masses traveling at a new equilibrium speed due to the conservation of linear momentum.

The mathematical description of the system is defined by the following measurable dimensions: craft mass, craft speed, human mass, and foil size. When energy is transferred in the system, stresses and strains appear. Local surface stress on the rider's tissue is expected to be the major contributor to injury.

2.5.2 ENERGY ANALYSIS

As previously stated, this is the case in which all energy losses are not accounted for. Therefore, in phase 1, the craft moves at constant speed towards the immersed body in the water, which is not moving. At all three stages, the total energy in the system shall be conserved. The potential energy is constant, so we can calculate the total energy of the system at stage 1 as:[1]

(1) $$E_{k,c,1} = \frac{1}{2} m_c V_{c,1}^2$$

The kinetic energies are expressed as:

(2) $$E_{tot} = E_k + E_p = E_k$$

(3) $$E_{k,b,1} = \frac{1}{2} m_b V_{b,1}^2$$

The total kinetic energy shall be conserved from stage 1 to stage 3:

(4) $$E_1 = E_3$$

(5) $$E_{k,c,1} = E_{k,c,3} + E_{k,b,3}$$

In phase 3, the craft's velocity and the underwater body are the same, at equilibrium. During this time, the total kinetic energy of the two masses combined is conserved. The energy loss due to water drag force is neglected due to the system's much more significant kinetic energy.

(6) $$V_{c,3} = V_{b,3}$$

[1] The symbols can be found in the Glossary section

(7) $$\frac{1}{2} m_c v_{c,1}^2 = \frac{1}{2} (m_c + m_b) v_{c,3}^2$$

Combining eq XX with eq XX and solving for vt2:

(8) $$V_{c,2} = \sqrt{\frac{m_c v_{c,1}^2}{m_c + m_b}}$$

The body has been accelerated from 0 to an equilibrium speed and has absorbed part of the craft's kinetic energy. Using Newton's second law, we can estimate the average force acting on the body during the impact.

(9) $$F_{\text{avg}} = \frac{m_b (V_{b,1} + V_{b,3})}{\Delta T}$$

Which gives an average force of nearly 15kN. The force that the foil exerts on the body is not constant during the entire duration of contact. Instead, it follows a sine-squared time history, starting and ending at zero and peaking approximately halfway through. The area under a force-vs-time curve is the impulse provided by the force. The average force, calculated above, is the constant force that acts for the same duration as the actual force and encloses the same area under its force-vs-time curve (providing the same impulse) as does the actual force. Data for force-vs-time curves for a body may be reasonably well fit by a function of the form:

(10) $$F(t) = F_{\max} \sin^2(At)$$

Due to the symmetric nature of this curve, the maximum force applied is double the average. This force is acting on an application point on the body; however, it is applied to the contact surface between the body and the hydrofoil's leading edge in reality.

The contact area of a foil strike on a surface is shaped as a rectangle, so the area is:

(11) $$A = lL$$

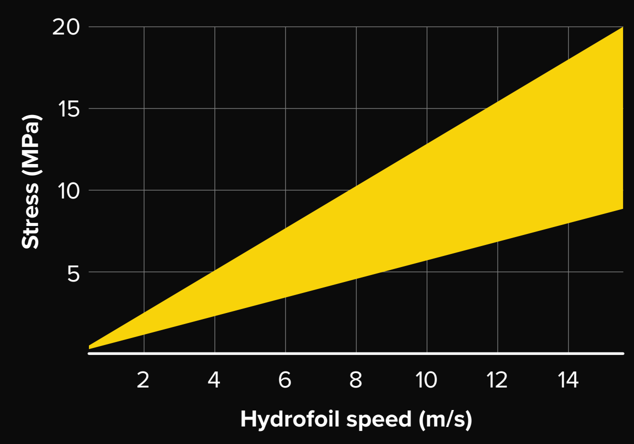
Finally, the distributed maximum stress on the body is:

(12) $$\sigma = \frac{F}{A}$$

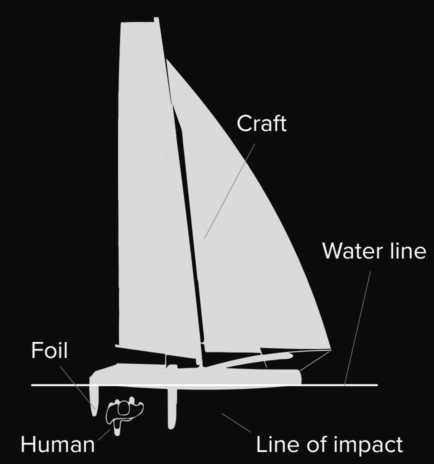
2.5.3 NUMERICAL SOLUTION

Based on experimental evidence by Stefan Breedveld, the impact duration of a similar speed rigid object on tissue ranges from 0.04 to 0.08 seconds. The masses from the crafts have been gathered from the technical specifications of the manufacturers. For reference, the average size and mass of a human were taken into consideration. The following results are valid for a leg being struck by a foil on the thigh. Confidence intervals bounded by the best and worst case scenarios are plotted in the graphs below. Factors such as material bending, moment of inertia of the craft, slippage, decrease in lift, and more have been estimated to decrease the stress by a factor of 0.5.
For example, a Nacra 17 hydrofoil striking a leg at 7.5m/s applies a maximum force of 15kN. Over an estimated area of 8cm^3, yeilds a stress of nearly 6MPa. Such area was measured using data from the World Sailing Incident Reporting and foil manufacturers.

Confidence interval of stress applied to thigh vs hydrofoil speed



Schematic of crash



2.5.4 CONCLUSIONS

The confidence interval shown in the graph was generated to enclose the confidence intervals of all three foiling disciplines. It gains significance knowing that these crafts can reach top speeds exceeding the wind speed. Based on wind statistics of several European sailing venues, a foil strike is more likely to happen in the 5-10m/s range.

A primary objective derived from this analysis is to create a product that can effectively decrease the applied stress to the human tissue. The energies and forces calculated in this model will serve as a guide in designing such a product.

2.6 Protective clothing

Functional and specialized

2.6.1 BODY PROTECTION IN OTHER SPORTS

Personal protective equipment is adopted in numerous sports. In light of the crash dynamics analyzed earlier, it is logical to compare foiling sailing incidents to sports. Product features and technologies from other sports can be translated to sailing and implemented into a wetsuit.

Contact sports, such as basketball, American football, and soccer, often involve impacts with other players. Body protection in these sports protects athletes from impacts through several pads, lined and often reinforced with a hard shell, located on areas of the body frequently involved in impacts.

Incidents involving a sharp external object are often seen in ice/snow sports such as ice hockey and ice skating, where the sharp blade of the skate imposes an impending danger. Athletes regularly wear protective suits or inserts that are resistant to cuts from impacts with sharp blades. The skin of speed skaters is nearly wholly covered from head to toes. Ice hockey players deem it imperative to wear a neck cut protector because, during an incident, a skate can wind up between the chest protector and helmet, causing a severe injury. Cut protective textiles such as Dyneema, Kevlar, and Cordura blends are often employed in technical protective clothing.

2.6.2 PROTECTIVE SAILING WETSUITS

Since the project's scope focuses on sailor's clothing, it is vital to have a complete view of how sailors dress and what is available on the market. Sailing possesses a wide range of technical clothing and accessories for all kinds of athletes, disciplines, and temperatures. Clothing brands approach the entirety of the dinghy sailing with a general strategy and sell wetsuits compatible with all kinds of sailing classes. In recent years, they have started considering the problems of impacts in high-speed crafts and making specialized suits. Observing and reverse-engineering the best protective suits on the market can help determine risk factors and dangers that high-speed sailors are subject to.

The suits investigated in the retail research protect from impacts inside the boats. These suits consist of neoprene, fleece, and lycra combined with additional protective padding and reinforcement on the body's critically exposed areas, such as the joints. An example is shown in the image on page 28. Although effective over the area they cover, this solution leaves parts of the body unprotected and exposed to foil strikes. Research from physical and online retail shows that sailing garments for protection from cuts and impacts are not tested against industry standards. As mentioned by the sailors in the interviews, they would like to have protective wetsuits proven to work.

Only one wetsuit, made by Forward WIP, features spandex and reinforced Kevlar panels to provide better tear resistance against sharp objects [12]. The marketing description of such a suit does not describe this feature further. A visual examination of this suit shows that there are areas of the suit not covered with Kevlar, which are exposed to the dangers of foil strikes. A similar suit was being worn by a sailor who had a recent injury from a foil strike. The rudder elevator of the Nacra 17 barely missed the Kevlar protection and injured the athlete with a skin tear of about 15cm in length and significant depth [2].

Finally, there is no sailing-specific cut and impact protection for the feet, hands, and neck. In the World Sailing Incident Reporting, there have been accidents causing significant injuries to these body parts: two cut feet and one neck impact.

2.6.3 SAILORS CLOTHING CHOICE

In general, the choice of wearing protective clothing is subjective. Therefore, it differs based on internal and external factors for each person. Several of these variables have been identified and evaluated against sailor's decisions through a section of the one-to-one interviews and participatory observation. The methods for recognizing such variables include user observations and the visual analysis of the collected sailing photographs and videos. Furthermore, during the one-to-one interviews, athletes were explicitly asked how often they wear protective gear, what influences their decision to wear it and what they do and do not like about it. The objective of this study was to identify the pain points of current wetsuits and discover potential areas of improvement and innovation in the product to be designed.

Internal factors

First, the sailor's crash track record is the most influential variable. Athletes who have never been involved in crashes only wear the protections required from the class rules. Then, the sailors that have been involved in medium to severe incidents often choose to wear additional protection. Finally, only two athletes, who have been seriously injured, actively seek to wear forms of protection from different sports disciplines. For instance, some Nacra 17 sailors are known to wear soccer leg shields to protect from impacts.

Another influential factor is comfort. More than half of the interviewed people consider external protective wear to be uncomfortable and limiting body movements. Wearing additional body protections drains more energy for the athletes as they have to perform more work to stretch and move such protections when sailing.

Cost is the last decisive factor in the adoption of protective wear. Most individual athletes do not actively seek to buy a complete set of protective wetsuits costing upwards of €500 unless their sponsors can provide financial support [12][13].

External factors

Weather conditions are the most influential external factors in the choice of protective clothing. Faster wind speeds and taller wave height present an increasingly higher risk of crashing. The conditions draw athletes who own protective clothing to wear it before launching on the water.

Sailors have no means to make an objective decision on personal protective equipment because they are not tested and do not declare their effectiveness transparently. Protective sailing clothing descriptions are limited to mentioning the materials and qualitative claims on their performance; this is the case for the wetsuits listed in the previous table.

The final external factor and most complex is sentiment. Sailors from different teams spend lots of time socially interacting ashore because of the necessary preparations. These interactions, followings, and friendships extend outside sailing events in other aspects of life and online. Stories, videos, and pictures of crashes can spread fast and be viewed by many people [14]. These events may trigger athletes to desire protection and take action, overcoming the internal factors mentioned above.

Dressing constrains

It is important to note that sailors dress up on the shore before going into the water. Once out, changing clothes is not convenient, even nearly impossible during a race. Coaches often carry clothing options on the rib. Their sailors can decide to change between a race and another. Multiple races are performed daily, so sailors can be on the water for extended periods, reaching even eight hours. Regattas last from one day to eight days of racing.

© Zhik

2.7 Injury characteristics

Where and how are they injured?

The objective of the following statistical analysis was to determine the past frequency of accidents involving foiling classes, quantify the risk that foil sailors are currently exposed to, and compare it with other sports. The data has been gathered from the World Sailing Incident Reporting, published health studies, and integrated with the one-to-one interviews.

2.7.1 STATISTICS

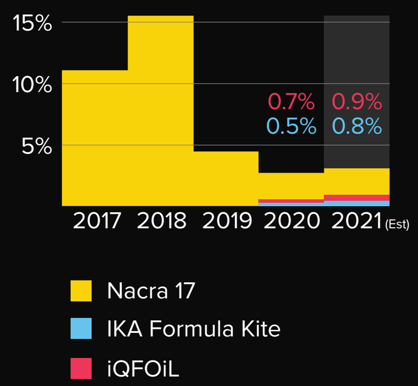
In 2020, of 2181 sailors of the Olympic foiling classes, 12 injuries from serious accidents were reported [1]. All of these have required medical attention and a period of rest ranging from weeks to months.

Nearly half of the injures sustained on a foiling boat are caused by a foil or rudder strike. Of the 31 severe crashes on foiling classes since 2017, 13 of them involved a foil strike.

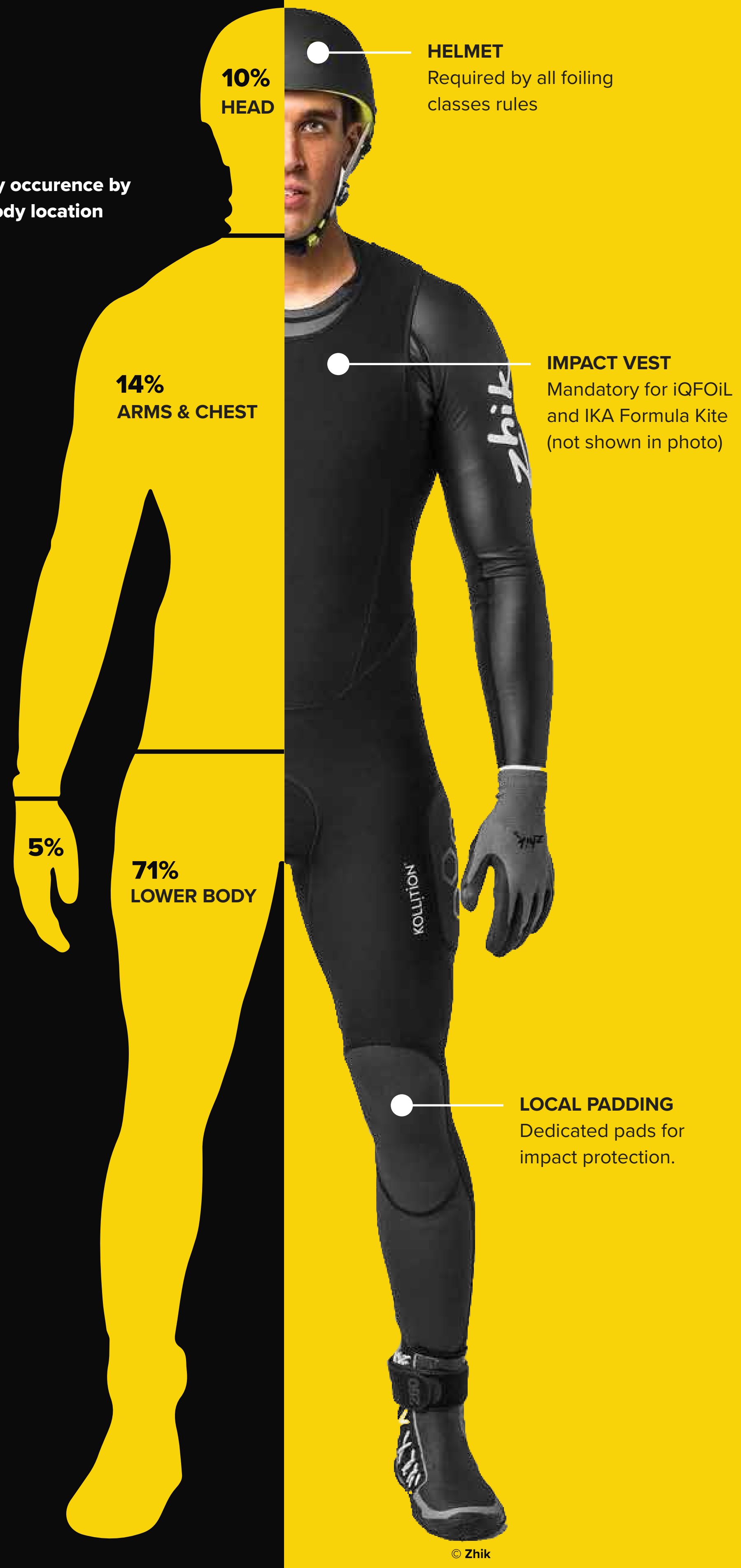
The relative number of incidents decreases every year. The Olympic committee announced the Nacra 17 as the first foiling Olympic class in 2017 as soon as it launched its foiling version. Hence the rise in popularity and a spike in the number of injuries. The number of injuries has since decreased to an estimated 3% in 2021.

The iQFOiL and IKA - Formula Kite were announced Olympic classes for the 2024 Olympics in late 2020, so it is expected that they will become more popular in the upcoming years. Furthermore, the 2021 Olympics will be the last appearance of the RS-X windsurf class (a conventional non-foiling windsurf), so the same athletes will be transferring to the iQFOiL soon. A slight increase in the relative number of foiling-related incidents is likely to be seen. The iQFOiL and IKA Formula Kite have already started their 4-year training cycle for the 2024 Olympics.

Average yearly severe injury rate of foil sailors



Injury occurence by body location



2.7.2 ANATOMY OF INJURIES

To define the current situation to be solved and as a form of prevention, it was indispensable to identify the types of injuries that foiling athletes are currently suffering. The sailors, coaches, and medical professionals described such injuries in the interviews and the World Sailing Incident Reporting.

Blunt trauma, also known as blunt force trauma or non-penetrating trauma, is physical trauma or impactful force to a body part [3]. Blunt impact injuries generally can be classified into four categories: contusion, abrasion, laceration, and fracture [4][5][6].

Penetrating trauma is an injury that occurs when an object pierces the skin and enters a tissue of the body, creating an open wound [7]. In addition to causing damage to the tissues it contacts, medium- and high-velocity projectiles cause a secondary cavitation injury. As the object enters the body, it creates a pressure wave that forces tissue out of the way, creating a cavity that can be much larger than the object itself; this is called "temporary cavitation" [8]. The temporary cavity is the radial stretching of tissue around the object's wound track, which momentarily leaves a space caused by high pressures surrounding the projectile that accelerate material away from its path [9].

2.7.3 EFFECT OF CRASHES AND INJURIES ON MENTAL HEALTH

Accidents have both temporary and permanent implications on the mental health of athletes. Injury is often accompanied by depression, tension, anger, and low self-esteem, particularly in competitive, seriously injured athletes [10].

The post-recovery mental implications do not significantly impact their racing performance once back on board, based on the interviews. After a successful rehabilitation, they return to their original mentality, sailing in the same manner as before the incident. They cannot envision a different injury scenario than the one they have already experienced, except for when a similar situation reappears before them. The memory may play in their head, causing temporary loss of focus and consequent exposure to the risk of crashing once again.

2.7.4 CLASS RULES AND RECOMMENDATIONS

The Nacra 17 class rules enforce the use of a personal floatation device, helmet, and cutting device. Body protection is optional.

In the iQFOiL, a helmet, whistle, and impact vest, which can also act as a personal floatation device, are mandatory. Additional body protection is allowed but not mandatory.

IKA Formula Kite: A helmet, knife, and impact vest are mandatory.

The Nacra 17 class publicly discusses the topic of safety on their website at sailing events. Safety is well advocated in this class and openly discussed with athletes and federations. The class also advises first aid training to the coaches and athletes. The Nacra 17 implements boat design changes based on risk assessments and feedback from the sailors. It is worth mentioning that the design of the rudder elevator is changing in 2021 and will be considered in the physics of impact section of this report.

"Keeping safe while sailing is a core value of the Nacra 17 Class Association."

-Nacra 17 Class [2]

The iQFOiL website does not have a section dedicated to safety. The class does not gather detailed information from crashes.

The IKA Formula Kite does not have a dedicated safety section on its website.

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2.8 Future vision

The most safe and desirable foiling wetsuit experience

Spotlight: Design a protective wetsuit for sailors of the Olympic foil classes

2.9 Design brief

Design a wetsuit for foilers

2.9.1 PROBLEM DEFINITION
Research has shown that foil strikes are an impending danger to sailors' safety. The protective wetsuits available on the market are not designed with foil impacts in mind. Furthermore, sailors find these suits uncomfortable and doubt their effectiveness leads them not to wear them. The future product shall provide users with a comfort level consistent with the level of protection required and be desirable to purchase and wear regularly.

2.9.1 DESIGN SPECIFICATION
The design specification is a list of objectives that a product to be designed has to meet. It provides the designer with the criteria by which the 'value' or 'quality of the (intermediate) outcomes of designing is judged. Some objectives are essential for reaching a goal; others are merely desirable. A requirement (or 'demand') is an objective that any design proposal must necessarily meet. Objectives that are not essential in this sense are called 'wishes'. A design proposal that does not meet one or more of the requirements is, by definition, not an acceptable solution.

The setup of the design specification is based on the primary objectives and by working systematically through a checklist developed by Pugh [11]. Combining such a checklist with the interest of the project stakeholders had led to a list of design requirements or design specification. The complete list of requirements is found in the Appendix.

2.9.1 PRIMARY OBJECTIVES

The product will effectively minimize the damage of a foil strike on the body while maintaining a similar comfort level compared to a conventional wetsuit. The material is expected to not tear with foil strikes up to 10m/s and transfer the least amount of force. The protective layer, during impact, will dissipate the energy from the foil onto a larger surface over a more extended time compared to current suits. Such a mechanism should, in theory, protect foil impacts up to a certain speed, after which it would decrease the severity of their injuries.

Here follow four primary objectives:

Impact protection

Protect sailors from impacts with boat parts, especially with foils, avoiding blunt trauma.

Cut protection

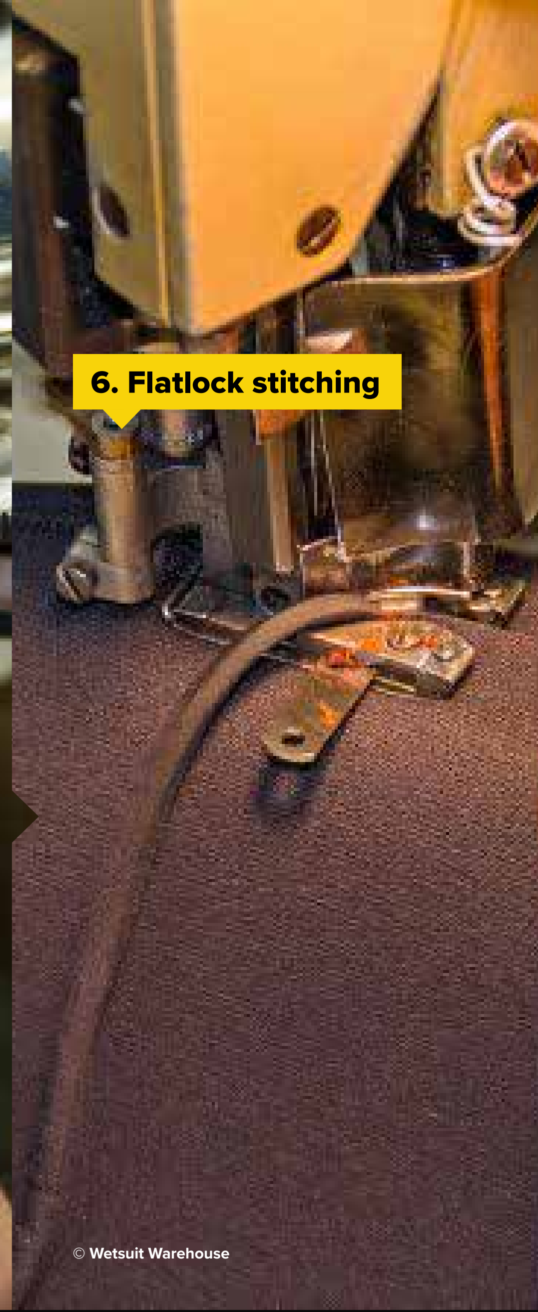
Offer cut protection according to industry standards, to defend sailors from foil cuts.

Enticing comfort

Minimize impedence to motion with a stretching suit that conforms to each athlete.

Futuristic appeal

Introduce a game-changing look that will maximize desireability and set a new trend.

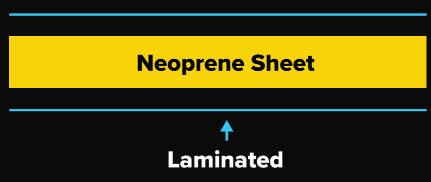


2.10 Wetsuit manufacturing

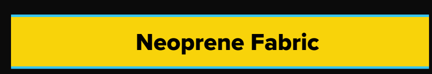
How a wetsuit is made

Before designing a wetsuit and eventually introduce a new technology or manufacturing method, it is important to learn how they are currently produced and what techniques are used.

Laminating

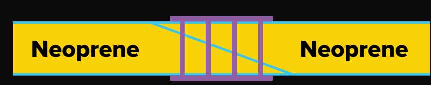


Sheeting



Glueing & bind stitching

Flatlock stitching

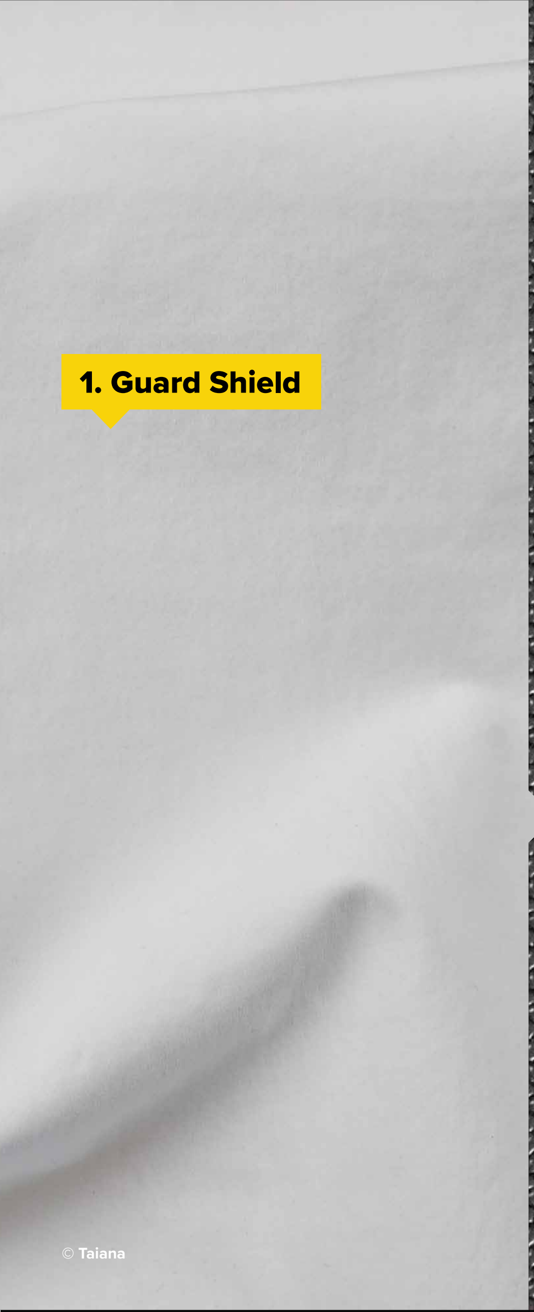


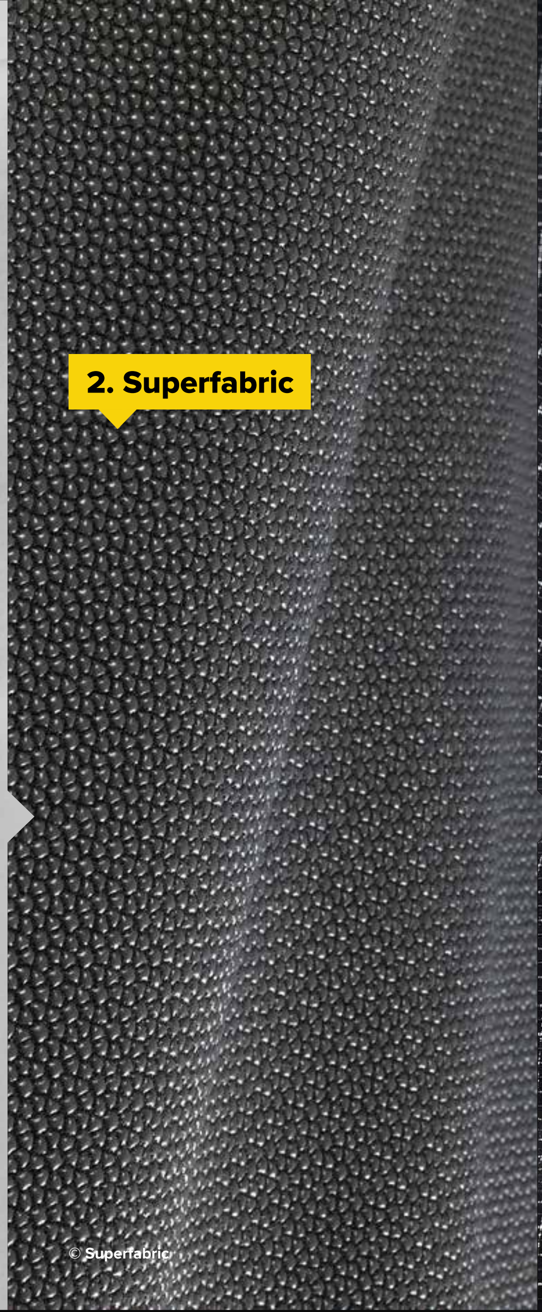
A wetsuit is a garment that is made from neoprene. Neoprene is a family of synthetic rubbers that are produced by the polymerization of chloroprene. As described by Possess Sea Industrial Co., this rubber, which is manufactured in rolls, can be processed by lining the surfaces with layers of nylon or polyester through a process called lamination (1). One side is meant to be in contact with the skin, so it is chosen, prioritizing comfort, weight, and humidity control. The other side, the outer layer of the wetsuit, is chosen based on stretch, durability, abrasion resistance if necessary, and aesthetics.

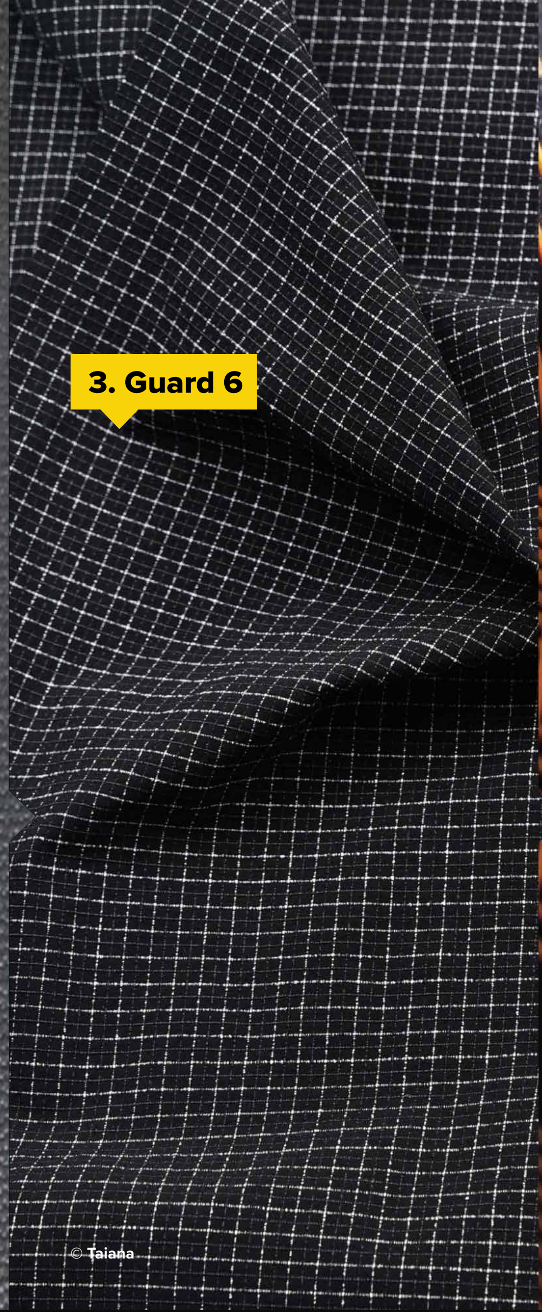
These rolls are sold by the meter by manufacturers and distributors to wetsuit companies. Because wetsuits are composed of different types of neoprene, the wetsuit warehouses store stacked sheets of neoprene (2). A wetsuit is made of stitched and glued panels. Such panels are cut out from the sheets of neoprene by a machine (3). Each panel is glued along the edges (4) and stitched. There are different stitching techniques. The most popular being glue bind (5) and flatlock stitching (6).

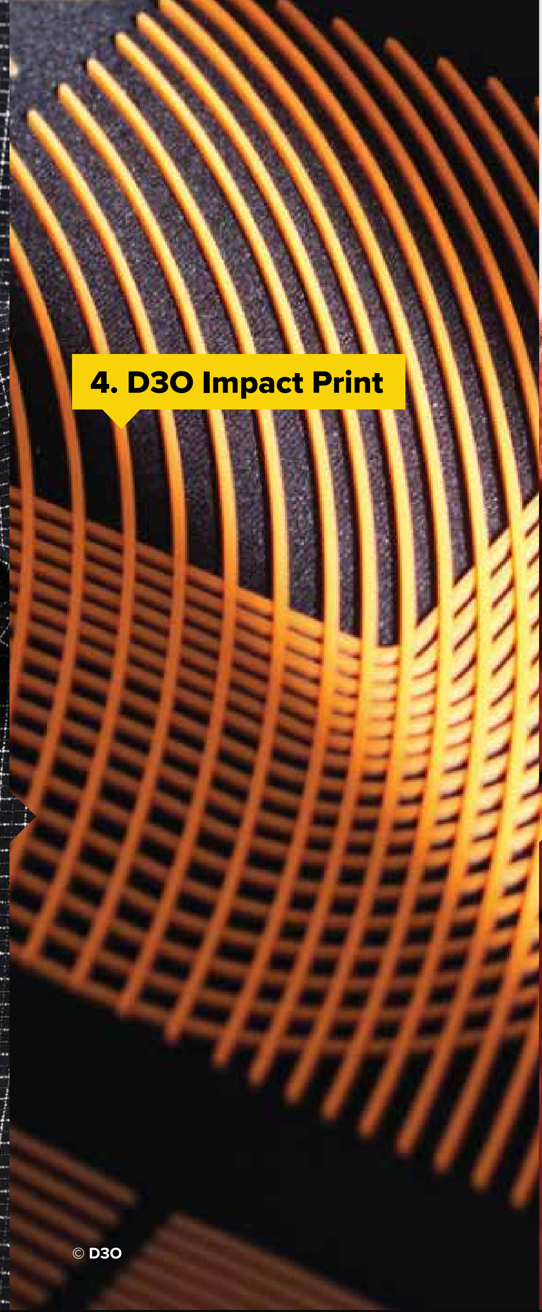
In the first case, after the two pieces of neoprene fabric are bonded with glue, the seam is then sewed without creating penetrating pinholes. Because the sheets are not penetrated, the waterproofing performance is ensured. The neoprene should be thicker than 2mm to apply this type of stitching.

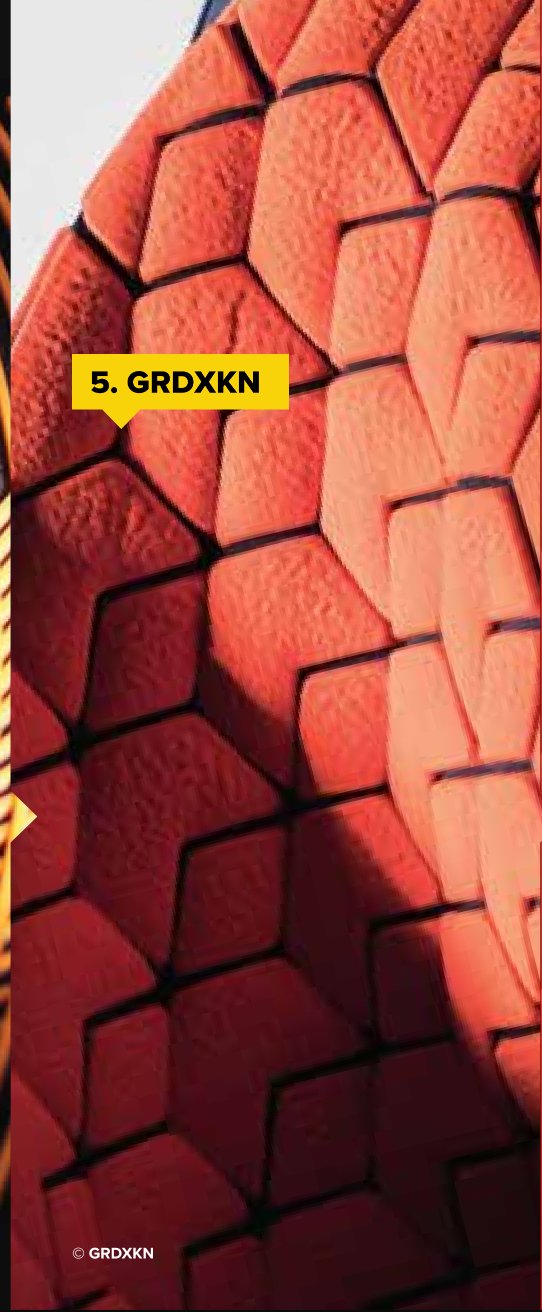
In the second case, after the two pieces of neoprene fabric are overlapped, four stitches and six lines are crossed through the neoprene fabric for a smooth closure. This technique provides good firmness due to the number of threads and their applied tightness at the cost of not being waterproof since the sheets are penetrated.

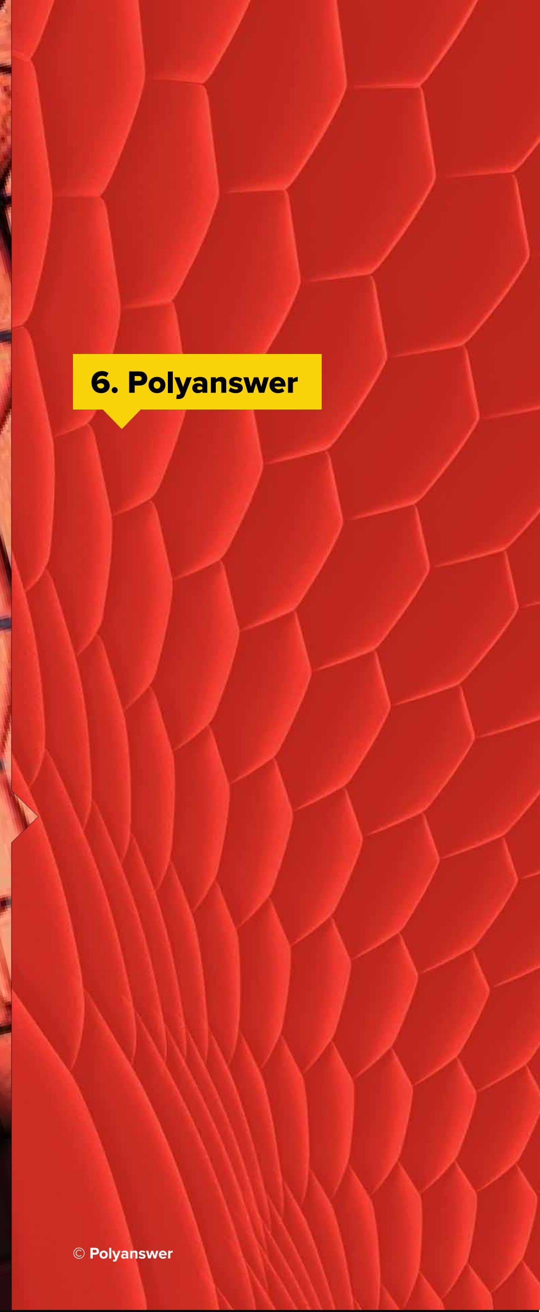












2.11 Material exploration

Seeking the right materials

Thanks to expert consultations and the previous research into various fields, here follow the descriptions of promising materials that may find their way into watersports.

The six materials depicted above have been researched and selected due to their potential application in the project. They are principally divided into cut protective and impact protective materials since protection from foil strikes requires both.

The table on the right gives an overview of the performance, applications, and companies behind each potential textile technology used in the wetsuit.

	1. GUARD SHIELD	2. SUPERFABRIC	3. GUARD 6	4. D3O IMPACT PRINT	5. GRDXKN	6. POLYANSWER
TYPE	Dyneema woven textile	Reinforced neoprene	Woven textile	Viscoelastic foam	Polyurethanic foam	Viscoelastic foam
THICKNESS	0.5mm	2mm	0.4mm	0.4mm - 10mm	0.5mm - 5mm	1mm - 10mm
ABRASION RESISTANCE	High	High	High	Medium	High	Not available
IMPACT PROTECTION	High	High	High	Medium	High	Not available
STRETCH	High	Low	High	Not available	High	Low
CURRENT APPLICATION	Speed skating	Military	Cycling	Sports	Sports	Not available
OTHER	High	High	High	Medium	High	Not available

Section 3
Conceptualization

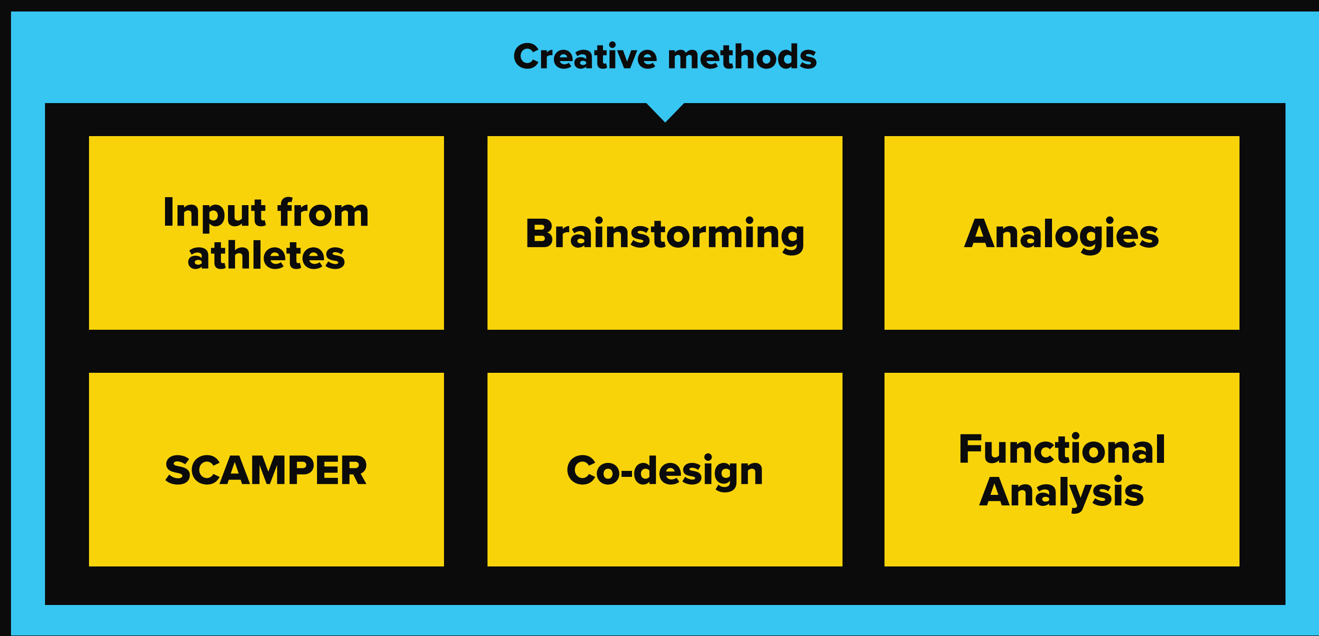
from Provisional Design to Final Concept

The concept development phase of the design process started with creating a provisional design and, after evaluation, ended with a final selected concept. Diverse creativity methods were used, including co-design, analogies, and functional analysis to create ideas. Creativity methods cannot replace domain knowledge; they only aim at enhancing creativity-relevant skills. The ideas developed were based on the resolution of the previously defined primary objectives. These were formulated as objective-based questions that each idea should solve. As many ideas as possible were gathered, and judgment was left out.
Further inputs were taken into account. For example, in the final section of four one-to-one interviews, athletes were asked questions about their ideal wetsuit. Such ideas were discussed together and taken into consideration. By using analogies through form similarity and function, other ideas were added to the pool.

Ideas were clustered and selected using idea clustering, SCAMPER, and functional analysis methods. Subsequently, three idea combinations were polished into three defined concepts, each with its advantages and drawbacks. Such properties were defined qualitatively, and then each concept was evaluated against one another based on their fulfillment of the primary objectives and critical evaluation. The best combination of features was selected to define the final selected concept.

This section concludes with a general description of the final concept and the reasoning behind each design decision.

Ideation strategy



Objective-based questions

1. How to dissipate energy?
2. How can it protect from foil cuts?
3. How can it stretch well?
4. How can it look unique?

3.1 Functional analysis

Define and combine

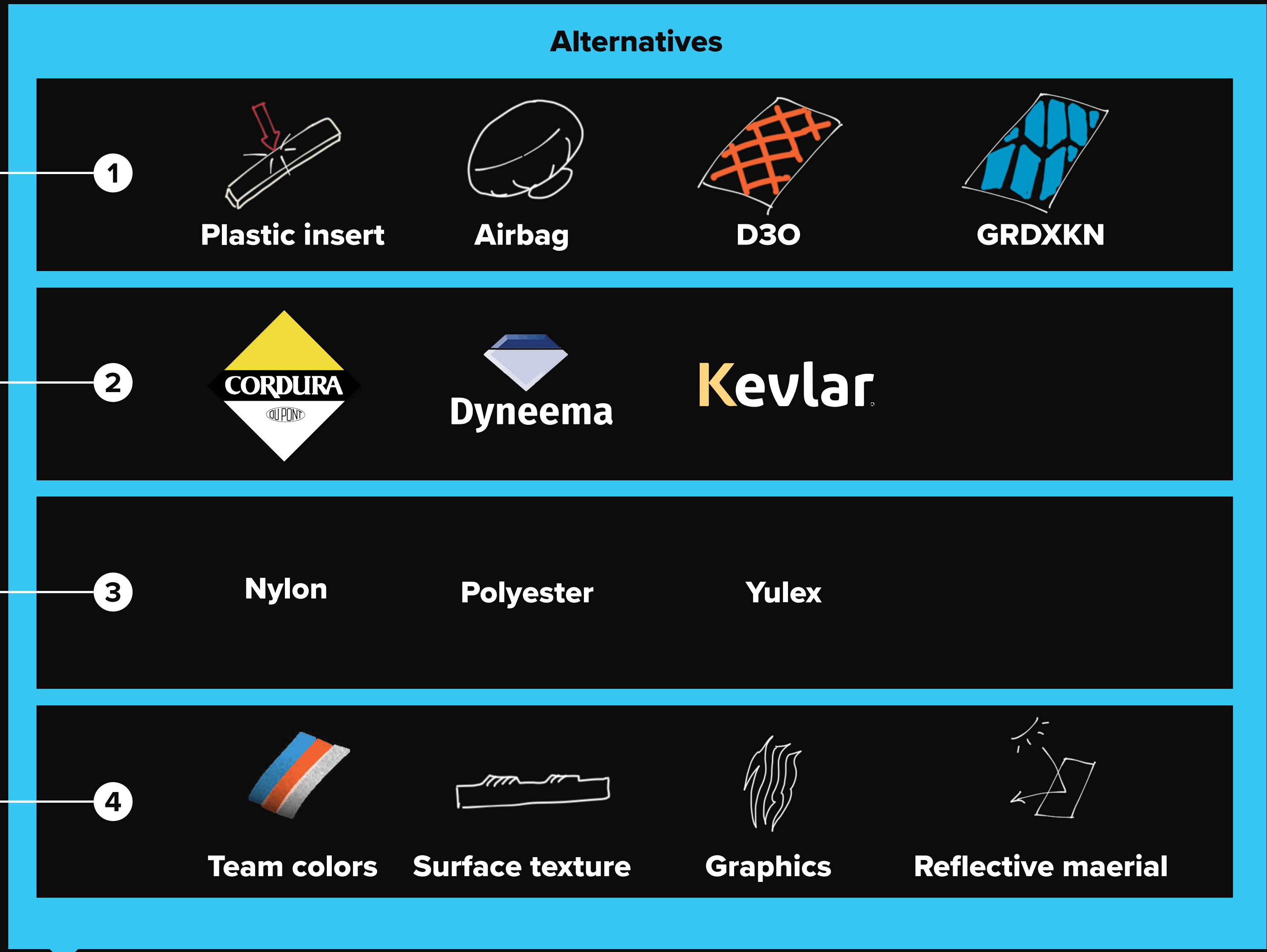
Due to the vast number of alternatives for each of the wetsuit functions, a functional analysis was an effective tool to keep track and combine them for defining concepts.

The chart is articulated with a row for each of the objective-based questions. Solutions, placed in columns, are proposed for each question, obtained from the developed ideas or researched appropriate solutions. For developing preliminary concepts, it is possible to select alternatives graphically by moving down each row (function) and selecting the best objective-based question solution. Such activity is performed critically by considering the validity, effectiveness, and compatibility of each solution.

These particular solutions have been developed using the previously mentioned ideation methods and by selecting existing applicable solutions discovered in the research.

The chart above shows a simplified view of the morphological chart. The output of the chart is the design concepts, which are described in the following subchapters.

Morphological chart (simplified)



Concepts

A — 3.2 De-fence

B — 3.3 Gridlock

C — 3.3 Cage

3.2 Concepts

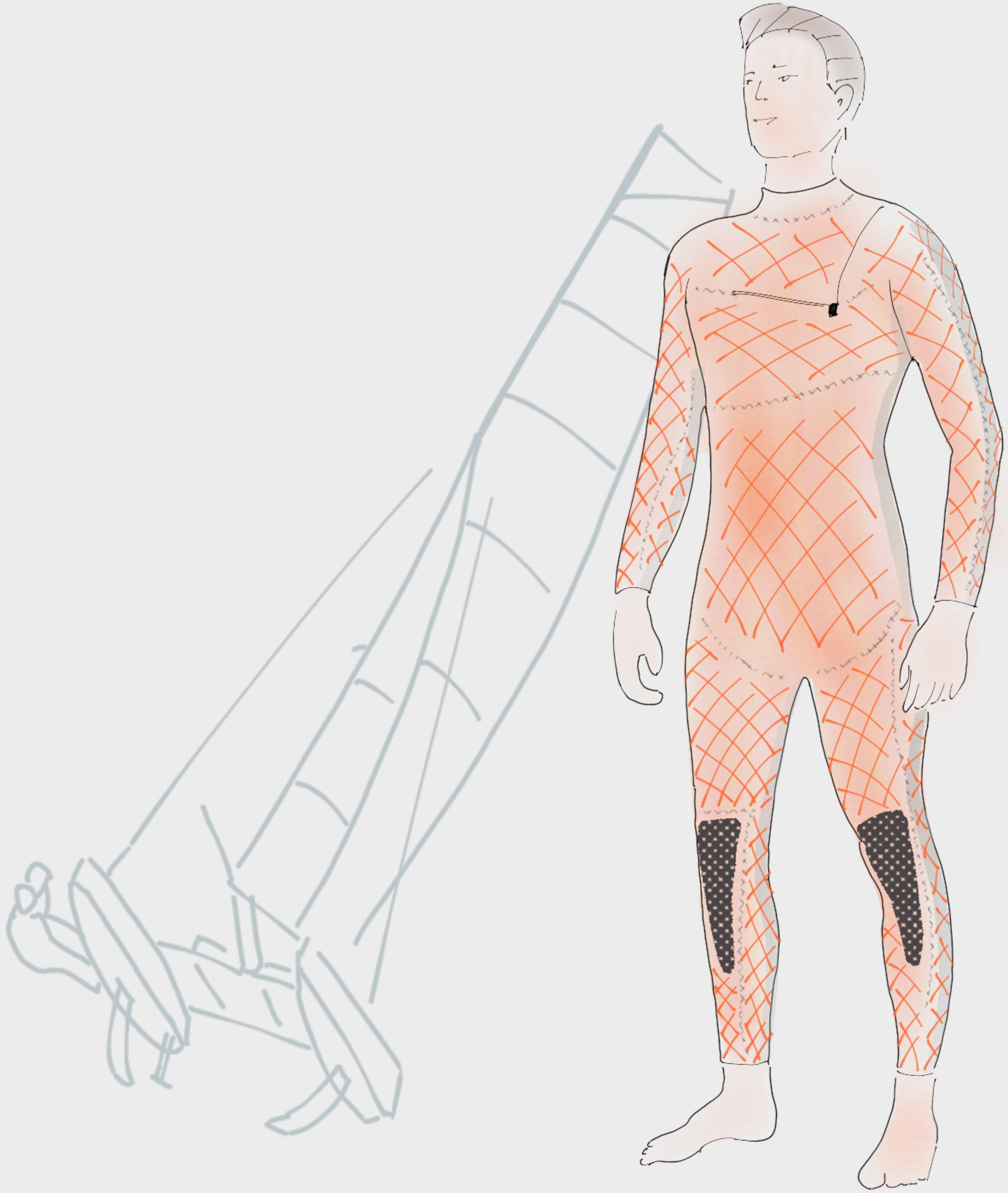
De-fence

The De-fence is a wetsuit for all foil sailors that is light, warm, flexible, and with safety embedded within. The previously explored textile technologies (Dyneema blend lining and D3O® Impact PrintTM) are used to protect from blunt traumas on the entirety of the wetsuit's surface. The Dyneema blend protects from tearing, while the D3O dissipates the energy from

D3O® Impact PrintTM is applied to the lower fabric layer and then bonded to the foam with assembly glue into the final neoprene construction. This design allows controlling the stretch, thermal control, and protection levels at every wetsuit panel with the following parameters: D3O pattern density and thickness. The pattern density controls how close each line of D3O is printed, resulting in more or less surface cover. The thickness controls how much material is printed on every line in terms of its height. A denser geometric pattern and higher thickness provide the best warmth and impact protection but the least flexibility. This setting is optimal for panels that do not require stretch, such as the abdomen and back of the legs. Similarly, a less dense and thinner D3O® Impact PrintTM pattern allows for better flexibility while still maintaining a sufficient level of protection. This configuration is suitable for panels near the joints, where the neoprene should stretch up to 60% of its original length.

The internal and external layers are made with a high-stretch blend of nylon and Dyneema resistant to cuts from sharp objects and strong abrasion. This material is also skin-friendly, making it perfect for extended hours of use without causing rashes.

The most critical design decision for this concept is the positioning of the D3O® Impact PrintTM. Applying it to the innermost layer between the fabric and foam could yield a weak bond between the two. In this position, however, the D3O is not exposed to abrasion and increases durability. Printing the D3O on the outermost layer is another good alternative that avoids the problem of assembly strength. The D3O would still perform as intended and have an engaging visual story on the wetsuit.



Nacra 17 shown for context, not the only application

3.2 Concepts

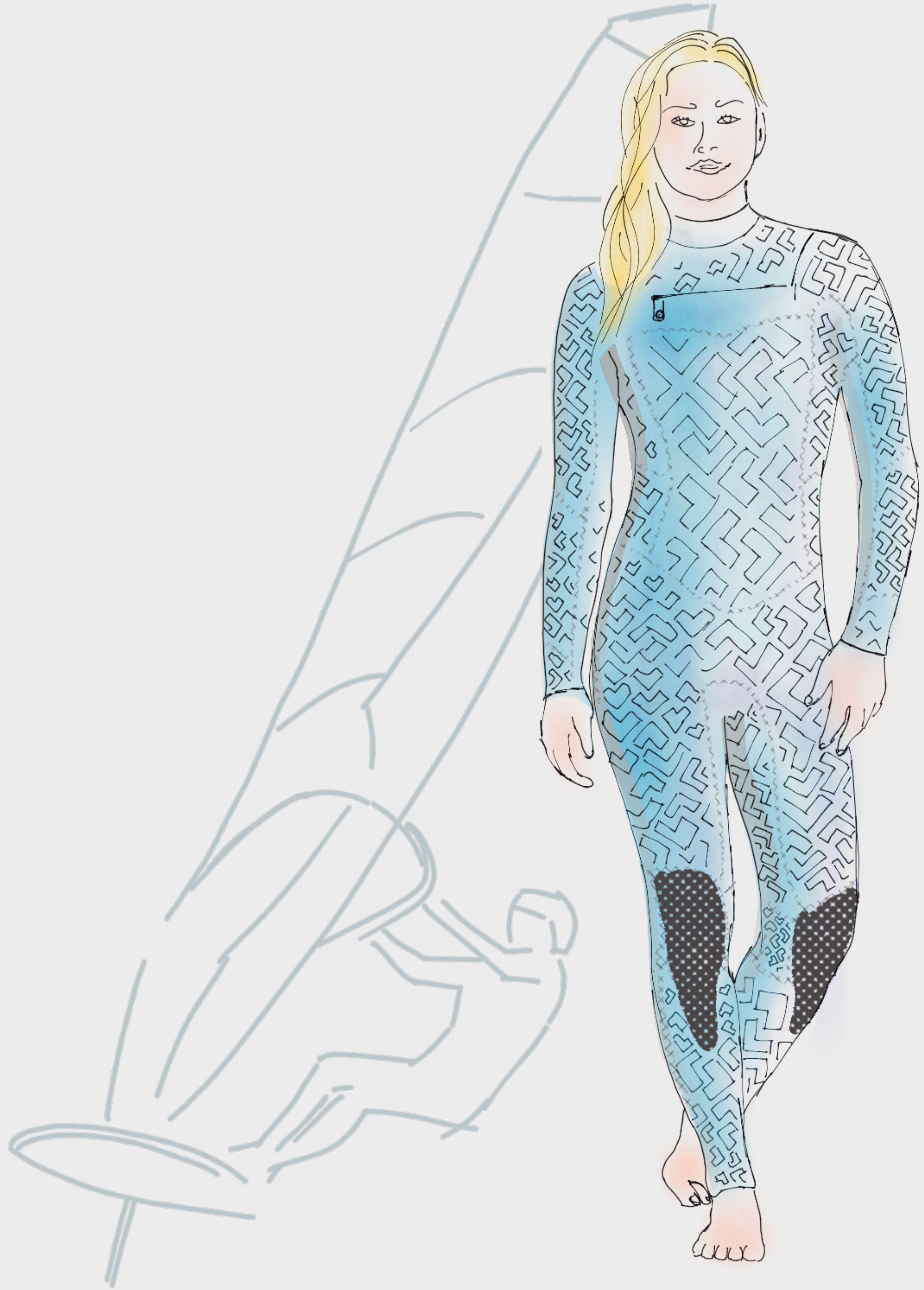
Gridlock

The Gridlock wetsuit is a statement of confidence and security for foiling sailors. An external pattern of the GRDXKN material covering the entirety of the wetsuit

The GRDXKN technology is the protagonist of this concept, which according to GRDXKN, provides exceptional durability, flexibility, and good protection from impacts. It is manufactured by printing a layer of polyurethane onto a fabric base, which reacts with heat and raises into a foam. The pattern is applied outside the wetsuit thanks to its resistance to abrasion and aesthetic appeal. The thickness is controlled by the amount of polyurethane printed on the fabric layer. The pattern shape and size can be controlled, depending on the panel on which it is printed. A smaller pattern enables optimal flexibility and can be used around the joints where the material is stretched in multiple directions. A larger pattern size, being less flexible, is used on the abdomen and back panels of the suit.

The outer lining is made of a Dyneema and nylon blend, which is cut-resistant and skin-friendly. This material is also quick to dry, making it convenient for athletes to dry their suits after a session quickly.

GRDXKN, a patent-pending technology, does not disclose the technical specifications of the material, so its performance must be tested. The choice of the base material on which the foam is generated is essential and should be strong, a blend of nylon and Dyneema would be ideal, but it should be tested for compatibility with GRDXKN.



iQFOiL shown for context, not the only application

3.2 Concepts

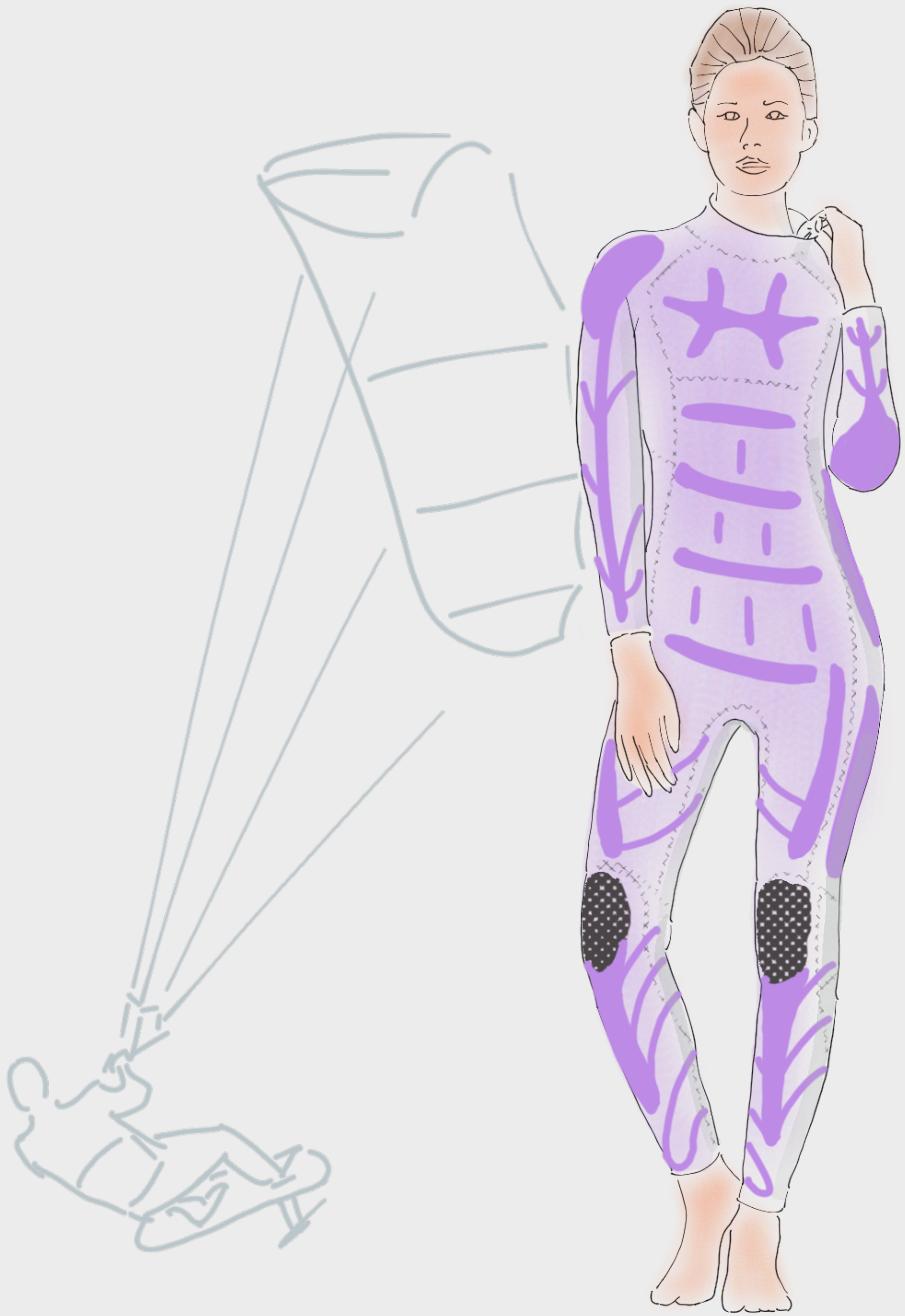
Cage

The Cage offers adequate impact protection from foil strikes to foiling sailors. The wetsuit's impact resistance is delivered by rigid plastic inserts along the entirety of the suit. The plastic inserts cause a protrusion on the layers above, making the internal structure discernible from the outside, therefore, aesthetically pleasing.

For the first time in watersports, plastic inserts are not limited to only covering the joins. Such internal structure works like an exoskeleton that protects sailors from foil strikes to any part of their body. The plastic inserts design must be made one by one and respecting the shapes of the suit's panels. They can be manufactured at a low cost using plastic injection molding and then combined with a foam lining for comfort. For optimal flexibility and strength, they can also be manufactured using a multi-material 3D printer, which can create single parts with materials of different properties. Such a printer allows creating an insert softer on the outside and harder on the inside, removing the need for an additional foam lining.

The inside of the suit is equipped with pockets in which the user can place each plastic insert. This feature allows the user to control the protection and flexibility he desires by choosing the number of inserts before wearing it. For example, if the sailor is already wearing an impact vest, it is possible to wear the suit without the plastic inserts in the chest and back.

Similar to the previous concepts, the joints are covered with anti-abrasion material, which is helpful, for example, on the Nacra 17, where the sailors are often on their knees.



IKA Formula Kite shown for context, not the only application

3.3 Evaluation

Evaluation

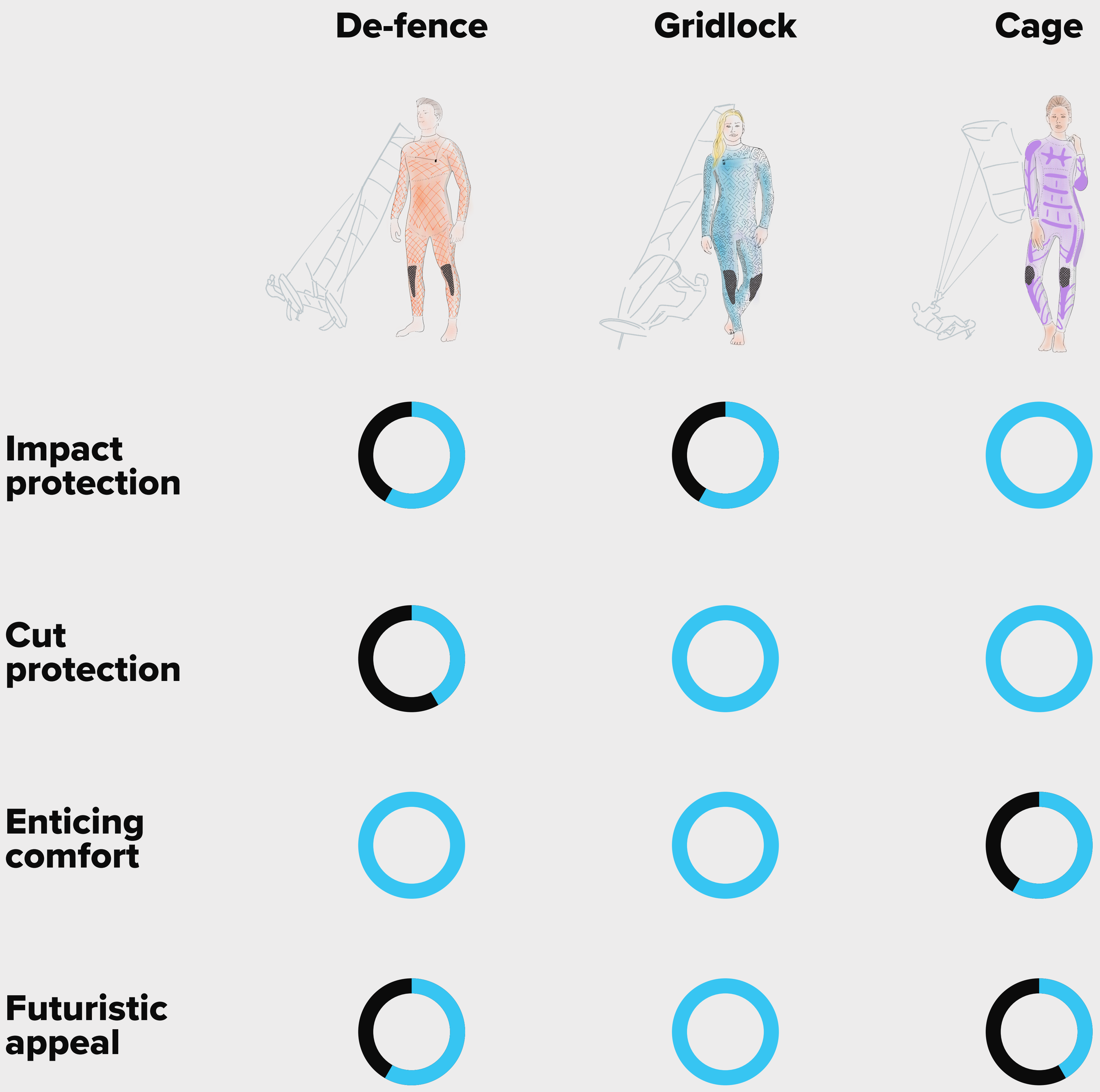
To the right is a framework for the evaluation of the concepts. Each concept is scored qualitatively based on the previously defined objective-based questions.

Regarding impact protection, all three of the concepts implement a solution to protect sailors from impacts. De-fence uses D3O Impact Print, a technology that uses viscoelastic foam to dissipate energy from impacts. Viscoelasticity is the property of a substance exhibiting both elastic and viscous behavior. Gridlock uses GRDXKN Structure Printing, a polyurethanic foam optimized for impact protection based on the ingredients, such as industrial hemp in the reacting solution. The Cage makes use of the most rigid material of the three for impact protection. A harder material is the most effective at dissipating impact forces over a larger surface, therefore offering the highest impact protection.
Impact protection generally comes at the cost of decreased comfort for the user. Sailors do not prefer a wetsuit that is heavier and less flexible. That is why, De-fence and Gridlock, being lighter and more flexible, score higher in the evaluation.

Gridlock and Cage have a layer of Guard material for complete cut protection. The De-fence wetsuit is not compatible with the Dyneema textile materials. This information was discovered when speaking directly to the head of sales at D3O.

Finally, the De-fence and Gridlock concept score highest on the aesthetic point since the patterns and colors of the impact protection technologies are discernible from the outside. It is a well-known fact that wetsuits are generally similar to one another, and these types of innovative graphics are the first of their kind in watersports.

Such a framework serves more as a guide for developing the final concept than a severe selection. There are other objectives from the list of requirements and practical limitations of the implemented proprietary technologies that were taken into account for the final concept development. For example, the GRDXKN company had shown interest in the project and even proposed to make a specific mixture and texture for the application. Further, after speaking directly to D3O, it was understood that the D3O Impact Print Technology was not as developed as it is currently being marketed.



3.4 Concept selection

Gridlock, but better

In light of the previous evaluation, the final concept was developed by selecting the best combination of features for each primary objective. The Gridlock concept is the highest-scoring among the three. The previous table can be viewed as a framework in which different advantages, drawbacks, and requirements can be drawn for each concept.

First of all, the D3O Impact Print technology is not compatible with the intended application; that is, it cannot be applied to a custom textile base. The GRDXKN can be printed on a broader range of fabrics, therefore ideal for offering impact protection on the entirety of the wetsuit's surface. The plastic inserts of the Cage effectively disperse energy from a foil strike since they are harder than D3O and GRDXKN (Shore A50) and distribute the impact force on a larger surface. However, this protection comes at the cost of decreased comfort and flexibility. In fact, in terms of comfort, the Gridlock and De-fence concepts are the best because GRDXKN and D3O are more compliant.

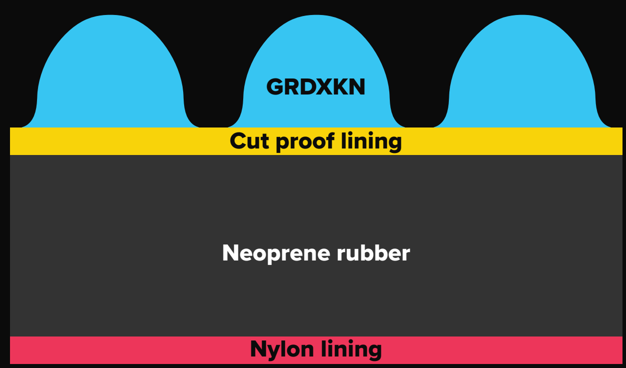
Aesthetically speaking, the De-fence and GRDXKN are visually distinguishable from any other conventional wetsuit. The D3O is only orange, but the GRDXKN can be colored in just about any color. This feature would potentially allow the national team to color the GRDXKN layers using the national shades. It was not mentioned in the research; however, it is an easily observable fact that, at current sailing events, the nationality of each sailor is not distinguishable from their clothing. A clearly defined coloring scheme would visually tell the nationality of a sailor, just as in any other Olympic sport.

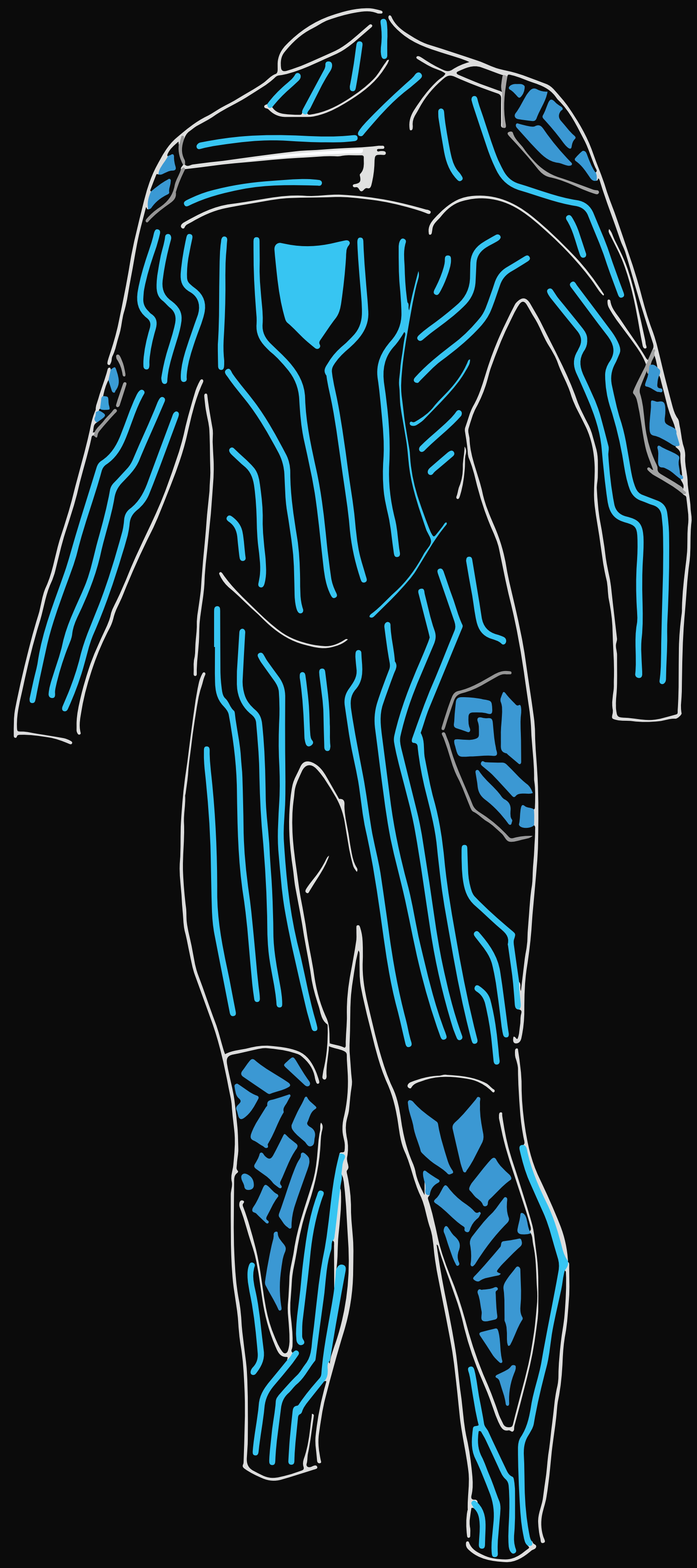
As for comfort, the Cage concept, although allowing the convenience of choosing when to use certain protective inserts, is the least flexible suit because of the higher rigidity of the plastic compared to D3O and GRDXKN. Because of the continuous movements of sailors, a more compliant suit is preferred and less fatigue-inducing.

Finally, in terms of cut protection, the Cage and Gridlock concepts are compatible with the use of a cut-proof lining, which could be the Guard Shield by Taiana.

The final wetsuit concept features GRDXKN on the outside, in a similar pattern as the De-fence concept. The GRDXKN is printed on the outer fabric lining, which is the Guard Shield by Taiana. This lining is connected to the neoprene rubber, which is in contact with the inner lining, made with conventional nylon or polyester. The GRDXKN is also printed using a denser pattern on the joints, back, hips and shoulders.

Side view of new material





Section 4 Embodiment design

from Final Concept to Validation

Assessing and advancing the final concept into reality is the objective of the embodiment design phase of the project. The product is developed in detail, and visuals are created for it. A 3D model was also developed for visually describing the concept to the project stakeholders. Physical prototypes were created to check the lamination bond and for impact tower testing.

The product's name is *Websuit 1*, which is a protective wetsuit for Olympic foiling sailors. It is a play on words between wetsuit and web since the GRDXKN pattern resembles a web wrapped around the body. The product is based on achieving the four primary objectives: impact protection, cut protection, comfort, and looks. Among these, impact protection is considered a priority, as it is key to solving the defined problem. Furthermore, the lining used in the wetsuit already has cut protective properties certified by the manufacturer. Comfort and looks are still weighed in the choice of materials and locations of protection. After defining the fundamental features of the product, prototypes are made to prove the feasibility and intended functioning of the product. Several challenges are encountered in this process, and the resolution of the most peculiar ones are presented in the following chapters.

The prototyping phase also describes the physical collection of materials and technologies from different companies, which were likewise relevant for the analysis section. Because materials such as neoprene and nylon lining are not easily retrievable from local retail stores, optimal planning and contact with specialized European distributors were crucial for staying on track with deadlines. Furthermore, the main challenge of the prototyping process was finding the correct bonding between the neoprene rubber and the fabric linings. The lamination process, explained in chapter 2.10, is strictly performed by machinery, which evenly covers the correct amount of coating to maximize adhesion and stretch. Such machinery was not accessible, so this process was performed by hand. Furthermore, the lining glue used in manufacturing is not sold in retail stores, so the most similar glues were purchased and tested iteratively.

At the same time, the GRDXKN prototypes were produced at the facility in Germany. Collaborating remotely with GRDXKN, numerous GRDXKN samples were developed using different "ink solutions", patterns and base textiles. The most significant challenge encountered at this stage is the process of activation of the GRDXKN. The ink is first in liquid form, and after heating to 150°C, it turns into foam. At this temperature, the elastic fibers of the Guard Shield shrink and decrease the stretch properties of the overall fabric.

Finally, combining the learnings from the bonding and GRDXKN printing, the final prototypes were developed. These prototypes were used in tests performed to prove the intended functioning of the envisioned product. The reinforced neoprene is subjected to impacts of various energies and differently shaped objects from an impact tower, which also measures the energies at play through integrated sensors. These tests were performed to investigate the kinetic energy absorption properties of the GRDXKN foam, conventional neoprene, and reinforced neoprene. Reinforced neoprene refers to the materials used in Websuit 1, which is the combination of nylon lining, neoprene rubber, Guard Shield and GRDXKN. After this, the reinforced neoprene and conventional neoprene were subjected to energy impacts similar to a foil strike to determine if they would break under such stress. The reinforced neoprene showed positive results from the testing because the GRDXKN has good impact absorption properties and did not break with the higher speed impacts. A cavity was formed on the conventional neoprene sample.

Websuit 1

4.1 Concept detailing

A closer look to Websuit 1

The Websuit 1 kicks off a new line of protective wetsuits for all kinds of fast Olympic sailors. Full-length woven Dyneema lining is stacked with lightweight neoprene and GRDXKN foam— a sensational mix of comfort and unprecedented protection. It is impact, cut, and abrasion-resistant, with excellent stretch range to accommodate sailor's freedom of movement.

4.1.1 ALL-ROUND COVERAGE

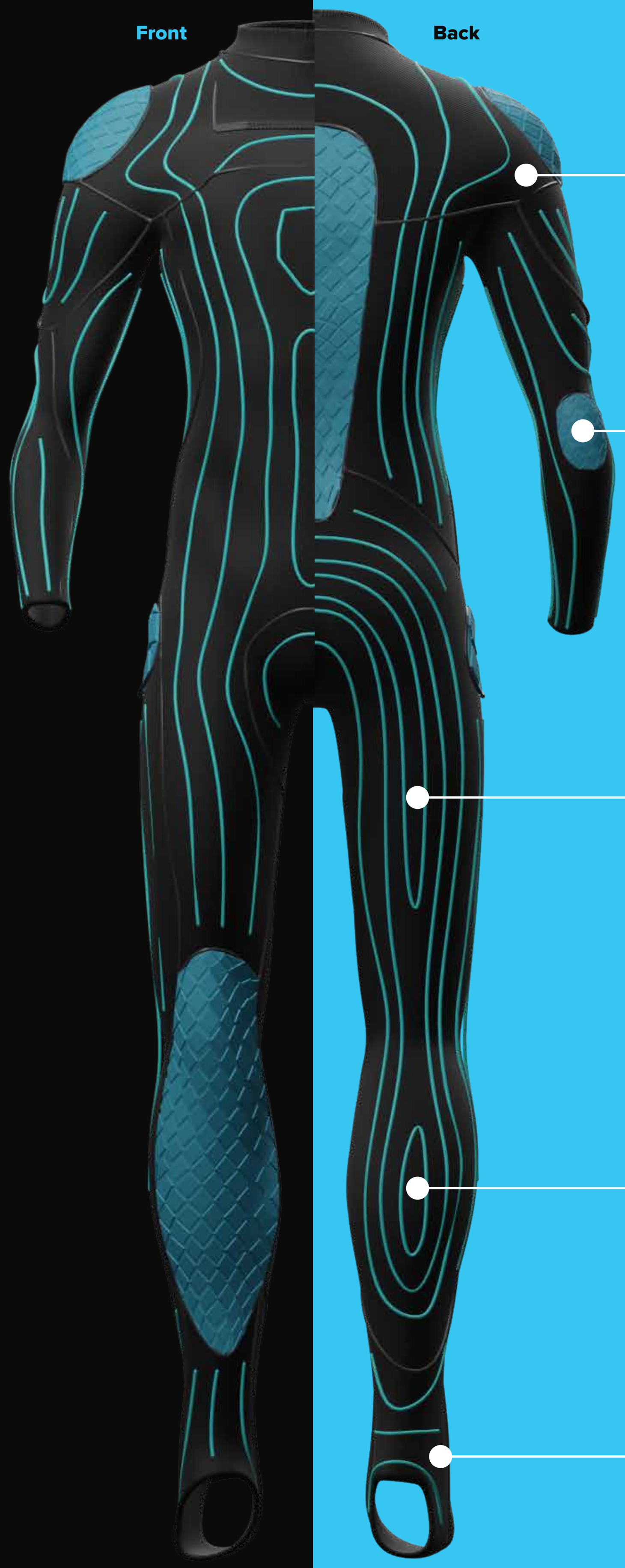
The Websuit 1 is made from reinforced neoprene panels featuring a cut and abrasion-resistant Guard Shield layer with high stretch and flatlock stitching. Coupled with a unique GRDXKN grid pattern on the shell, the Websuit protects the whole body from foil strikes.

4.1.2 DESIGNED FOR OLYMPIC FOILING SAILORS

Insights from foil sailors and extensive research helped create a wetsuit designed specifically for the most intense flying sessions. 3D mapped body fit, strong, flexible, and fast-drying materials make the Websuit 1 the most advanced and desirable protective wetsuit for foilers.

4.1.3 MATERIALS AND FUNCTIONALITY

The Websuit 1 offers protection on all the surfaces covered, from the neck to the ankles. Several parameters are set at each area of the suit's surface to control the local properties and behavior. The assembly of the suit adopts four different types of neoprene, developed specifically for this wetsuit. These parameters include, but are not limited to, the thickness of the neoprene rubber layer (3mm, 2mm, and 1mm), the vertical thickness of the GRDXKN foam (1mm and 2mm), the density of the GRDXK geometric pattern (25%, 50%, and 75% relative surface coverage).



CUT-RESISTANT LAYER
Made with Guard Shield, a light and flexible material, which Taiana claims to protects from cuts.

LOCALIZED IMPACT PROTECTORS
Made with a dense pattern of GRDXKN, panels on the joint areas offer protection from impacts experienced inside the boat. Such panels are found on the back, shoulders, hips, knees, shins, and elbows.

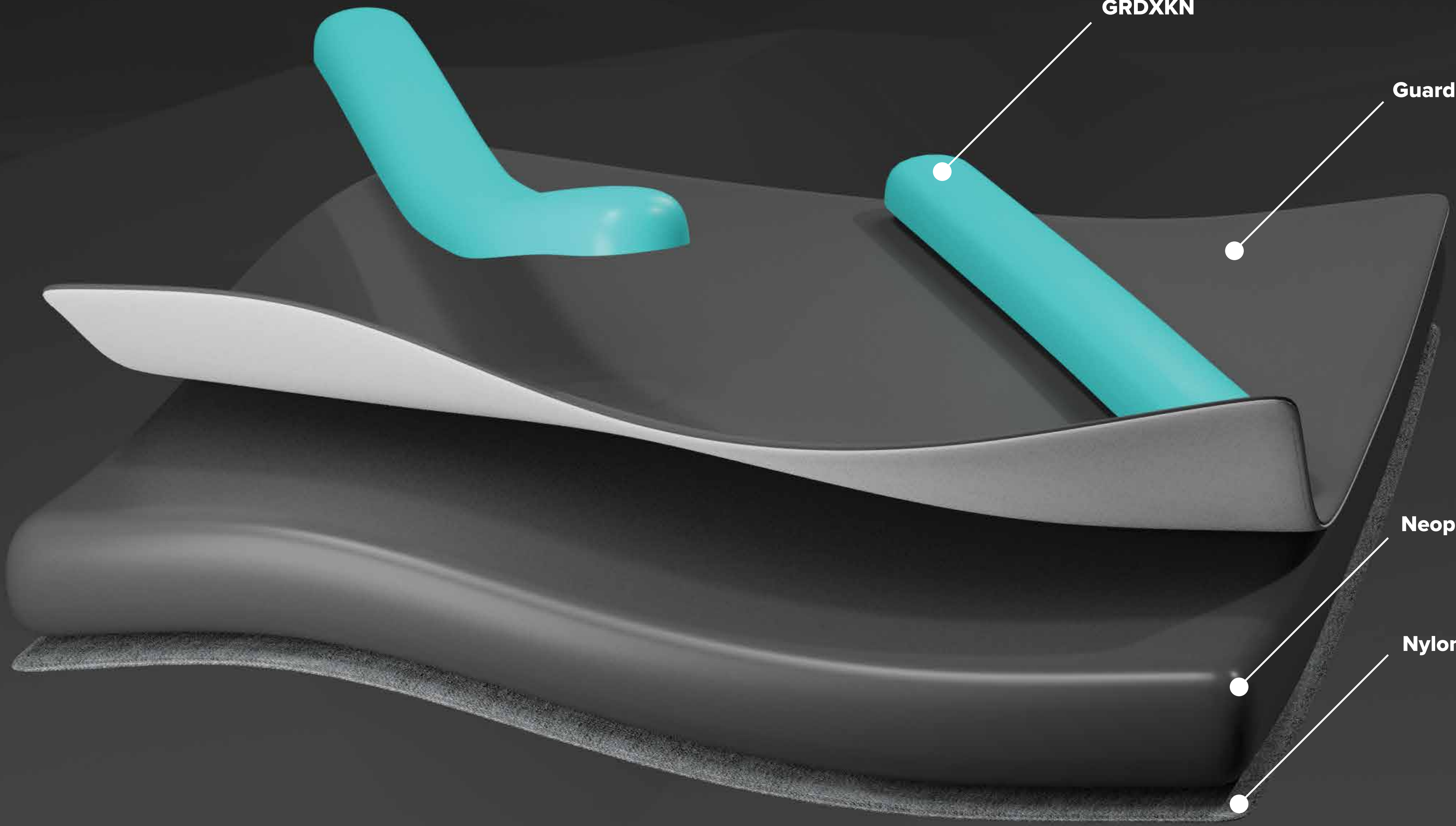
SUSTAINABLE MATERIALS
Mate with Yulex natural rubber, a renewable & plant-based alternative to petroleum & limestone based 'neoprene' that is sourced sustainably [17]. The GRDXKN is also water based and solvent-free.

GRDXKN IMPACT PROTECION
Covering the entirety of the suit is an exoskeleton of GRDXKN filaments, which protect sailors from unexcpected impacts with foils.

ANKLE AND HEEL PROTECTION
The protection Guard Shield and GRDXKN extend to the heels, wrists and neck. No area is left completely unprotected.

4.2 Protective neoprene

A first of its kind



4.3 Collecting and combining materials

Developing the material

Several material samples have been gathered throughout the project. From the initial explorative research phase, wetsuits and protective suits from other sports were gathered for analysis (1). One suit that has provided inspiration and guidance in the concept design is the cut protective speed skating suit used by the Dutch national team. This suit fits similarly to a wetsuit because it adheres to the body, acting as a second skin. The cut protective material was not disclosed; however, it appears similar to the Guard Shield.

A D3O panel, GRDXKN, and Superfabric were also collected when exploring impact protective materials (2). When exploring the D3O products, an informative meeting with the head of sales at D3O was conducted. It was learned that the D3O Impact Print technology was not as developed as it was being advertised. After reaching out to the owner of GRDXKN, a Munich-based company, a meeting was conducted to discuss the potential of the application. It was assessed that the company would assist the project development by providing technical advice and material prototypes with GRDXKN.

While exploring cut protective linings, more fabric samples, including Cordura, Ripstop HD, Guard 6, and Guard Shield, were obtained for evaluation and testing (3). The Guard 6 and Guard Shield were generously provided by Taiana, an Italian performance textile company. Kinetech is a brand owned by Taiana, which designs and manufactures performance textiles for sports applications.

Finally, in the latest stages of prototyping, open-cell single-lined neoprene samples were received from D&D Italia, the leading European supplier of Sheico neoprene. The polyurethane glue was also purchased from them.

PRELIMINARY PROTOTYPING
The preliminary prototyping phase started after the concept evaluations were performed. The Guard 6 and Guard Shield materials were selected as lining for the suit. The activity commenced with the trials of material assembly with the neoprene rubber. The first test was performed using Vlesofix as a bonding glue. Vlesofix is a film glue that is placed between two textile surfaces, and after melting with heat, bonds the two together. With a layer of Vliesofix and Guard 6 or Guard Shield, the neoprene foam was placed under, then pressed by hand with an iron. The bonding was successful since it provided good adhesion. However, the dried Vliesofix caused the material fibers to lose their stretch properties, leading to a final assembly with low stretch. The outer surface of the Guard Shield showed visible white coloring. The probable cause of the loss of stretch was attributable to the penetration of the glue through the material surface. Once dried, the Vliesofix did not allow the woven fibers to stretch. Several iterations on small samples were performed before the Vliesofix was abandoned.

Photo of first neoprene prototypes using Vliesofix

4.4 Bond improvements

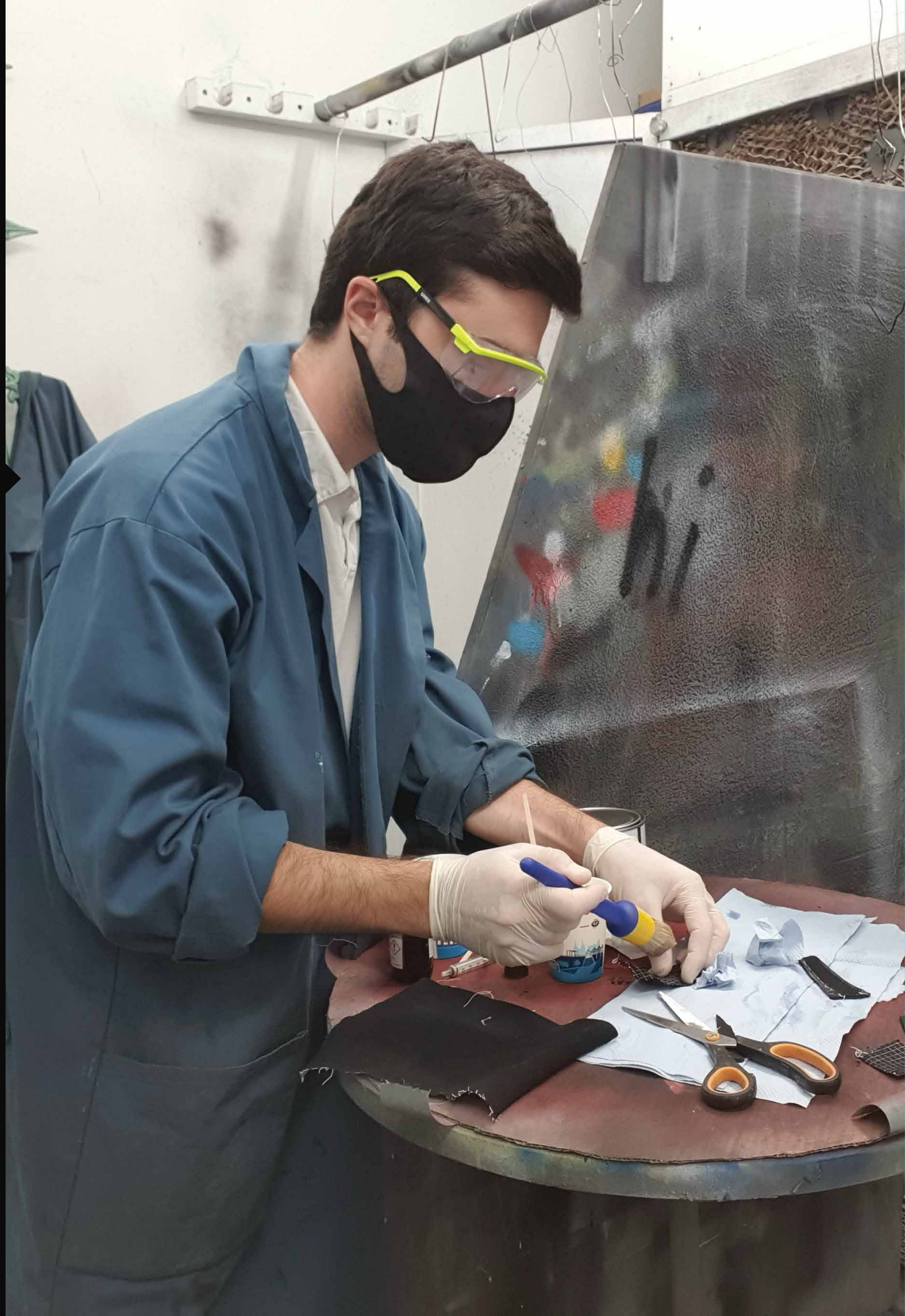
Prototypes with polyurethanic glue

Further prototyping was performed at the TU Delft laboratories. With an improved glue for bonding and specialized assembly machinery. The final result was a two-side lined neoprene assembly that could be sent to Germany to apply the GRDXKN layer.

These prototypes were made following an improved assembly method. To avoid direct inhalation of the glue, the mixing and application were performed in the paint lab, where the air was actively circulated. The glue was first dissolved with 10% of the activator. The activator is intended to increase the efficacy of the glue on surfaces. Each surface was cleaned with isopropyl alcohol and dried for 15 minutes. The glue solution was applied evenly on both contact surfaces with a single-use brush: the open cell neoprene and lining (Guard 6 and Guard Shield).

These were then hand-placed on top of each other and pressed to avoid the formation of air bubbles. After air-drying for 15 minutes, the assembly was taken to the heat press machine. The top plate, in contact with the lining, was heated to 70°C. The lower plate, instead, in contact with the rubber, was heated to 35°C. The assembly was pressed with a maximum load of 200kgf for up to 60 seconds. It is recommended not to exceed these values to avoid the thinning of the neoprene rubber. The assembly was removed and allowed to dry for 48 hours. A total of 8 iterations were made, all with different sizes, materials, and amounts of glue. With the Guard 6 and Guard Shield, two final neoprene assemblies were made to send to GRDXKN.

These prototypes demonstrated an excellent adhesion because, when tearing them apart, the neoprene layer was splitting at its core and not where the contact with the lining is. However, because the glue was applied with a brush, the optimal amount of coating was exceeded. On smaller samples, where less glue was used, the stretch of the assembly was wholly maintained. However, on larger samples, the stretch deteriorated because the glue had slightly hardened. The glue, however, did not penetrate the Dyneema layer.



SECOND PHASE PROROTYPING

The glue that was used needed to be activated at a temperature of 70°C. Hence, an essential tool for the correct realization of the neoprene samples was the heat press. The heat press can maintain any set temperature on each of its plates.

While one neoprene sample was being heat pressed, the following neoprene sample was drying after being coated before activation. This method enabled performing more iterations in a smaller amount of time.

Below is a photo of the heat press prototyping phase. On the following pages are photos of the results.

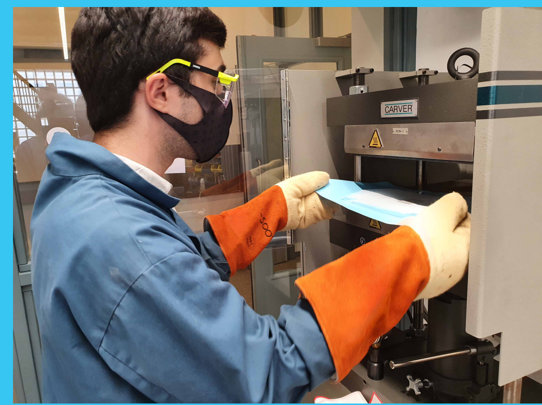
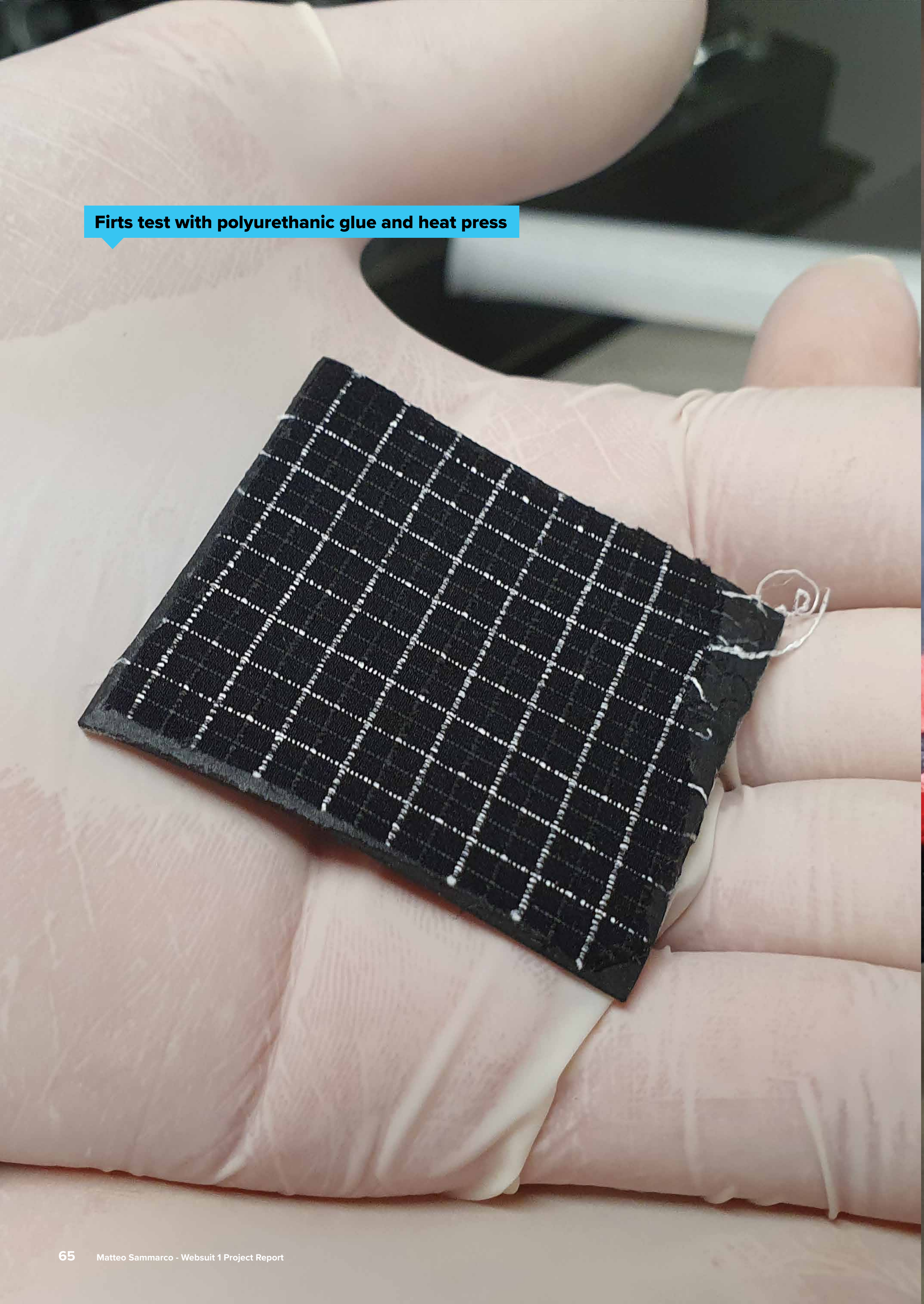


Photo of Matteo Sammarco operating the heat press


Firts test with polyurethanic glue and heat press


Double lined neoprene prototype

4.5 GRDXKN application

Applying the GRDXKN

GRDXKN is based on two-dimensional screen printing technology. A liquid solution is mixed based on the desired functional and aesthetic properties. Different values of hardness can be assigned to the foam, as well as any color. The details and the exact formula is classified information; however, it is water-based and solvent-free. A stencil determines the output pattern and shape. The pattern has a significant influence on the stretch, protective and aesthetic properties of the final material. Any two-dimensional shape can be created as long as a stencil can be created for it. The stencil for this case was made with a laser cutting machine. When designing the shape, it should be kept in mind that specific geometries, such as zig-zags and curves, have certain advantages compared to other shapes. The stencil is placed over a base textile, and the GRDXKN in the liquid state is poured over. The liquid is then heated to 150°C, where it transforms into polyurethane foam.

The objective for creating GRDXKN prototypes was to prove that the technology could be applied to the Guard Shield material or any similar Dyneema-based textile and evaluate its adhesion properties. After demonstrating good adhesion properties, the prototypes were tested to evaluate protection. The samples were processed in the GRDXKN facility in Germany, where the Guard Shield samples were shipped. Around 15 iterations were necessary to reach a final prototype with the desired properties.

Heating the material was the most critical step of this process, as it was seen that the elastic material woven into the Guard Shield was sensitive to the applied heat. In an oven at 150°C, the Guard Shield material lost its stretch properties. The Guard Shield is composed of 42% Polyethylene, 37% Polyamide, and 21% Elastane. It was not possible to determine which of the three materials of the woven textile was reacting to the heat. It is likely to have been the Elastene since the result was a loss of stretch. Because the neoprene rubber already offers the required elastic properties, the protective textile layer can be produced directly without the Elastane. Guard shield is, in fact, a fabric that is not originally designed to be a lining; it is used on its own in speed skating suits, hence, the use of Elastane. However, the process continued with the Guard Shield, and the following prototypes were heated using localized heat sources, such as a heat gun. The outcome was successful, as the localized heat only activated the GRDXKN without melting the woven material.

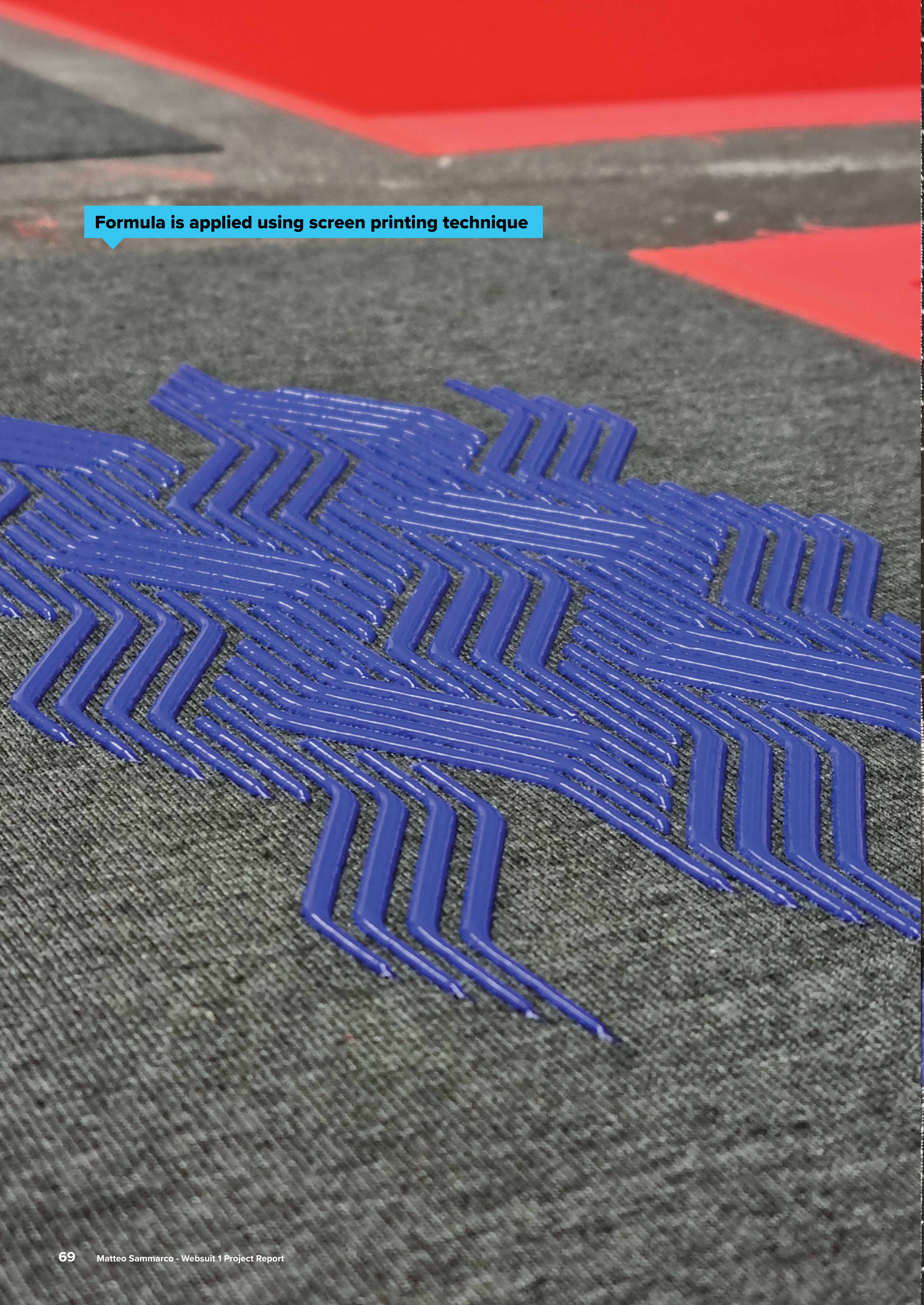
4.5.1 PATTERN DESIGN

The study of the GRDXKN pattern is a valid topic since it greatly influences the final material properties. When designing the shape, it should be kept in mind that certain geometries, such as zig-zags and curves, have particular advantages compared to other shapes. Take, for example, two points, A and B, on a fabric. Connecting these points with a straight line of GRDXKN yields a material that, along the AB direction, does not show optimal stretch. Connecting A and B with a longer line than the AB segment, such as a zig-zag or a curve, yields better stretch along the AB direction. The shape of the GRDXKN extends because of its geometry.

Furthermore, because foil strikes hit along a straight line on the body, a GRDXKN filament with multiple directions has a higher chance of getting in the way and protecting the body.

4.5.2 NEW STEP IN THE MANUFACTURING PROCESS

IIt was assessed during prototyping that the GRDXKN should be printed after the neoprene lamination process. It was therefore determined that the GRDXKN printing process would happen near the sheet cutting stage. With reference to chapter 2.10, the new step would appear before or after step 3. The lined neoprene sheet is laid on a flat surface; then, depending on if the process is machine- or human-run, the stencil/s is placed over it. Each panel of the wetsuit has a specific GRDXKN pattern designed for it. All these patterns can be mapped out on the same stencil to cover the whole neoprene sheet. The positioning of each panel coincides with the cutting locations. The GRDXKN ink is then placed onto the neoprene using the screen printing technique. The stencil is removed, and the GRDXKN is activated using a heat source. The wetsuit panels are then cut out, and the manufacturing process continues with the remaining conventional steps.



Formula is applied using screen printing technique

Formula is heated to 150°C reacting into a foam

4.6 Validation

Impact tower tests with neoprene

The correct functioning of the developed material is fundamental to the development of the product and is to be proven experimentally. Furthermore, sailors expressed concern over the fact that current protective wetsuits manufacturers do not disclose information about their testing methods if any.

The test is divided into two parts. The first is an adaptation of the ANSI/ISEA 138-2019 standard, where the properties of the materials are examined with low-energy impacts (10J). The second part examines the material behavior with a high-energy impact (30-40J) with a blunt object. The impact tower itself measures the dropper speed and applied force with integrated sensors.

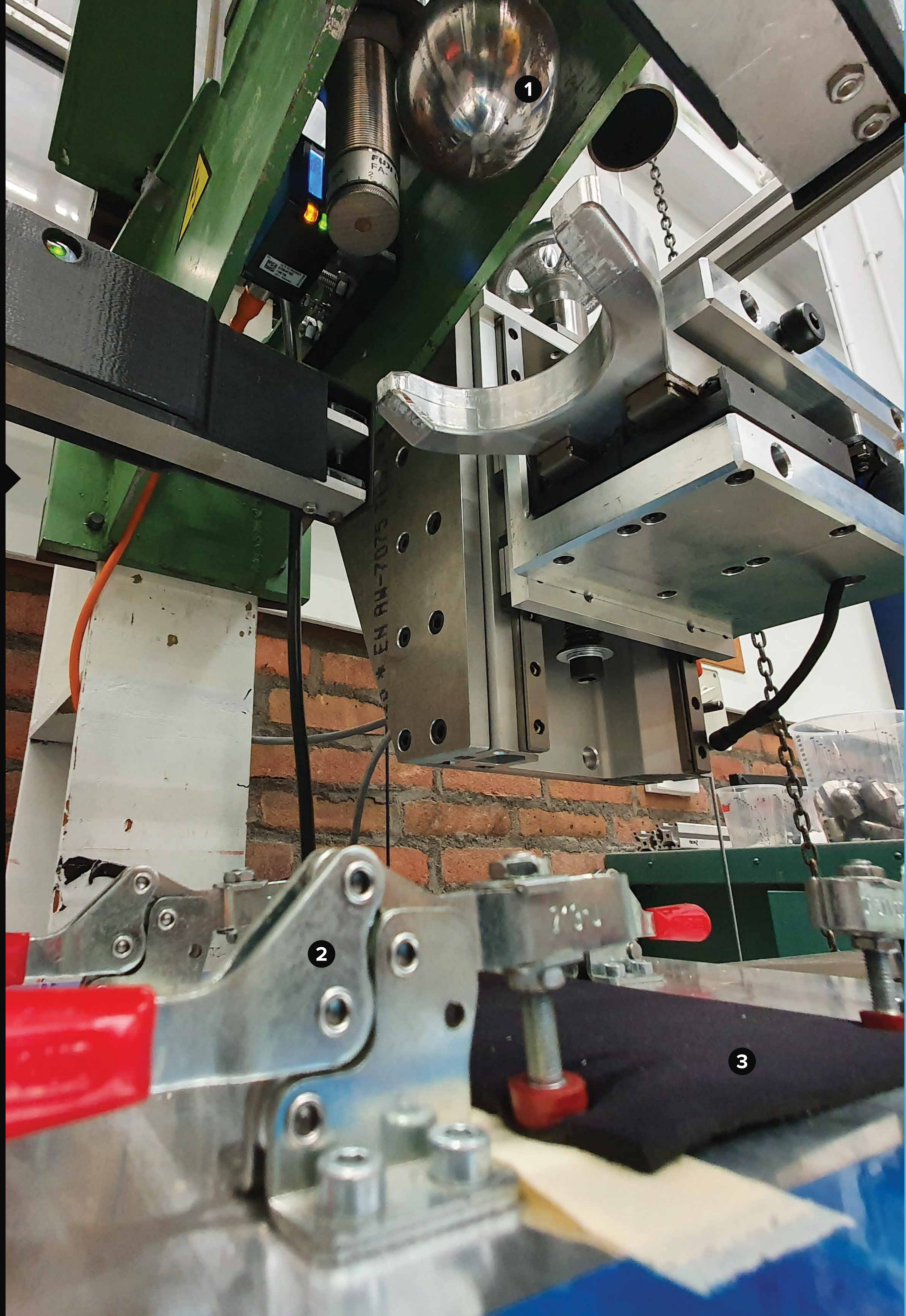
Hypothesis: The GRDXKN absorbs energy from a low-energy impact. The combination of Guard Shield and GRDXKN absorbs energy and does not break from a high-energy impact with a blunt object.

Materials:
Drop tower (1)
Video camera
Sample mount (2)
High-density polyurethane foam
Textile samples (3)
Ruler

Preparation: For each drop, the textile sample is fixed in place with four clamps onto a flat metallic surface for low energy impacts or on a foam block for high-energy impacts. The video camera is placed to the side, oriented parallel to the plane of the material sample. A ruler is placed in the camera frame near the expected impact location to measure the rebound.

Method: The polished steel dropper, of a total mass of 2.5kg, is raised to a height of 0.4m. The dropper is released in free fall onto two surfaces, first on a 3mm thick aluminium sheet, then onto the GRDXKN sample printed on lycra material placed over the same aluminium sheet.

The dropper impactor is replaced with different points for high-energy impacts with a blunt object. Point 2 was dropped from 1.5m, while point 3 was dropped from 2m. One conventional neoprene sample and one reinforced neoprene sample were used for each drop height.



4.6.1 RESULTS
40cm: the maximum applied force to the aluminum sheet was 8kN with 7.2J of measured kinetic energy. The maximum applied force to the GRDXKN sample was 4.5kN. Therefore, the GRDXKN+lycra sample absorbed 56% of the applied force.

1.5m: The foam sample was deformed due to the impact. The diameter of the hole in the foam was measured: 25mm for the conventional neoprene and 32mm for the reinforced neoprene. The Guard Shield + GRDXKN sample accounted for nearly a 40% increase in the impact area.

2m: The foam block with the conventional neoprene was broken in half. The dropper penetrated the conventional neoprene material sample. The foam block with the reinforced neoprene did not break. The Guard Shield and GRDXKN were undamaged, and the nylon lining showed minor fraying.

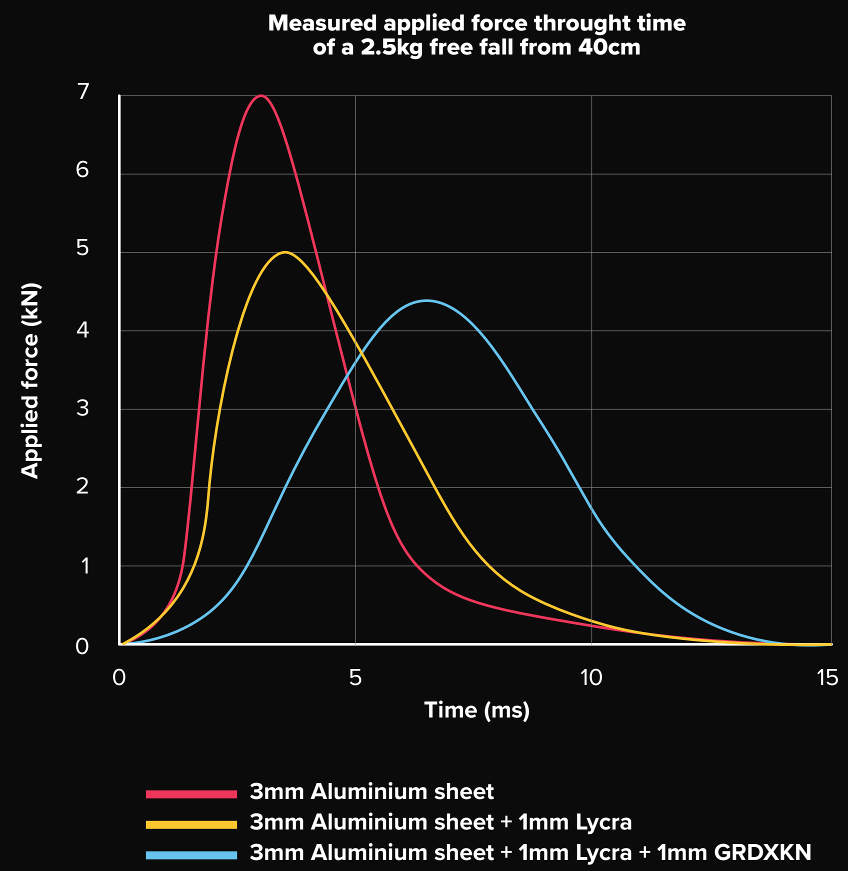
4.6.2 DISCUSSION
A circular section dropper is the only shape compatible with the used impact tower. A rectangular section dropper would cause load forces not aligned with the direction of impact, and this would invalidate the data reading from the strain gauge on the dropper. Furthermore, all the tests were performed once.

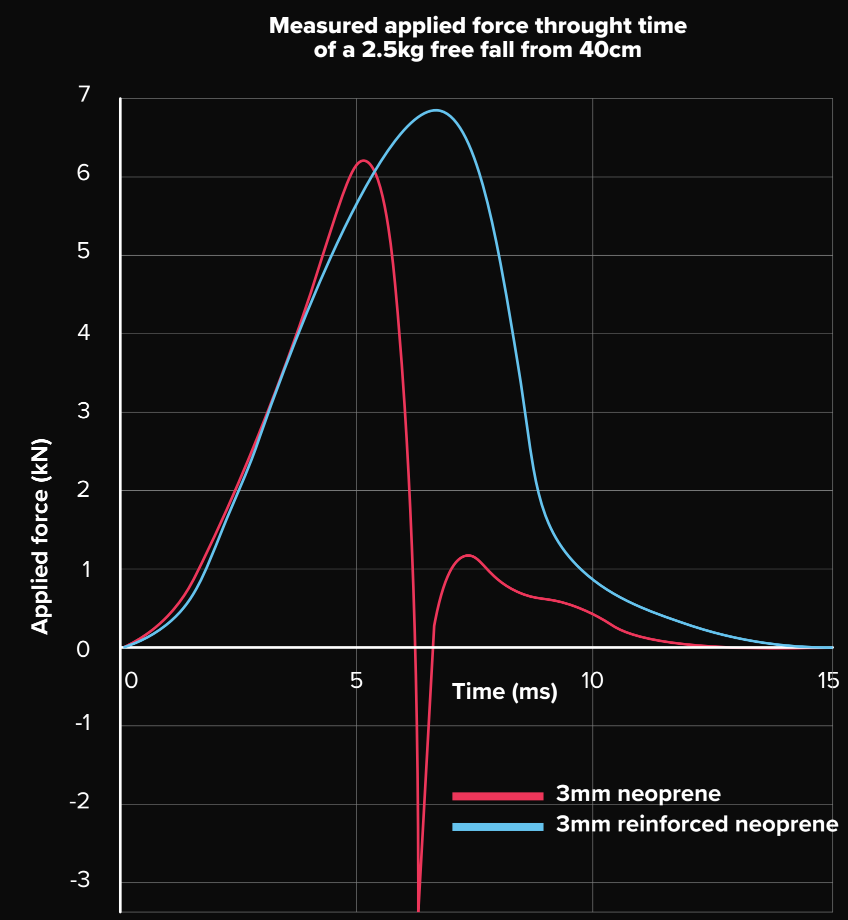
The GRDXKN material used was 1mm thick and not optimized for the application. It was the one used in the initial prototypes. A new mixture for 1.5mm and 2mm thicknesses is available in the sample collection and should be re-tested. It is expected to perform better than the one used in the tests.

An increase in impact area equates to lower stress.

4.6.3 CONCLUSIONS
In terms of energy absorption, the GRDXKN is showing positive results. Therefore, the direction of the study is correct. Conventional neoprene breaks where reinforced neoprene does not. The Guard Shield has proven to not break under the applied stresses. This property is added on top of the already achieved cut protection level, which is not released publicly from the manufacturing company.

Photo of moment of impact



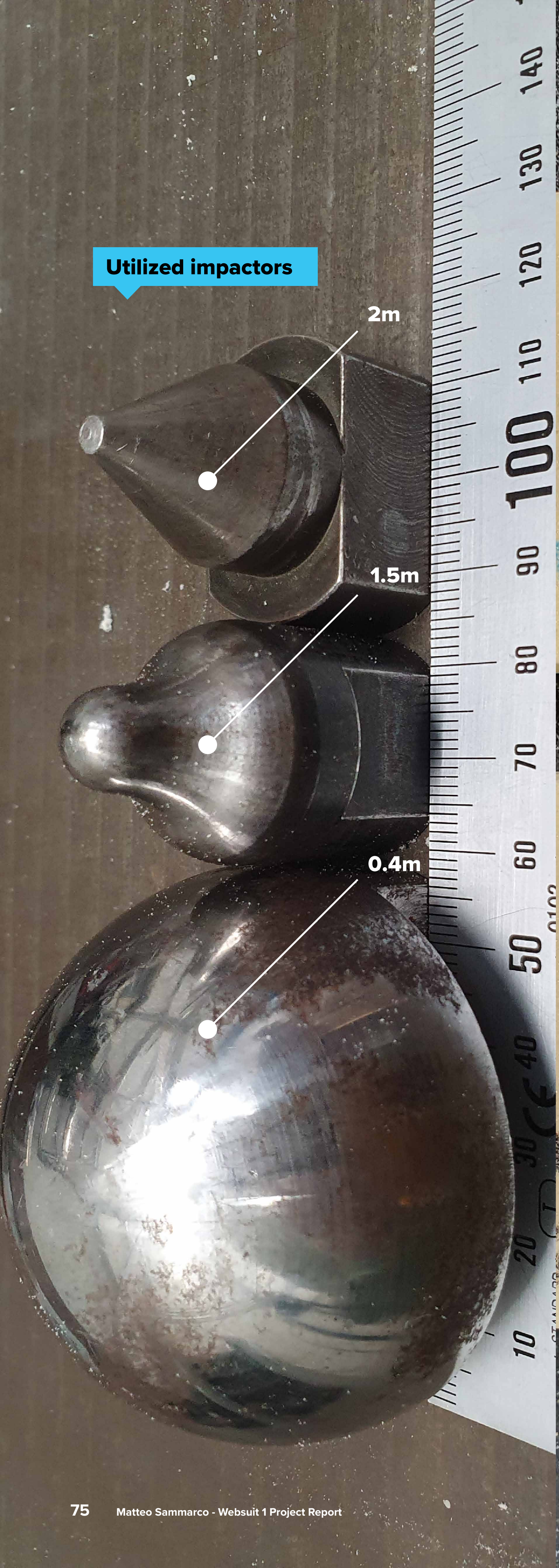


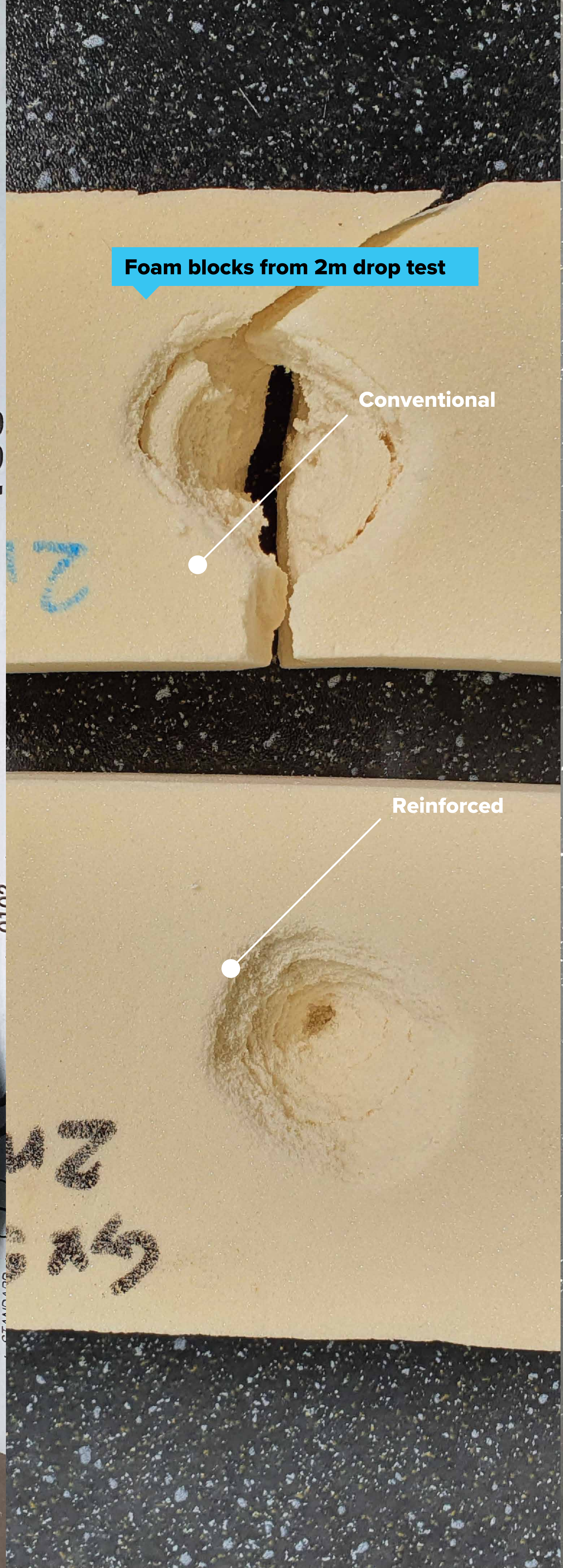
4.6.4 MEASUREMENTS

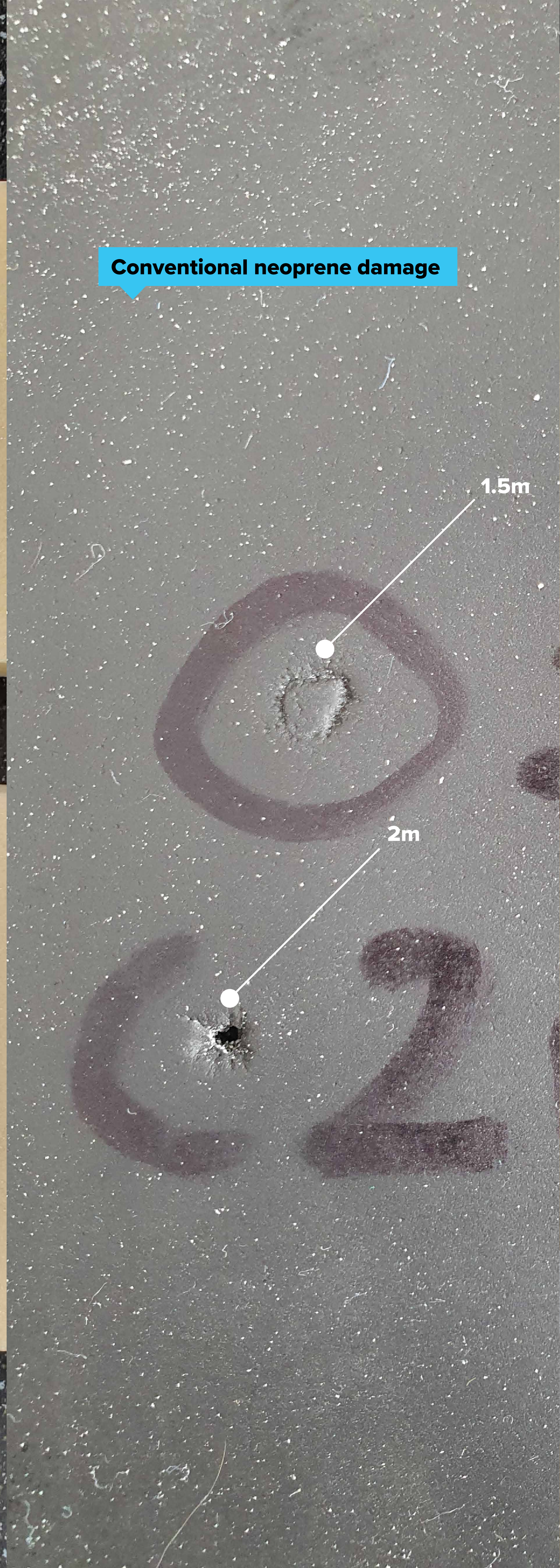
The graphs shown to the left represent the smoothed readings of the strain gauge equipped on the impact tower.

From the first graph, showing the measurements from the 40cm drops, it is possible to see that 1mm of GRDXKN can disperse the energy from the impact over a longer time than the single-layer lycra and aluminium sheet. In physical terms, the impulse is lower with the GRDXKN. Furthermore, the average applied force is decreased by a factor of two compared to the aluminium sheet.

The second graph represents the 2m drops, the case in which the foam covered by conventional neoprene was broken in half. This information is represented by the red curve, which around the 5ms mark drops negative due to the strain gauge measuring the vibrations of the dropper penetrating the foam, striking the metal base. This test was performed once.


Utilized impactors
2m
1.5m
0.4m


Foam blocks from 2m drop test
Conventional
Reinforced


Conventional neoprene damage
1.5m
2m


Foam blocks from 1.5 drop test
Conventional
Reinforced

Section 5

Conclusions

A first step connecting innovative textiles into the sailing world.

The project aims to create the most safe and desirable foiling wetsuit experience for sailors by designing a protective wetsuit. A vision originated from the primary objective of investigating dangerous events with foil sailors to research the mechanisms that cause injuries and develop a design solution to prevent them. The conclusion is that creating a protective wetsuit for Olympic foiling sailors is entirely possible.

The research performed provides an integrated perspective into the subject of foil sailing safety. After introducing the discipline, the highest risks to safety are identified as foil strikes. The most frequent types of crashes have been described concerning the position and movement of hydrofoils. The Nacra 17 sailors are usually struck by the rudder elevator. The iQFOiL sailors may likely be struck by another iQFOiL; however, the evidence is not vast. Finally, IKA Formula Kite riders can be struck by hydrofoils at various speeds and at different locations on the body. For the latter, the video evidence is vast. Hence, the problem is urgent. The mechanics and kinematics of crashes are reported both from a qualitative and quantitative standpoint, and these results serve as guidelines for testing protective equipment. Further research was conducted on the anatomical effects of crashes on sailors, for example, through the types of injuries and how their recovery period negatively affects their mental health and, consequently, their physical performance.

An explorative overview of current protective wear in sailing, other sports, and disciplines is presented as a source of information and inspiration. The manufacturing method of sailing wetsuits is relevant for comparison with the proposed manufacturing method. Many textile technologies suitable for the application are presented and compared with one another.

A list of design requirements for the wetsuit is redacted, and four primary objectives are established. Impact and cut protection are meant to deter injuries to athletes caused by impacts on the boats and with hydrofoils. This protection must be offered on the entirety of the wetsuit's surface. The third and fourth objectives regard comfort and aesthetics, which are two factors in attracting the use of such a suit. The GRDXKN exoskeleton and Guard Shield combination should provide good stretch. However, this property was not investigated in the research due to the lack of machinery necessary for laminating neoprene rubber. The aesthetics are unique since the color of the GRDXKN exoskeleton can be chosen. The GRDXKN patterns have not been seen before in any of the wetsuits researched in this project.

The prototyping phase of the project has proven that the GRDXKN can be printed on Guard Shield. However, in some cases, the heating process burned the material, making it lose some stretch. This fact was a result of several iterations. Furthermore, 100% Dyneema lining can be bound to neoprene rubber thanks to special glues. The experimental phase of the project showed how conventional neoprene is more fragile compared to reinforced neoprene. Reinforced neoprene has the Guard Shield and GRDXKN protections linings. Under the impact tower, the GRDXKN has been shown to absorb 56% of the maximum force applied compared to an aluminium sheet.

The reinforced neoprene has been shown to distribute the energy over a larger surface, which decreases the stress applied. Furthermore, it did not tear or break under stresses caused by high energy impacts. In contrast, conventional neoprene concentrated the applied force on a smaller area for the same energies and was torn.

This research provides the first steps into connecting innovative textile technologies with the sailing world. This report explores the topic of foil sailing safety. A solution to the injuries is proposed in the form of a protective garment. This project will be carried on by the TU Delft Sports Engineering institute and will eventually be manufactured for the athletes of the 2024 Olympics.

Section 6 Recommendations

The Websuit 1 is the first of its kind, and it is clear that some design decisions were made based on favoring feasibility over functionality for the project's success. For example, the number of layers has increased by one, which might impact the stretch of the material and consequently the athlete's comfort. It is recommended to produce machine-made reinforced neoprene prototypes to evaluate their stretch and durability properties. Other variables have not been accounted for in detail in this study, such as the GRDXKN patterns and thickness. Furthermore, the project was conducted without a sales forecast and defined production and distribution partner. That is why it is important to consider product pricing as soon as the business relations are defined. This project has started connecting the Taiana and GRDXKN companies, which are business-to-business companies. The missing link is a business-to-consumer sailing brand to take it to the next steps. The Sailing Innovation Center has already identified potential candidates.

5.1.1 POTENTIAL ALTERNATIVES AND APPLICATIONS

Several ideas have not been considered in this project. Some because of their similarity to Websuit 1; others are just out of reach regarding time and budget. Here are some product ideas and Websuit 1 variations that are also potentially suitable for foiling sailors.

WEBSUIT 1S

The Websuit 1.s is the summer version of Websuit 1. Interviews and photo evidence suggest that sailors avoid wearing protective gear in the summer because of the heat. Websuit 1.s is made with Guard Shield and GRDXKN. The development process of this garment is faster than Websuit 1 since the problems of bonding and stretch are minimized due to the absence of neoprene and nylon lining.

WEBSUIT 1T & WEBSUIT 1B

For simplicity, the Websuit 1 is a one-piece garment. However, as discovered in the interviews, the Nacra 17 sailors combine their clothing by choosing different tops and bottoms. They can wear separate clothing since they are not immersed in the water as much as the iQFOiL and IKA Formula Kite riders. Therefore, since a long-john and top are manufactured using the same techniques but with different panel shapes, it is recommended to offer this variant of the Websuit 1.

INTEGRATED PROTECTION IN THE NEOPRENE RUBBER

It is recommended to investigate the neoprene rubber material in light of different aspects. For example, researching various neoprene rubber foams or even developing a specialized neoprene foam that shows good impact absorption can further simplify the production of the wetsuit. Wetsuits are usually around 3mm thick, and in some instances, even 6mm in some regions of the body. The neoprene rubber accounts for most of this space, so it makes sense to take advantage of this space for absorbing impacts. As seen in the research and the tests, conventional neoprene rubber does not withstand impacts from foil strikes. It would be interesting to develop a rubber foam that does not break under those stresses and may even show viscoelastic properties. This solution would avoid applying the external GRDXKN protective layer, as the impact protection would be directly integrated inside the neoprene.

PROTECTIVE GLOVES AND BOOTS

Research from online and physical retail has shown that gloves and boots are not designed to protect sailors from foil impacts. Not only the suit but also the gloves and boots should be made with protective materials. It is also interesting to develop a neck gator that protects from wind and cuts while keeping sailors warm.

For the product's success, the project should continue prioritizing the following topics—first, the evaluation of the most appropriate GRDXKN material, pattern, and thickness. The GRDXKN foam can be produced with different ingredients, which control its hardness, abrasion resistance, stretch, and rebound control. The impact protective properties should be tested according to an industrial standard, such as the ANSI/ISEA 138-2019. Then, the base textile material should be developed with a performance textiles company because the Dyneema material is susceptible to the heating process. Dyneema alternatives, such as Kevlar and Aramid, have a higher melting point at around 500°C.

Glossary

Blunt trauma: the injuries resulting from energy transfer in impacts to the body that do not cause breakage of the skin. (International Organization for Standardization)
Cavitation: the formation of an empty space within a solid object or body. (Oxford Languages)
Closed-cell neoprene: a type of neoprene foam where the cells are pressed together, so air and moisture cannot enter. Closed-cell foam is much more rigid and stable than open-cell foam. (Tiger Foam)
Daggerboard: a kind of centerboard that slides vertically through the keel of a sailing boat. (Oxford Languages)
Foil system: Hull appendage primarily used to produce vertical lift and affect leeway.
Garment: an item of clothing. (Oxford Languages)
Harness: A garment with a set of straps and fittings by which a sailor hangs when reaching out of a sailboat.
Hydrofoil: A hydrofoil is a lifting surface, or foil, that operates in water. (Wikipedia Contributors)
Kinematics: the branch of mechanics concerned with the motion of objects without reference to the forces which cause the motion. (Oxford Languages)
Laceration: a result of a shearing force that causes deep skin tearing through the epidermis and sometimes through the dermis and subcutaneous tissues. (Tara L. Harris)
Laminate: overlay (a flat surface, especially paper) with a layer of plastic or some other protective material. (Oxford Languages)
Leading edge: the foremost edge of an aerofoil, especially a wing or propeller blade. (Oxford Languages)
Lift: A fluid flowing around the surface of an object exerts a force on it. Lift is the component of this force that is perpendicular to the oncoming flow direction. (NASA Glenn Research Center)
Lining: a layer of different material covering the inside surface of something. (Oxford Languages)
Mechanics: the branch of applied mathematics dealing with motion and forces producing motion. (Oxford Languages)
Multihull: a boat with two or more, especially three, hulls. (Oxford Languages)
Open-cell neoprene: a type of neoprene foam where cells are deliberately left open, making the foam softer and more flexible. (Tiger Foam)
Protective clothing: clothing including protectors which cover or replace personal clothing, and which is designed to provide protection against one or more hazards. (International Organization for Standardization)
Protective clothing: clothing that covers or replaces personal clothing and is designed to protect against one or more hazards. (International Organization for Standardization)
regattas
Rudder: a flat piece hinged vertically near the stern of a boat or ship for steering. (Oxford Languages)
Seam: a permanent junction between two or more pieces of material created by sewing, welding, or other method. (International Organization for Standardization)
Stress: pressure or tension exerted on a material object. (Oxford Languages)
Trailing edge: the rear edge of a moving body, especially an aircraft wing or propeller blade. (Oxford Languages)
T-rudder: a rudder with a hydrofoil whose shape resembles the letter "T".
Viscoelasticity: the property of a substance of exhibiting both elastic and viscous behaviour, the application of stress causing temporary deformation if the stress is quickly removed but permanent deformation if it is maintained. (Oxford Languages)
Weave: form (fabric or a fabric item) by interlacing long threads passing in one direction with others at a right angle to them. (Oxford Languages)
Wetsuit: a close-fitting rubber garment typically covering the entire body, worn for warmth in water sports or diving. (Oxford Languages)

SYMBOLS FROM CHAPTER 2.4
E energy
p potential (subscript)
k kinetic (subscript)
c craft (subscript)
b body of the athlete (subscript)
σ stress
A area

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