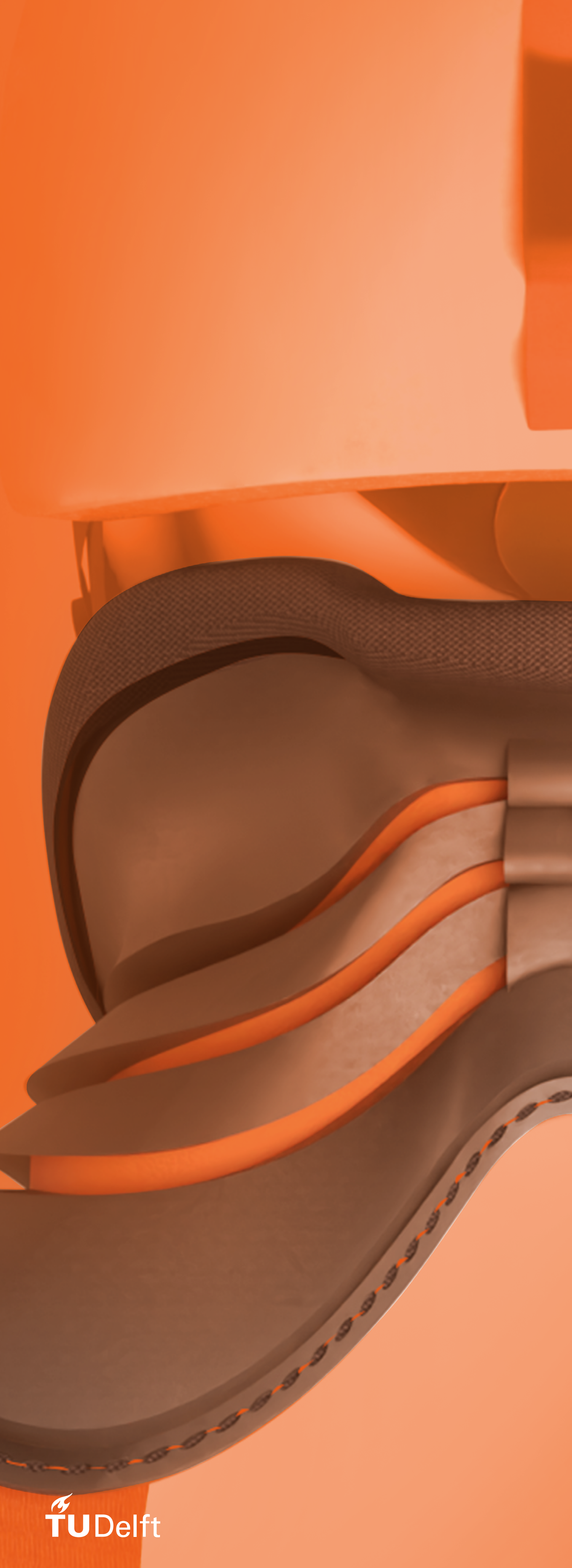
CERVI

Neck Protection for Winter Sports



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SUMMARY

This thesis emphasises the need for neck and cervical spine protection in winter sports and proposes a design which aims to fill in the current market gap.

Current winter sport back protectors are made for impact protection, but they do not protect the spine from the most common fall biomechanics such as compression, hyperextension, hyperflexion and lateral bending. Additionally, they do not protect the neck and cervical spine, which is one of the most frequently injured sections of the spine and the area which leads to the most severe long-term consequences if injured.

To address the problem, existing back protection equipment was analysed and cervical spine protection from other fields. Sketching and rapid prototyping were used for idea generation and concept proofing. Prototypes were then tested for comfort whilst skiing and for extreme movements with special test set-ups.

The outcome of this thesis is CERVI, a feasible product concept supported by a high-end prototype. CERVI restricts cervical compression and hyperextension without limiting the neck's natural, comfortable range of motion. It can be worn independently or integrated with the SPINES winter sports back protector. CERVI addresses a critical gap in current winter sports protective gear and aims to raise awareness of the need for cervical spine protection in winter sports.

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TERMINOLOGY

cervical spine - upper part of the spine (neck)
thoracic spine - middle part of the spine (back)
lumbar spine - lower part of the spine (lower back)
neck hyperextension - hyperbending of the neck towards the back
neck hyperflexion - hyperbending of the neck towards the chest
compression - axial loading
SCI - Spinal cord injury
ROM - Range of motion
D3O - protection material developed by the company D3O
PUR - Polyurethane
TPU - Thermoplastic Polyurethane
NC - Neck circumference

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INTRODUCTION

Winter sports such as skiing and snowboarding, are known for their risk of injuries, with spinal column injuries being some of the most severe leading to permanent disability (Wakahara et al., 2006; Michel et al., 2010). This led me to the question what if there was a solution that could make it possible to ski safely?

In recent years, protective equipment has become an increasingly important part of skiing and snowboarding due to technology advancements, access to information, awareness about safety and the possible consequences. Helmets are now worn by almost everyone on the slopes and the use of back protectors, knee pads, wrist guards and impact pants are also becoming more popular. According to a survey done with 1550 participants back protectors are now the second most worn protective equipment. (Michel et al., 2010) While helmets protect the head and back protectors safeguard the thoracic and lumbar spine, there is **no dedicated protection for the cervical spine**.

This gap in protective equipment motivated me to develop enhanced back protection for winter sports. The proposed design aims to bridge the protection gap between head and back protection by incorporating neck protection.

1.1 Problem Definition

The cervical spine is the most frequently injured part of the spinal column in skiing accidents (Michel et al., 2010; Bigdon et al., 2019), yet most protective gear focuses on the thoracic and lumbar regions, leaving it exposed (Market Research Appendix C). Knöringer et al. (2013) even hint that wearing back protectors might lead to more severe injuries of the cervical spine as the thoracolumbar spine becomes more rigid in the lower regions and forces from impacts may transfer to the more mobile cervical spine, which is unprotected.

Back protectors also do not protect from axial loading applied vertically along the spine, which happens during head-first impacts—such as when a skier falls forward and the head hits the ground. This situation is particularly dangerous for the cervical spine because it becomes compressed between the head and the torso. This type of loading can make the spine buckle or bend and it could lead to burst, compression and distraction fractures. **This is especially concerning because skiers mostly tend to fall forward** ((ISEA) International Sports Engineering Association, 2025; Bigdon et al., 2019; Kary, 2008). Next to compression, forward falling can also result in hyperextension and flexion of the cervical spine.

Whilst it is evident that cervical spine protection is needed, the challenge lies in how to protect the cervical spine without restricting the freedom of movement. As a restrictive device could also increase fall risk (Wick et al., 2013) and reduce the enjoyment of the sport. Moreover, protective gear must balance a professional look whilst avoiding an assistive appearance, as the latter may discourage users from wearing it.

The following problem statement is formulated:

"How to protect the cervical spine without restricting freedom of movement?"

1.2 Assignment

*"Design a solution to **protect the cervical spine area** of **winter sport enthusiasts**, which **prevents injuries** whilst **skiing** (or snowboarding) and **fits in the style** of existing **winter sports products.**"*

1.3 Stakeholder

Spines is a company founded by Menno Streefland who himself suffered a spinal cord injury during skiing. He started Spines as a way to help others do the sports they love protected by wearing a back protector. This includes skiing, snowboarding, horse riding and cycling. Spines is devoted to raising awareness about the necessity of back protectors and helping the treatment of spinal cord injuries. This is why 15,00€ of every protector purchase is a donation to spinal cord injury research.

This project will be an inspiration for next-generation back protector for Spines, where the cervical spine is also protected. Such a protector could provide Spines with the significant advantage of being the first company to provide winter sports neck protection and have them stand out among some of the biggest winter sports brands.

1.4 User Group

The user group for which this product is intended are recreational skiers from children to adults. However, since it is a novel product it shall first be developed and tested for adults (18-66 years old) before adapting it for children. This choice was made due to the complexity of sizing with children's necks, aesthetic research for children's products and also the neck databases consisting of data for the 18-66 years old population. According to research done by IGLU SKI (2024) average skier age is growing with the majority of the skiers being 45-65+ years old.

1.5 Research Questions

Based on the encountered problems the following research questions were formulated as a starting point for the research:

1. What is the most common way of falling during skiing?
2. What are the biomechanics of the fall?
3. What are the most common injuries?
4. What is the range of motion of the human neck?
5. Sizing and dimensions?
6. What is the user perception of protective gear?
7. What are available neck protectors on the market?
8. What materials are these products made of?
9. How are products currently certified?
10. How to validate the product? How much energy should the product dissipate?

1.6 Project Approach

Firstly, the current state of the art should be analysed. This includes existing winter sport back protectors and neck protectors used in other sports such as motocross, American football, hockey and Formula 1. During this, the norm by which the products are certified should be noted and analysed.

Next, the freedom of movement and the biomechanics of a fall should be researched to understand what should the device protect the user from.

Since it is a novel product sketching and ideation will be done parallel to the research process from day 1.

After the initial research phase is done, ideation should continue with low-fi prototyping. In case some of the prototypes offer promising directions refined prototypes shall be made.

Some of the prototypes could be taken for tests on the field at a skiing location.

Based on insights from prototypes further sketches, prototyping and research should be done in the directions needed. This includes test set-up for the prototypes, refinement of the prototypes based on discovered disadvantages or new rounds of ideation and prototyping respectively to satisfaction with current prototypes.

After this, a few concepts should be formed.

Based on a thorough reflection of the concepts one concept should be chosen to continue with.

Next a development stage will follow of the chosen concept by doing further research, technical detailing and higher-end prototyping.

The prototype created at the end of the development stage will be used for user testing and a tensile loading test.

During the development stage, additional research will be done on neck sizing and manufacturing of the product.

Finally, the complete solution with integrated user feedback and manufacturing method in mind will be visualized digitally.

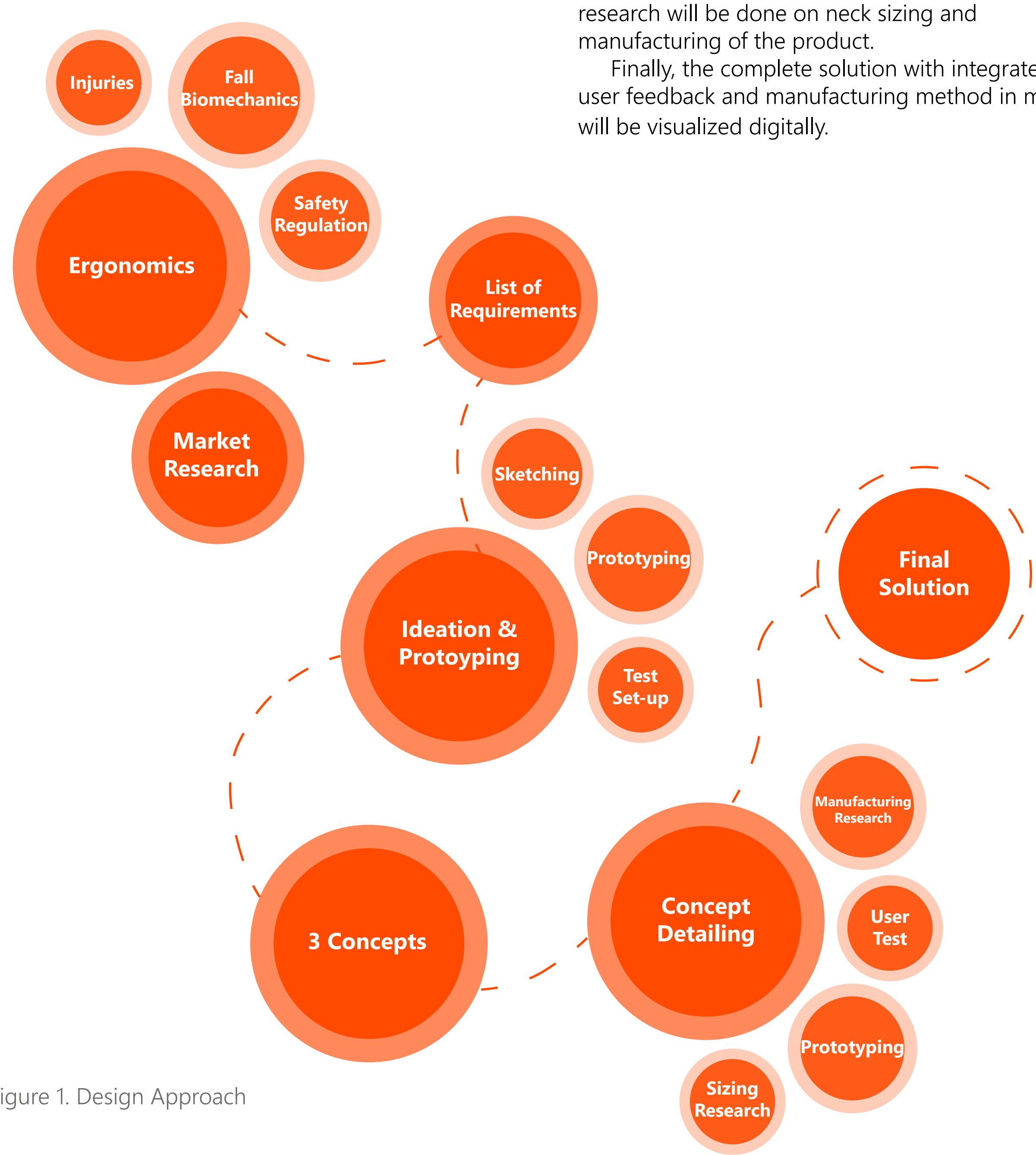

Figure 1. Design Approach

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Research

To gain the necessary knowledge on designing a new protector, extensive research was done on the market to see the gaps in current protective equipment and also to gain insights into their composition and materials.
Next, the most common skiing injuries were researched, followed by biomechanics of a fall, safe versus dangerous way of falling, the range of motion of the human neck and the existing safety certification of products on the market. Lastly, based on all gathered information a list of requirements was made.

2.1 Market Research

To begin with, the current state of the art was explored starting with back protectors. The back protectors usually cover the thoracic and the lumbar spine. This is relevant for developing cervical spine protection because the solution could possibly be integrated with the back protector or the design could be inspired by existing principles of back protectors. They are attached to the back of the wearer through the use of straps, belt or they are directly integrated into vests, backpacks and jackets. The protectors protect from an impact force by dampening it and/or spreading it over a larger area. The back protectors can be split into three types - hard, soft and airbags. The mesh of the back protector vest (see fig. 2) is often made from a mix of polyester, elastane and nylon.

Figure 2. Fabric Pocket of SPINES Soft Protector

2.1.1 Hard Protectors

Hard protectors are made of plastics such as Polypropylene (PP) or Polycarbonate (PC) and they have high penetration resistance, protecting the user from sharp objects (see fig. 3). However, they do not offer as much energy absorption of the force as soft protectors. They are also heavier than soft protectors and are experienced as less comfortable by the wearers. They are glued or sewn to the fabric. Sewing is one of the most expensive parts of the protector production process due to the complicated shapes which require manual labour.

Figure 3. Raven Hard Protector

2.1.2 Soft protectors

Soft protectors main component is an insert made of visco-elastic foams such as Polyurethane (PU), D3O or Ethylene-vinyl acetate (EVA), which makes them adaptable to the user's body when heated (see fig. 4). The advantage of the soft protectors made from polyurethane-like foam is that they would harden upon impact and dampen the impact force (Sport Conrad, 2024). The harder the impact the more the protector will harden, thus spreading the impact over a larger area. They can also recover after an impact and take their original shape again. The price range of these protectors is 35-150€.

Figure 4. SPINES Soft Protector

2.1.3 Airbags

Airbags are usually integrated into a vest (fig. 5) and have a container filled with compressed gas (CO2) (fig. 6). Through the use of sensors, a fall can be detected and the airbag is activated. The airbags have proven to be better at dissipating force, yet the air canister needs to be replaced after every activation (in most cases) by a manufacturer. This makes them a much more expensive solution than passive hard and soft protectors starting from 300€. Another important factor is that the air canister is activated by a strap which is attached to the motorcycle/ horse saddle or through sensors which are trained to recognise a crash.

Figure 6. Air Canister

Figure 5. Mockup Black Winter Sport Vest. From *Vecteezy*, by P. Zhuravlov, n.d. https://www.vecteezy.com/photo/3737247. Licensed under Vecteezy Free License (with attribution).

2.1.4 Cervical Spine Protection

To get inspired on how existing back protectors can be improved existing protection for the cervical neck area in other sports was looked at. Such as motocross braces which contact with the helmet, hockey scratch-resistant bibs, Formula 1 Hans device, American football collars and others.

Atlas Tyke (Motocross)
An example of a motocross neck brace is the Atlas Tyke (fig. 7). It contacts the chest and back trapezius muscles, and its upper surface follows the helmet shape to transfer impact forces from the helmet into the muscles, protecting the neck during head-first falls. Earlier braces had a single rear contact point over the spine, but testing showed that two side contact points are safer, spreading impact into the muscles. This is a key takeaway for the development of winter sport neck protectors. A challenge by skiing or snowboarding would be that helmets often don't cover the face, thus reducing contact with the brace. Atlas Tyke costs 185€.

Figure 7. Air Black Neck Brace.
From *Atlas Brace*, n.d., https://atlasbrace.com/collections/braces/products/air-black., © 2025 Atlas Brace Technologies, Inc

Aegis Interceptor (Hockey)
Neck protectors can also be found in hockey. This is among others due to scratch injuries from the puck which could be fatal. An example of such is the interceptor G by Aegis (fig. 8). It consists of a cut-resistant fabric and a D3O insert which absorbs and spreads the impact same as back protector D3O foam insert. This interceptor costs 52€.

Figure 8. INTERCEPTOR G. From *Aegis Impact*, n.d., https://www.aegisimpact.com/cdn/shop/products/interceptor-g_2048x.png?v=1641494933., © 2025 Aegisimpact. 2019 Aegis Impact Protection. All Rights Reserved.

Necksgen REV2 Lite (Racing)
Head and neck protection is also used in car racing to prevent injuries during crashes. An example is the NecksGen REV2 Lite (fig. 9), a lightweight carbon composite device that connects the helmet to the shoulders via tethers. It is attached to the body through a harness system. It limits head movement, is FIA and SFI certified, and costs around 400€.

Figure 9. Necksgen Rally Pad. From *NecksGen Inc.* n.d., https://necksgen.com/cdn/shop/files/rally-pad-rear-view.jpg?v=1709762223&width=1800., © 2025 NecksGen Inc.

Z7 (American Football)
Neck protection is also used in American football to reduce the risk of neck and spine injuries. An example is the Z-7 NECK BRACE (fig. 10), a neck strap that attaches to the shoulder pads to limit excessive head and neck movement during impact.

Figure 10. Football Neckbrace for Football Help Protect from High Impact Injuries. From *Amazon*, n.d., https://www.amazon.com/z7-Football-Neckbrace-Protect-Injuries/dp/B08HR1ZKJF

Kapsul Atlas (Various Sports)
An example of neck protection made for a wide variety of sports such as motocross, mountain biking, winter sports etc. is the Kapsul Atlas (fig. 11) soft neck brace worn under the jersey that helps reduce rotational and compressive forces on the neck. It is made from flexible, breathable materials for comfort and costs around 110€.

Figure 11. Kapsul™ ATLAS. From *Kapsul Tech*,n.d., https://www.kapsultech.com/storage/2021/09/pillar__3.png., © 2025 Kapsul. All rights reserved.

Conclusion
It is noticeable from the market research that existing back protectors do not provide the necessary protection for the biomechanics of a ski fall such as hyperflexion, hyperextension and axial compression. However, inspiration can be drawn from neck protectors in other sports fields. The main take-aways are that the forces should be spread away from the spine sideways, a combination of hard and soft materials might be needed to provide comfort and adjustable sizing, D3O and Polyurethane foam can be used for the soft parts. And lastly, a -contact point with the helmet or attachment to the helmet could aid restricting the movement.

2.2 Ergonomics

2.2.1 Injuries & Biomechanics of a Fall

Spinal cord injuries (SCI) account for 2-10 % of all winter sports injuries, with 81,7% of those being caused by skiing. Whilst the percentage is not very high, SCI injuries are among the most severe because they lead to permanent neurological disorders (Reid & Saboe, 1989). The spinal cord is a bundle of nervous tissue which extends from the brain to the first vertebrae of the lumbar spine. It is inside the spinal column surrounded by the vertebrae. The spinal column consists of three sections - cervical, thoracic and lumbar (see fig. 12).

Vertebrae C6, C-7, T-12 and L-1 are the most commonly fractured in the spine. (Nightingale et al., 1997; Kary, 2008)
The higher the injury on the spine the worse the neurological dysfunction, which makes it crucial to protect the cervical spine during extreme sports. Unfortunately, the rate of SCI is thought to be increasing over time due to the development of winter sports and their acceptance by a wider audience (Michel et al., 2010; Ackery et al., 2007). The main mechanism of injury is falling (79,6%) and the remaining are collisions or near collisions (10,7%). (Dickson & Terwiel, 2021)

The most common falling mechanism by skiers is forward with a head-first impact, which could be followed by a forward roll. Forward rolling is the worst fall scenario where the most injuries can be sustained. Sliding is the opposite of rolling in a falling scenario because that helps to spread the impact forces over a larger area. (Dainese, 2023)

The head-first impact could result in cervical spine compression, distraction, hyperextension, hyperflexion and lateral flexion ((ISEA) International Sports Engineering Association, 2025; Bigdon et al., 2019; Kary, 2008). According to research done by (Gertzbein et al., 2012) 94,7% of winter sport injuries on the spinal cord are compression injuries. Simple compression fractures are the most common, followed by burst- and distraction fractures. Experiments done with human cadavers also confirm compression as a common cervical spine injury due to the abrupt stopping of the head followed by the oncoming torso which has inertia, leaving the cervical spine compressed by the two. (Ivancic, 2012; Nightingale et al., 1997)

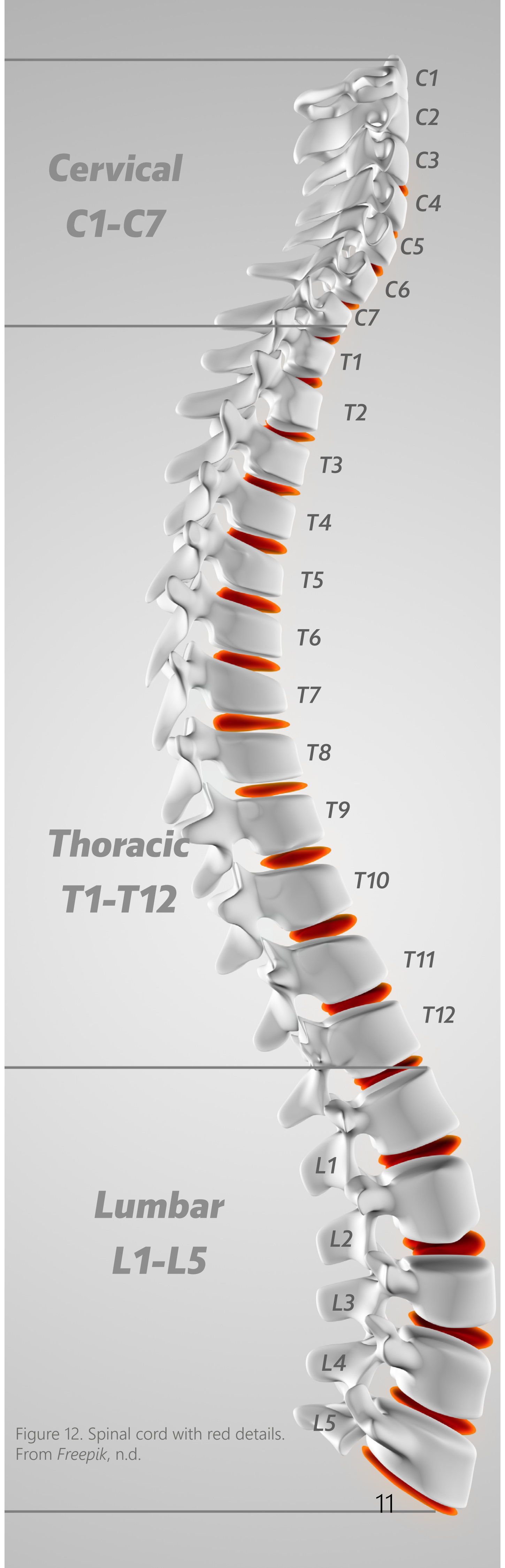


Figure 12. Spinal cord with red details.
From *Freepik*, n.d.

To better explain the fractures, an overview is presented of exemplary falling scenarios:

Scenario 1 Hyperflexion:
The skier falls backwards (fig. 13), landing on the back of the head. This forces the neck into hyperflexion, where the chin is driven toward the chest. This will cause the anterior part of the cervical spine to compress and the posterior to extend.

Figure 13. Hyperflexion Scenario

Scenario 2 Hyperextension:
The skier falls on their face (fig. 14), whilst their torso continues moving forward. This causes hyperextension of the neck, where the posterior part of the neck will compress and the anterior part will extend.

Figure 14. Hyperextension scenario

Fractures by hyperextension and hyperflexion are classified as B- and C- type injuries. Examples of such fractures are Hangmans Fracture (C2), Extension Teardrop Fracture (C2, C3, C4, C5) and Clay-Shoveler's Fracture (C6, C7, or T1) (Pape et al., 2022) (Bello et al., 2024) .

Scenario 3 Fall on top of the head:
The skier falls on the top of their head which leads to axial loading (see fig. 15). Axial loading causes A-type cervical spine injuries such as compression and **burst fractures**. By burst fractures, the vertebra breaks into multiple pieces. Examples of compression and burst fractures are Jefferson Fracture which happens to C1, anterior compression fractures and fractures of the spinous process of the vertebrae. (Pape et al., 2022)

Figure 15. Compression Scenario

Scenario 4 Lateral bending:
The skier falls sideways and the head is forced to bend laterally (see fig. 16). Lateral bending can result in unilateral facet fractures or dislocations and may also stretch or compress nerve roots. (Kaufman et al., 2017)

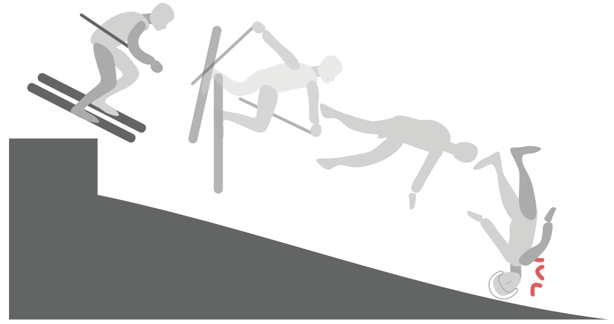


Figure 16. Side Fall Scenario

Other possible scenarios for injury are rotational and distraction injuries. By rotational one, the skier falls while twisting. This creates torsion in the cervical spine. Rotational force can lead to facet joint dislocations or fracture dislocations.

Whilst these scenarios give an idea of the possible falls and fractures related to those, the act of falling is hard to predict and it is possible that a skier can undergo a combination of those scenarios and injuries.

It is important to note that whilst hyperextension and hyperflexion of the neck are dangerous, in human cadavers experiments flexion and extension prove to be crucial in avoiding cervical spine fracture due to compression. This is because flexion and extension help the neck muscles absorb some of the impact energy (Ivancic, 2012; Nightingale et al., 1997). This means that whilst, hyperflexion and hyperextension are injuries that should be prevented, some degree of flexion and extension should be allowed so that the damage of a compression injury can be reduced. Since compression is the most common and dangerous injury, it is the one that should have the highest priority for a neck protector, followed by hyperflexion, -extension and lateral bending.

After establishing how forward fall can cause hyperextension hyperflexion, compression and distraction, it is important to understand what is a less injury-prone mechanism of falling. Mattos (2014) explains that the best way to fall is to get as close to the ground as possible before the fall. Uphill is the best way to fall because a skier is naturally closer to the ground uphill than downhill. In case the skier is about to hit something they should try to direct their skis toward the object they are about to hit and their head away from the object. Once the skier has stopped sliding the skis should be downhill and they should be able to get up and move aside.

Interviews with ski instructor and experienced skiers also gave insights on what is the correct way of falling and what mistakes skiers make.

"You should always try to fall sideways. The skis should always be down the hill and your head up the hill. The head is always up the hill. What non-professionals often do as a mistake is they would fall with their head down the hill, opposite of the correct falling technique."

- Ski Instructor, 10 years experience

"Falling sideways with your head up the hill, skis down the hill and sliding is the best way to fall without injuring yourself. Falling is a skill you should practice and make an instinct, often people panic and fall in an uncontrolled way which leads to injury.

-Experienced skier, 12 years in ski club

Research done by Hume et. al (2015) also shows that beginners are more likely to sustain injuries from falls, whilst experienced skiers usually know how to fall and if they get injured it's a result of a jump or another air manoeuvre.

A leading factor in sustaining an injury is the strength of the impact force. Therefore, its important to understand what are the injury risk thresholds for neck compression, extension, lateral bending and flexion. The Neck Injury Criterion (Nij) is a biomechanics metric used in automotive industry to evaluate the severity of a neck injury (© National Instruments, 2024). According to this criteration a mannequin Hybrid III, 5% female, which represents a small adult female and Hybrid III, male 50%, which represents average male adult can handle these forces before sustaining an injury:

Dummy Type	F_{zc} [N] Tension	F_{zc} [N]· Compression	M_{yc} [Nm] Flexion	M_{yc} [Nm]· Extension
Hybrid III; male 50%	6806	-6160	310	-135
Hybrid III, female 5%	4287	-3880	155	-67

Table 1. Neck Injury Criteration. From *National Instruments*, 2024, https://www.ni.com/docs/en-US/bundle/diadem/page/crash/neck_nij.html?srsltid=AfmBOOrAdzE_NSDEkEbwYFx-QSntTQYqJev-rDQgA0FrVP2sRT3PldcD,

This shows that the product should restrict compression forces above 3880N, flexion forces above 155N and extension forces above 67N. It is evident that the neck can withstand more than twice as much force in flexion compared to extension. There is no information on force thresholds by lateral bending. For reference, global peak compression forces experienced during a sled-based cadaveric experiment (15km/h) were 7531,6N in the neck at 46.6 milliseconds (Ivancic, 2012).

With an average skiing speed of 35,8 ± 13,8 km/h (Stepan et. al, 2023) the compression forces can be expected to be higher than this. However, further experiments should be done to quantify this.

Conclusion

To conclude, forward fall in skiing is the most injury-prone falling mechanism. In this case, the head reaches the ground first and the cervical spine gets compressed, hyperextended, flexed or laterally bent, leading to severe and life-threatening fractures. A safer approach to falling in skiing is with head up the hill backwards or sideways. This helps to reduce the distance from the skier to the ground, thus reducing the impact and spreading the forces over a larger area. Compression is the most severe injury, followed by extension, lateral bending and lastly flexion. Compression forces above 3880N become a high risk.

2.2.2 Range of Motion (ROM)

To understand at what point the cervical spine movements such as extension, flexion, rotation and lateral bending become harmful, I have looked at the Range of Motion of the head. According to DINED Dutch Adults 20-30 years old (2004) the comfortable joint excursion of the head is as follows:
- Rotation of head backwards is comfortable until 44°
- Rotation of head forward is comfortable until 24°
- Sideways movement towards the shoulder is comfortable to 38° on each side (lateral flexion)
- Sideways rotation of the head is comfortable to 71° on each side

This makes the maximum flexion/extension range 68°, lateral flexion 76° and rotation 140°.

Other studies, however, suggest bigger ROM than the one described in DINED. The Anatomy Standard by Janis Savlovskis and Kristaps Raits (2023) takes the average ROM based on in vivo studies done by Niewiadomski (2019), Lewandowski (2006), Anderst (2015), Zhou (2018), Kim (2013), Kauther (2012), Neumann (2002), Kapandji (2008), Kauther (2012), Dvorak (1992), Bergman (2005), Feipel (1999), White (1990), Edmondston (2005). The maximum ROM of the cervical spine according to them is as follows:

- Maximum extension of neck backwards is **63°**
- Maximum flexion of head is **64°**
- Maximum lateral bending is **49**° on each side (lateral flexion)
- Maximum sideways rotation of the head is **85°** on each side
(see fig. 17)

This results in a total ROM of approximately 127° in flexion-extension, 98° in lateral flexion, and 170° in rotation. Leatt Corporation (2019) suggest similar numbers for lateral flexion 86,4°and flexion/extension maximum range of 125° and specifies that those are the maximum ranges **before identifiable injury**.

Summarized differences between DINED and Anatomy Standard are shown in Table 2.

Movement	DINED(°)	Anatomy Standard (°)
Flexion/ Extension	68	127
Lateral Flexion	76	98
Rotation	142	170

Table 2. ROM differences

For the purposes of designing the neck brace the range proposed by the Anatomy Standard by Janis Savlovskis and Kristaps Raits (2023) will be used since it is focused on the cervical spine, rather than on head joint excursion and uses average values from a broad research base. The protector would have to limit the neck a bit before this maximum range of motion and come to a stop once this maximum range of motion is achieved (see Appendix E). Additionally, the product shall not restrict the flexion of the neck, due to the danger of breaking the jaw (Appendix E) and the higher force threshold by flexion as established in chapter 2.2.1.

Conclusion

Understanding the functional and maximum ROM of the cervical spine is critical to making a neck protector which provides safety and comfort. From this research it is clear that to achieve this the maximum allowable backward extension which the protector should allow is 63°, maximum flexion 64°, maximum lateral bending 49° on each side and maximum sideways rotation 85°.

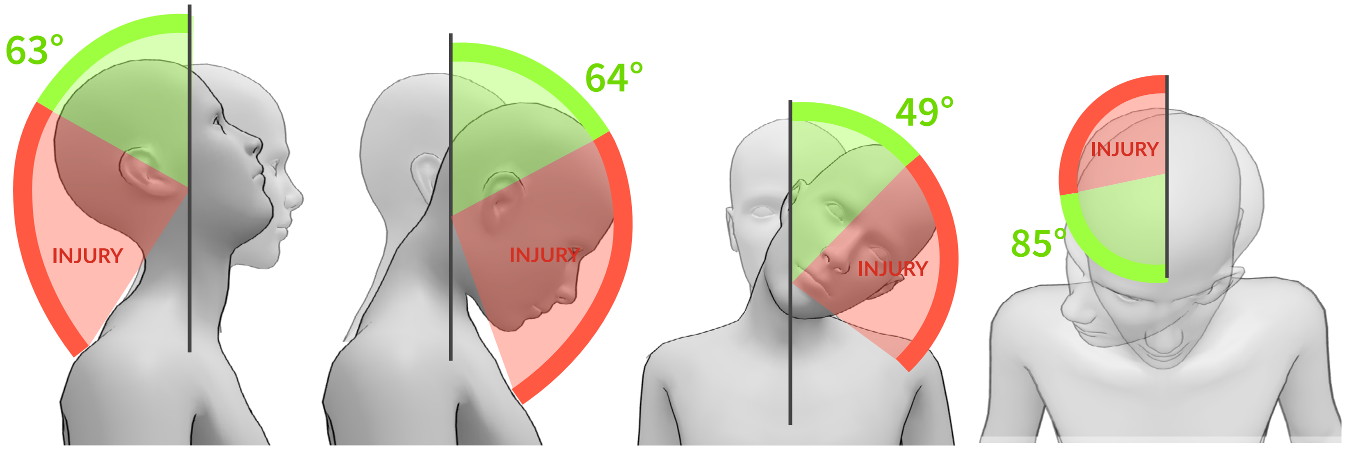


Figure 17. Cervical Spine Range of Motion

2.2.3 Safety Regulation

There is currently no safety standard specifically for winter sports, which is why current back protectors are tested on a safety standard for motorcycling equipment EN1621. This is an important factor to consider because motorcycling equipment is made to protect in case the user falls on the hard road specifically on the side curb or other hard objects, therefore the protectors are tested with an impact tool in a wedge shape which is dropped onto the protector (Schmitt et al., 2010).

The force which is transmitted to the inside of the protector shows the level of dampening/protection which the protector offers. The norm EN1621 has two levels of protection (see fig. 18). In both levels, the protector is hit with an impactor with energy of 50J. The impactor is a rectangular bar with a cylindrical impacting face.

The back protector is laid on a a steel anvil. Under the anvil, there is a piezoelectric loadcell mounted to 500kg mass. The impactor is dropped from 1m height on the protector in a series of tests and the loadcell measures the residual force on the inner side of the back protector.

Level 1: The average value from ten impact tests measured on the inner side of the protector should be < 18kN and the maximum force during all tests should not exceed 24kN.

Level 2: The average value from ten impact tests measured on the inner side of the protector should be < 9kN and the maximum force during all tests should not exceed 12kN.

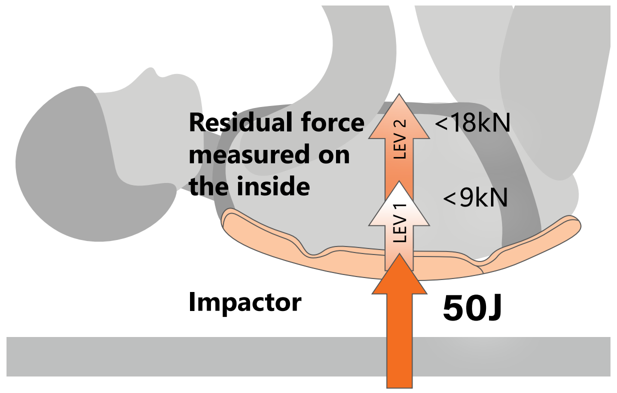


Figure 18. Norm EN1621 Level 1 & 2

For the protector to pass certification the following questions should all be answered with yes:

a) Can you get on and off a motorcycle?
b) Can you comfortably reach the controls of the motorcycle?
c) Can you turn your head and torso when on a motorcycle?
d) While performing the movements of a), b) and c):
1) Can you confirm that the adjustment system, if present, does not cause discomfort?
2) Does the adjustment system, if present, securely hold the protector in place?

It is evident that those are not applicable for winter sport protectors, yet for the purposes of validating the final design of the neck protector, similar questions could be made for the context of skiing:

a) Can you put on and take off your skis?
b) Can you turn your head and torso whilst skiing?
c) While performing the movements of a), b):
1) Does the adjustment system cause discomfort?
2) Does the adjustment system hold the protector securely in place?

Conclusion
Whilst a safety standard is needed, there has been doubt (Schmitt, 2010; Michel et al., 2010; Knöringer, 2013) whether the motorcycling standard is sufficient for winter sport equipment since it does not address the environmental conditions and the biomechanics of a fall by skiing (Chapter 2.2.1). Understanding the EN1621 set-up and the reason why it is designed like this (to imitate a road curb) confirms the inefficiency of the norm for winter sport protective gear certification.

2.3. List of Requirements

Based on the insights from the research, the following list of requirements was made.

Category	ID	Requirement	Origin
Ergonomics & Safety	ES1	The protector should reduce neck compression.	Chapter 2.2.1 & 2.2.2
	ES2	The protector should restrict head extension to 63°.	
	ES3	The protector should restrict side head rotation to 49°.	
	ES4	The protector should allow rotational movement of the head to 85°.	
	ES5	Whilst wearing the protector the user should:	Chapter 2.2.3 Safety Regulation
	ES5.1	be able to put on and take off skis.	
	ES5.2	be able to turn their head and torso whilst skiing.	
	ES5.3	have no discomfort from the adjustment system.	
	ES5.4	have the adjustment system hold the protector in place.	
	ES5.5	be able to pick up something from the floor by bending forward.	
	ES6	The protector should restrict the helmet from going over the edge of the protector (fulcrum effect).	Chapter 3.2.2 Field Research
	ES7	The protector should facilitate sliding.	
	ES8	The protector should protect the clavicle area.	
	ES9	The protector should transfer impact force to bigger muscles.	
Comfort & Desirability	CD1	The protector should allow heat dissipation.	Chapter 2.1 Market Research
	CD2	The protector should be as light as possible.	
	CD3	The protector should fit different neck sizes.	
	CD4	The equipment should be integrated in existing layer.	
Manufacturing & Costs	MC1	Optimize design for minimal stitching.	Client requierments
	MC2	The manufacturing process of the new product must be compatible with the SPINES existing production method.	

03

Ideation & Prototyping

In this phase, different ideas were explored. A lot of the generated ideas were quickly tested with low-fi prototyping to get an understanding of whether the ideas were feasible. The ones, which seemed feasible were further explored with more detailed prototypes. Range of Motion was tested by each prototype by myself and for compression loading a test set-up was made to see the product behaviour.

3.1 Sketching

Because the assignment involved creating a product that doesn't yet exist on the market, idea generation began on day one of the project to explore as many possibilities as possible (see fig. 19). Promising sketches were further developed with low-fi prototypes in the very early stages of the process (Appendix F). Every prototype gave an insight into whether the idea had the potential for further development and general insights into what shape should the product have.

Figure 19. Sketches

3.2 Prototyping

One of the directions explored from early on was a brace inspired by motocross neck braces which prevents extreme movement by contacting with the helmet of the driver and transferring the forces to the chest and the trapezius muscle at the back.

3.2.1 Motocross-inspired prototype

Goal: The purpose of this prototyping cycle was to see if the cervical spine protection device from motocross is directly applicable in winter sports.

Method: Prototyping was done with cardboard, foam, metal rods, PLA & TPU 3D printing.

Insights and Results are summarized below in fig. 20. They were used to develop the prototype which was used for field research.

Figure 20. Motocross-inspired prototyping cycle

3.2.2 Field Research

The last PLA prototype shape was printed also in TPU and tested on the slopes whilst skiing (fig. 21). Whilst this was not the set direction a prototype was needed to get insights from the field research.

Goal: Explore important factors related to product shape, comfort and range of motion in the setting, where the final product will be used.

Method: Wear a TPU 3D printed prototype whilst putting on skis, being on the lift and skiing for 1 hour.

Insights:

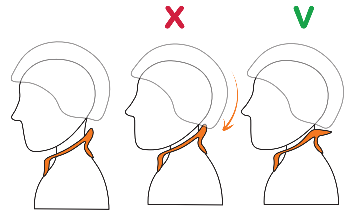


Figure 22. Fulcrum Effect

1) When leaning backwards the brace was going under the helmet and hurting the head instead of supporting the helmet. The back part of the brace should be curved outward to avoid this fulcrum effect (fig. 22).

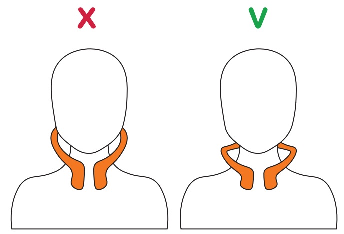


Figure 23. Jaw Freedom

2) The brace was rubbing the edge of the jaw by sideways rotation. The shape of the brace should be lower at this point and higher at the back where it contacts the helmet (fig. 23).

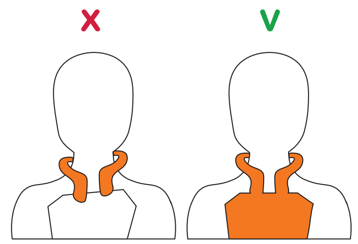


Figure 24. Separate vs. Integrated Neck Protection

3) Back protector and neck brace were two different pieces and the neck brace was being lifted upward from the back protector. An integrated solution would work better (fig. 24).

Conclusion

Wearing the prototype in the right skiing setting gave valuable insights about the product shape so that it does not restrict the user's ROM. Those insights were incorporated into the design process and the final design shape.

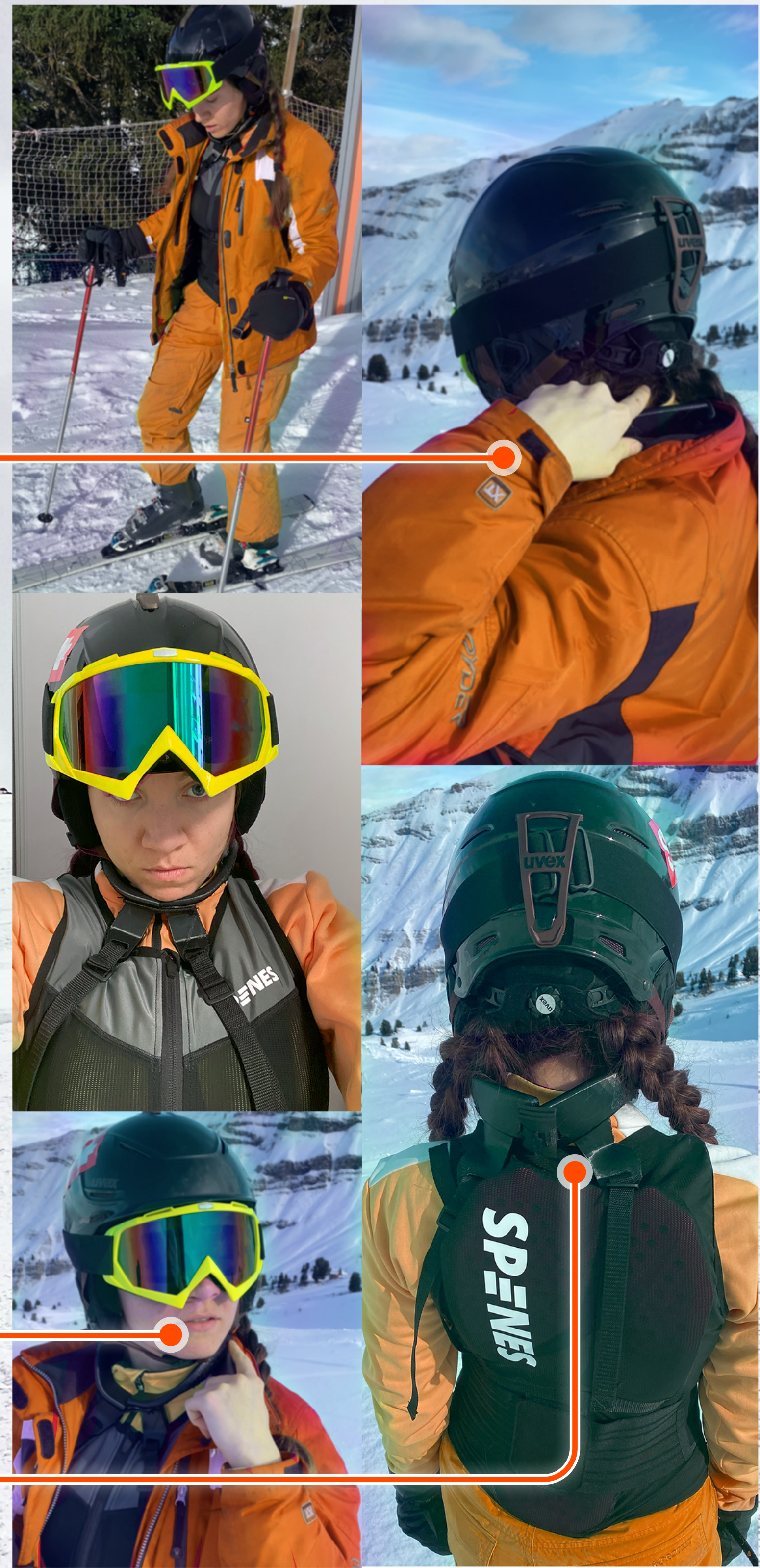
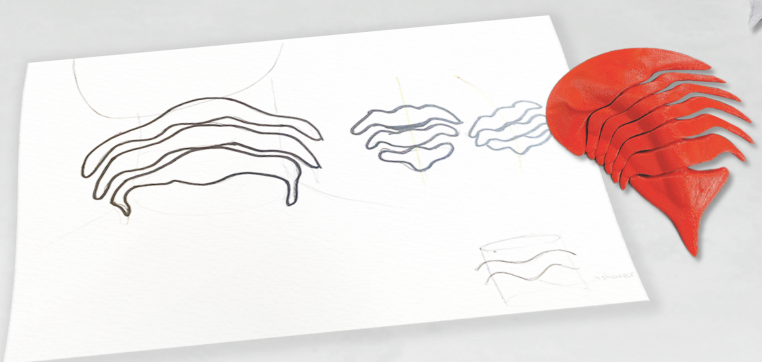


Figure 21. Field Research Images

Whilst the motocross-inspired brace was one of the directions I explored, the insights regarding comfort, fit and ROM collected from this direction were applicable to all of the others explored directions.

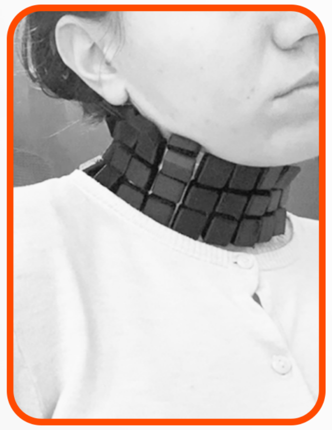
3.2.3 Articulated joints prototype
(PLA & Foam Prototype)

+ very nice gradual restriction of the movement
+ comfortable to wear
+ would be easy to integrate with the protector
– wide at the back so closing the jacket may still be hard
– acts as a hinge for the head; the upper surface should be cone shape as established from the motocross-inspired prototype



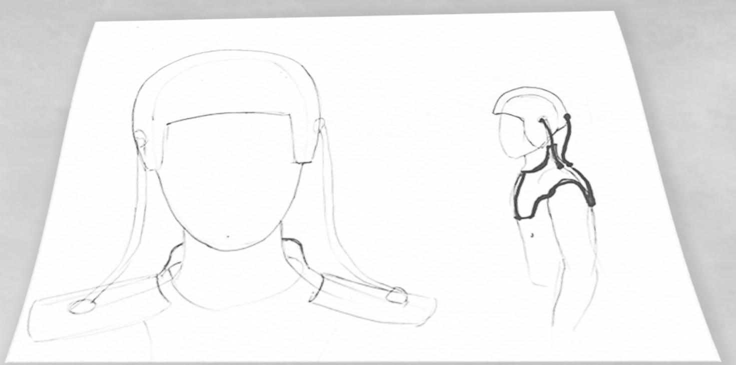
3.2.4 Trapezium shapes prototype
(TPU & Fabric Prototype)

+ trapezium shape is good to restrict movement in one direction and allow it another
– it choked the neck by flexion/extension, due to non-stretch fabric material
– pressure still went onto clavicles, ideally the pressure should be transferred
– not very comfortable-> fully enclosed and tight product around the neck may not be the best direction



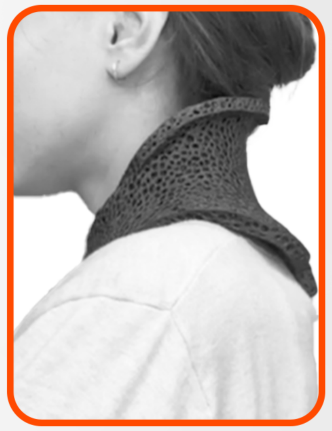
3.2.5 Formula 1 HANS Device-inspired prototype
(Nylon Straps Prototype)

+ once fully fixated the straps worked well and did not obstruct the vision
+ good for restricting rotation and flexion
– not good for restricting extension and compression
– straps pulled on vest -> restriction of movement is dependent on the stretchiness of the vest
– straps should be integrated into the vest and go under the arms to provide the needed fixation
– helmet attachment may not be desirable by the users



3.2.6 Lattice-inspired prototype
(TPU Voronoi Structure Prototype)

+ very comfortable shape with back and side extensions
+ voronoi structure was very strong and could provide good support and ventilation
– 3D printing took 17 hours for half of the product; printing time could be reduced significantly if thickness were to be reduced since the product was too rigid



Summary of prototyping insights:

- the front part of the neck protector should be lower than the back
- there should be space between the protector and the neck to avoid rubbing and irritation
- the rear piece should be split into two pieces to transfer impact to the muscles, rather than to the middle spine area
- if the protector is in two pieces during opening the middle back part of the protector would rub against the spine uncomfortably
- shoulder fit should be adjustable to achieve desired height
- a strap system is needed to keep the protector securely in place
-the back part of the brace should be curved outward to avoid this fulcrum effect
- the protector collar should be below the jaw by maximum head rotation (avoid rubbing)
- back protector and neck protector should have a good fit together (velcro attachment/ strap system/ puzzle shape connection)
- gradual restriction is desirable
- being able to fit the product under the jacket is desirable
- fixating the neck protector on the upper part of the back protector vest may not be sufficient, due to the vest being flexible

3.3 Tensile Loading Test

During the prototyping a lot of insights were collected on what should the shape of the brace be like (summarized on the previous page). Further, the range of movement was tested with each prototype. However, the behaviour of the prototypes under compression was still not tested. This is why a test set-up to test for compression was the next step.

Goal:
Find out how different shape protectors behave under compression.

Materials and Equipment:
1) 2 neck protectors (see fig. 25):
 a) Protector 1 was a motocross-inspired brace, made from TPU Varioshore 98A
 b)Protector 2 was inspired by articulated joints, made from PLA parts glued onto open-cell foam.

a) Protector 1

b) Protector 2 PLA & open cell foam

Figure 25. Protectors

2) Test Dummy
The test dummy's neck I made was inspired by the THOR 50th percentile adult male crash test dummy (see fig. 26a)). I chose THOR as the most advanced crash test dummy for frontal collisions (Jaśkiewicz et al., 2021). The components which are based on the THOR 50th percentile male crash test dummy are the neck hard and soft parts and their connection. Key differences are that in THOR the hard parts are made from aluminium and the soft ones from rubber (Humanetics Innovative Solutions Inc., 2018), whilst in my test set-up the hard parts are made from PLA and the soft ones from TPU (see fig. 26b)). The TPU parts were printed without an outer wall with a 20% gyroid infill. Additionally, THOR uses an advanced pulley system for the wire connecting the hard and soft discs, which I have replaced with steel wire fixated with clamps at the top and bottom of the neck.
The styrofoam head was bought ready for use. The torso was made of foam with a hot wire cutter. A helmet was secured to the head for a more realistic set-up. To secure the helmet a swimming cap and a normal winter cap were placed on the head, before positioning the helmet (see fig. 27).

a) THOR 50th percentile male neck

b) Neck made for test set-up

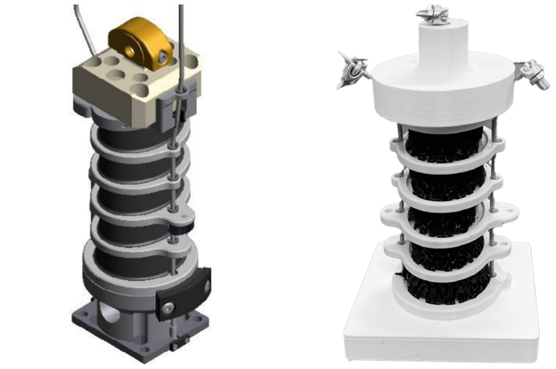


Figure 26. Test Dummy's Necks
a) Neck Mounting Platform Assembly. From *THOR-50M 472-0000 THOR-50 th Percentile Male Dummy User Manual 472-9900 [Rev. F]*, 2018, by Humanetics Innovative Solutions, ©2018 Humanetics Innovative Solutions Inc.
b) Neck made for test set-up, Own Photograph

Figure 27. Test Dummy Assembly

3) Equipment
The tensile loading machine used was Zwick 1446 (see fig. 28). 500N loadcell was used and the applied force was 100N.

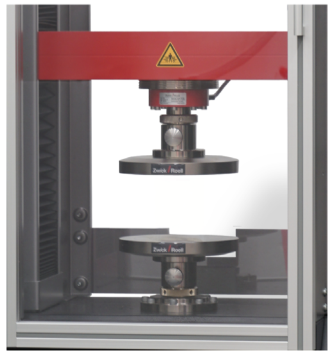


Figure 28. Compression test on springs. From ZwickRoell, n.d, https://www.zwickroell.com/products/static-materials-testing-machines/universal-testing-machines-for-static-applications/proline/, Copyright by ZwickRoell

Methods
In total 3 tests were run:
1) Without a protector, only the test dummy.
2) With protector 1 TPU (fig. 30a)).
3) WIth protector 2 PLA & open cell foam (fig. 30b)).
The force was applied slowly and incrementally.
The crash test stickers were not used. The loading procedures were video recorded with phone camera.

Results
Protector 2 (PLA) performed better in preventing compression than protector 1 (TPU) see fig. 29 below. The reason for this is that proctector 2 was higher, so it contacted the helmet earlier. Additionally, due to the wider contact area with the torso protector 2 had a better fit than protector 1. Protector 1 had four small contact points with the torso and it was sinking lower in comparison to protector 1. **This proves that height is crucial in preventing compression. Good torso fit is an important factor for height regulation.**

Another very important insight from protector 2 was that even a small contact point only at the back between the neck protector and the helmet is enough to prevent compression, meaning that the front and the side of the protector could be lower and only protect from hyper bending. This will help increase the comfort and keep the product minimal.

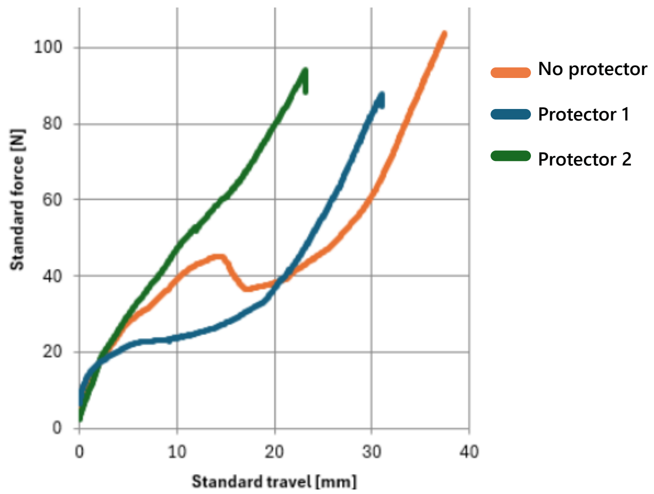


Figure 29. Tensile Loading Test Results

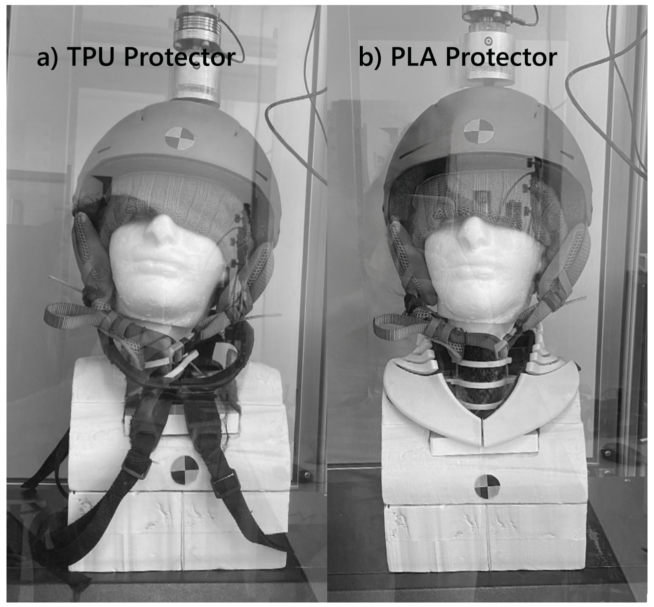


Figure 30. Tensile Loading Test Set-up

Discussion
The test aimed at providing general insights into product behaviour and not comparing material strength. Protector 2 performs better than protector 1 only because it contacted the helmet and helped resist the compression. Protector 1 on the other hand, did not contact the helmet or any point of the head even when the maximum force of 85N was applied.

Most important insights
- contact area between the helmet and neck brace only at the back is enough for compression prevention
- more contact area with the torso assures better fit
- height of the neck brace is crucial in compression prevention

Limitations
- The force was applied slowly, in real-life scenarios the hit would be sudden and the neck might behave diffrently. The reason for the low force application was the unknown stability and strength of the test dummy. Applying sudden force could have broken the dummy, before getting valuable information.

- The steel wires in the test dummy were laterally binding the PLA and TPU parts. This provided controlled movement laterally, but forward and backward motion of the neck was uncontrolled. Ideally, in a next iteration steel wires should also be placed at the anterior and posterior neck.

- THOR 50th percentile male dummy was chosen as a base inspiration due to it being one of the most popular testing dummies and ease of access to 3D files of the neck. Ideally, if a more realistic test dummy were to be made a THOR 5th percentile female would be the better choice since it would represent the most vulnerable testable small neck size of a female.

- The test was only for axial loading, but a more realistic scenario would be to have a slanted platform and test loading under an angle and check the behaviour of the neck and the behaviour under forward, backward and lateral bending. Such a platform was prepared, but it was not tested due to the instability of the neck in the forward and backward direction.

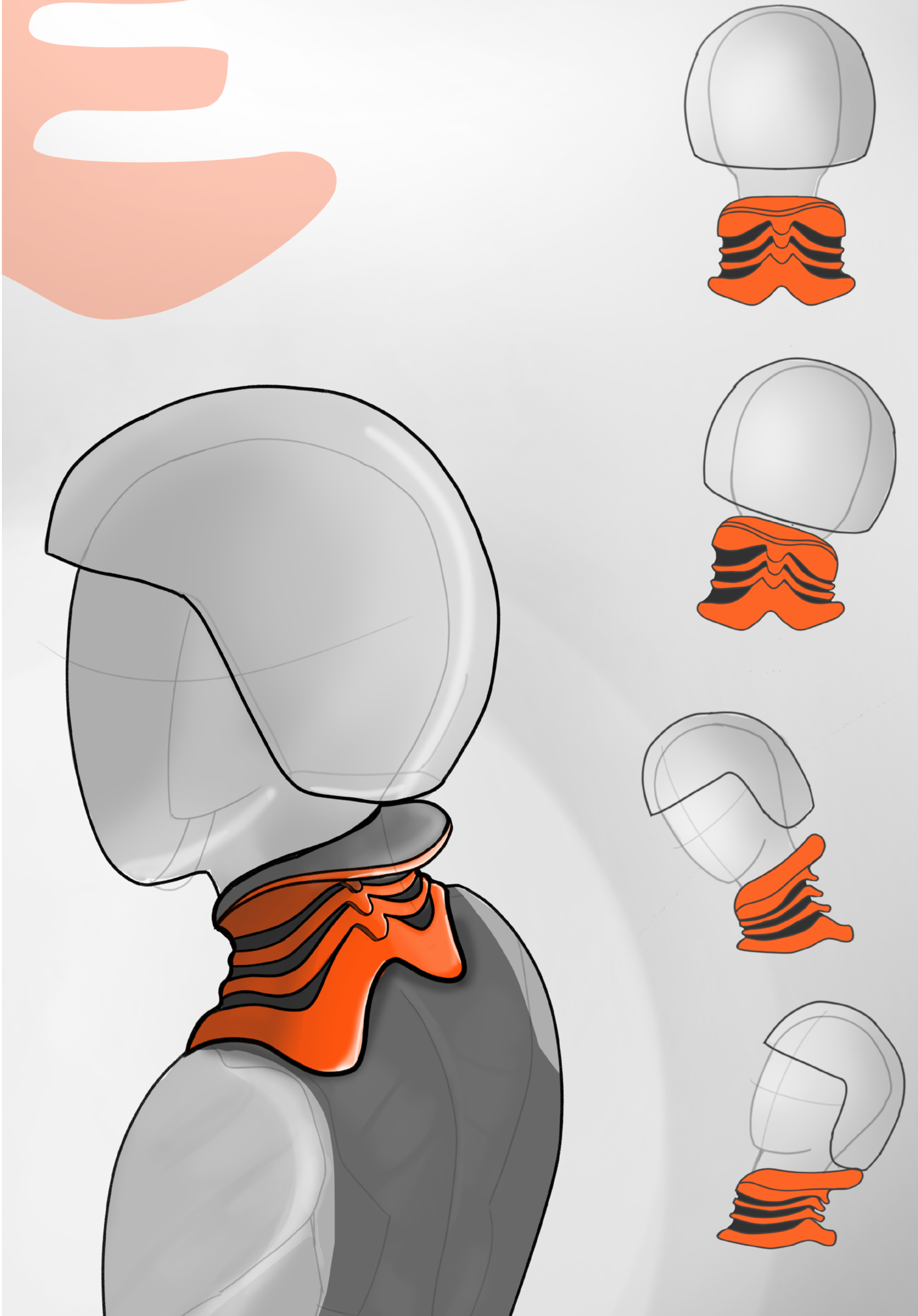
04

Concepts

From the Ideation & Prototyping phase, 3 concepts were made. With the list of requirements and the insights gained from the prototyping process, the 3 concepts were evaluated and one was chosen to continue with in the product development stage.

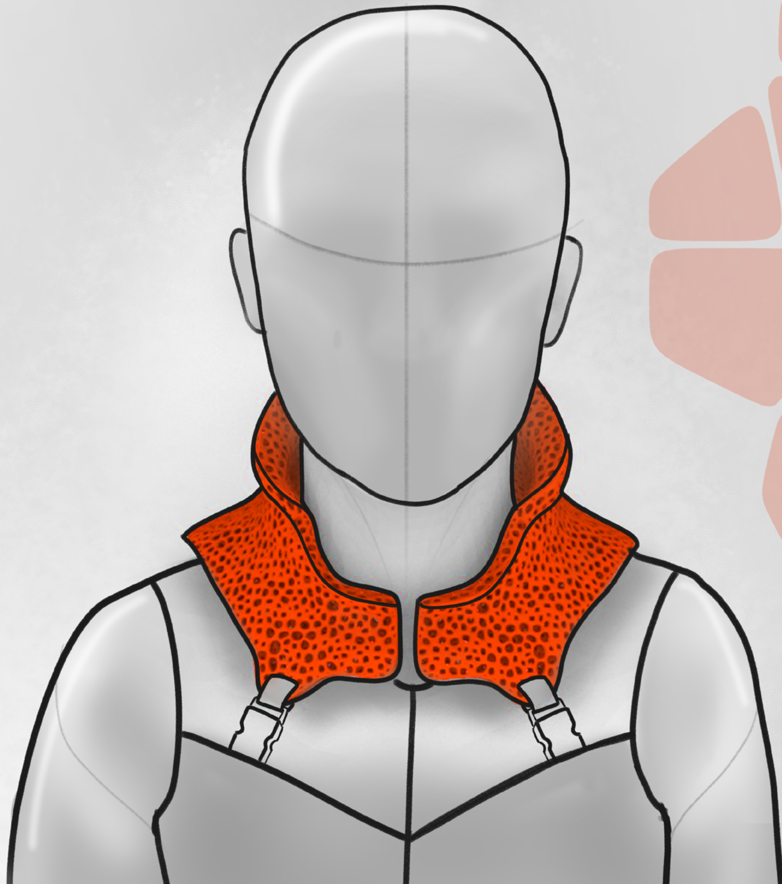
FLEX

This concept is based on chapter 3.2.3 Articulated joints inspired prototype. The flex protector restricts movement axially, whilst allowing lateral bending to a certain degree. It is further developed with spikes which restrict extension, bind the separate rings together and restrict compression. It also has a wider collar than the initial prototype which will contact the head and the helmet.



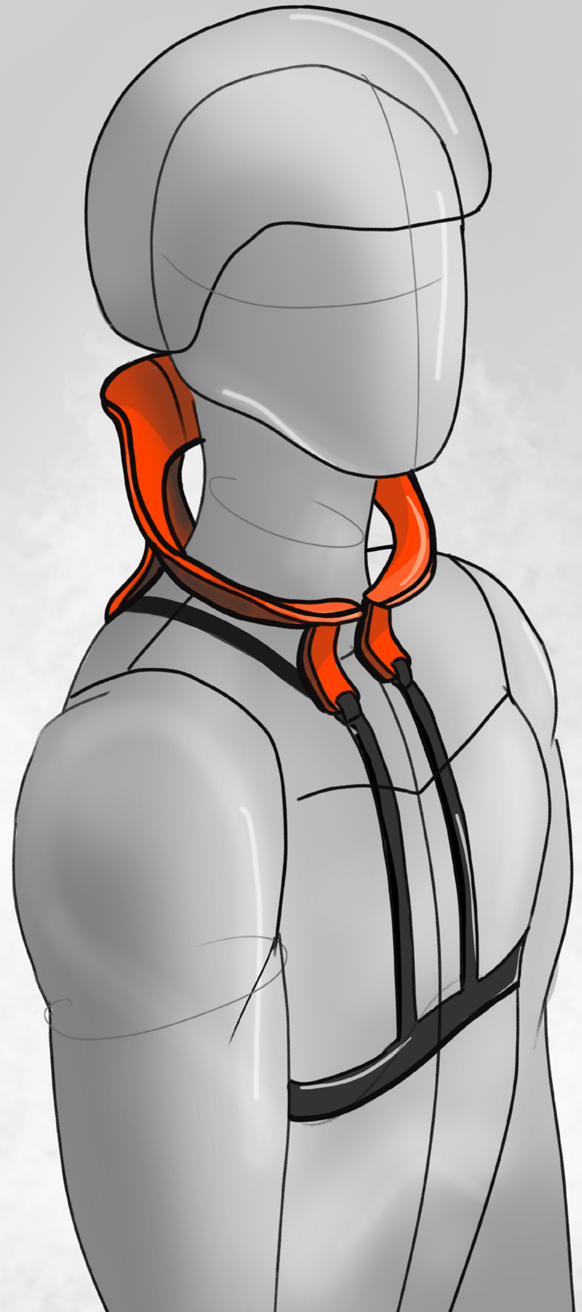
LATTIX

Uses a lattice structure to absorb shock uniformly. Inspired by chapter 3.2.6 and the experimentation with Voronoi structure. The structure could be optimized to collapse in a controlled matter and allow lateral bending, whilst being strong axially to prevent compression. The protector shall have an attachment to the back protector or it will be used stand-alone .



RIGIX

A more rigid solution, which transfers impact to the chest and trapezius muscles. This concept is based on chapter 3.2.1 Motocross-inspired prototype. It further offers a wider and more curved collar which ergonomically follows the neck and avoids fulcrum effect with the helmet.



4.1 Concept Choice

After thorough consideration, I decided to continue with the FLEX concept (see fig. 31). The criteria used for the assessment of the three concepts were comfortable range of motion, aesthetic look, heat dissipation, gradual restriction and production feasibility. Overall, FLEX had the most comfortable fit and it provided a gradual restriction of the movement. The LATTIX concept was at a disadvantage regarding the aesthetic look due to the lattice structure and the production feasibility since such structure would have to be 3D printed, thus increasing production time. RIGIX on the other hand, provided a more sudden restriction of the movement and it had a more bulky shape because it was not touching the neck.

As visible from the evaluation next steps with concept FLEX would be to adjust the design for better heat dissipation and make sure it has a slim fit.

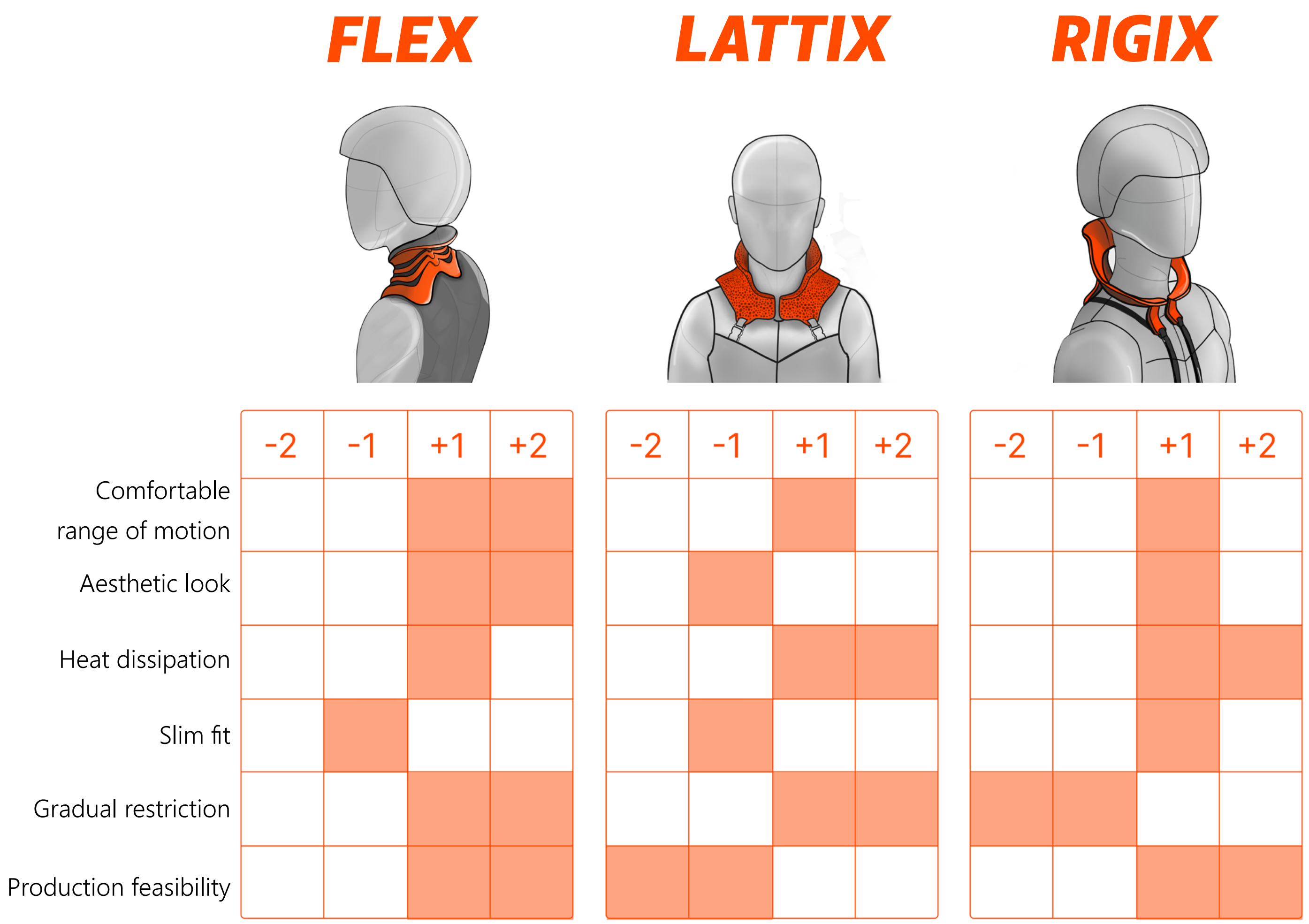


Figure 31. Concept Selection

05

Concept Detailing

This chapter describes how the concept was developed through prototyping building insights through each test and translating them into actions for next iterations. A final prototype was developed, which was tested with users. Additionally, topics such as neck sizing and manufacturing of the product were researched.

5.1 Neck Protector Development

The first step of the concept development stage was refining the shape of the neck protector. The first challenge which I focused on was the cutting surfaces which define the shape of the hard and soft pieces and how much give/compression there would be. Iteration A was cut with planes made with lines from the front and the back, iteration B was cut with planes made from lines from the back and the side. Cutting only with lines from one direction such as the back is not possible, because the front and the back of the product have a different shape (see fig. 32 below).

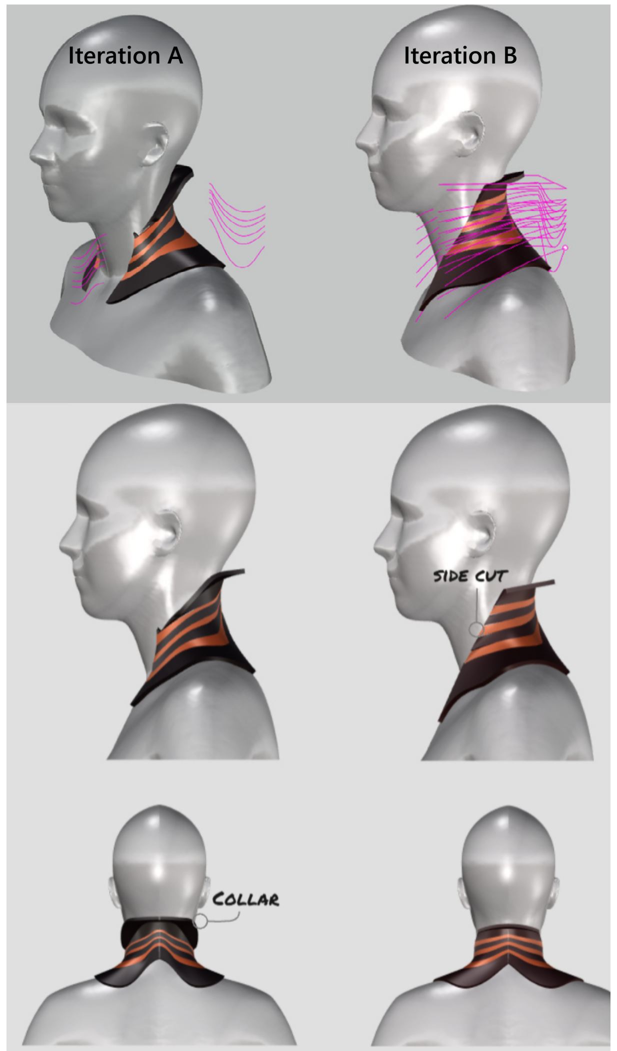


Figure 32. Concept Development First Iterations

Insights:
- Collar shape by iteration A is better than by iteration B as it also covers the sides.
- The shape of the resulting pieces from these cuts is very inconsistent by iteration A. Cut planes from iteration B are better.
- Side cut should be gradual and soft for safety.

The full iteration cycle of the cut planes is shown in Appendix J.

Some of the questions that arose during the iterations were the following:
1) How many axial layers (rings) should the product have?
2) Should there be soft spacing between the hard rings along the longitudinal axis at the back or not?
3) Should there be spikes to restrict extension?

Detailing Test 1.1
This test aimed at answering how many rings should the product have. For this two prototypes were made:
- one with 4 hard rings and one with 3 hard rings (see fig. 33 below).

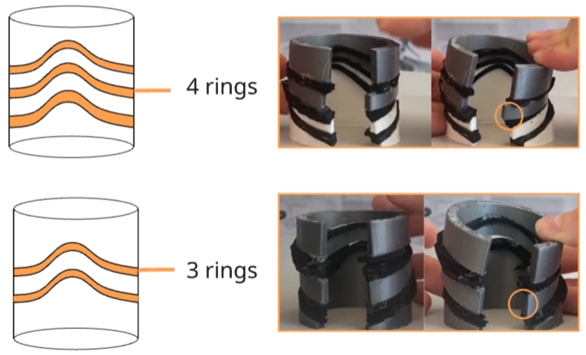


Figure 33. Detailing Test 1.1 Prototypes

Insights:
- One thing that was observed with this prototype was that the middle rings collapse inward when the prototype is compressed. This is undesirable as it will cause pressure and discomfort on the user's neck.

- With fewer rings the product will possibly not follow the user's neck very smoothly.

- Hard to draw conclusions from such simplification.

Action:
Start with fewer rings (3 rings) and check how the inward collapsing behaves with a model that accurately follows the human neck.

Detailing Test 1.2
This test aimed at answering two questions.
1) Should there be spacing between the hard rings at the back?
2) Should there be spikes restricting extension?
(see fig. 34 below for visual explanation)

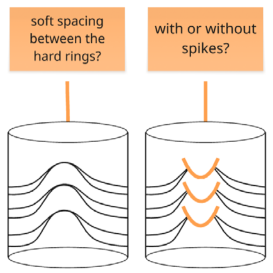


Figure 34. Detailing Test 1.2 Research Questions

Figure 35. Detailing Test 1.2 Prototypes

For this test one prototype was made with no spacing between the hard rings in the middle of the back and with spikes at the back (fig. 35).

Insights:
- No soft spacing at the back does facilitate a transfer from compression force to forward motion, but it also acts as a hard stop, which is not desirable.

- Spikes at the back were not serving any purpose because extension was already restricted from the gluing of the hard and soft rings at the front.

- As observed by test 1.1 The middle ring by this prototype was also collapsing inward.

Action:
Remove spikes at the back, make spike/restriction railing system on the side to prevent the middle piece from bending inward.

The next steps based on test 1.1 and 1.2 were to check if error with inward collapsing rings was persistent by a non-simplified prototype shape and whether to add side spikes that would act as railing. These steps are visually present in fig. 36 below.

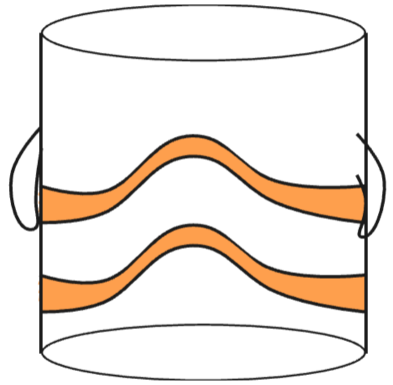


Figure 36. Imagined Product Shape Based on Detailing Test 1 Insights

Detailing Test 2
This test aimed at confirming the findings from test 1.1 and 1.2. Therefore, no new questions were developed but checking whether rings collapse inward and if 3 rings are sufficient or more rings are needed.

The prototype made for this test had a realistic shape and scale of the neck protector (fig. 37). For the development of the 3D model a female DINED mannequin was used with body weight of 58kg and 1680mm height. This resulted in a 400mm neck base circumference and 370mm horizontal neck circumference (Appendix I). This sizing was chosen due to the ease of testing by me. The prototype was printed from TPU with hardness 98A. For the prototype to have hard and soft rings, strong grid infill was used for the hard rings and a weaker gyroid infill with no outer walls for the soft rings.

Figure 37. Detailing Test 2 Prototypes

Insight 1: Middle ring is collapsing inward (orange circle on photo). Height of the soft ring is too big, making the contact between the two hard rings impossible.
Action: It is possible that if there are more hard rings, and the soft rings are smaller in height there would be sufficient contact between the hard rings to transfer the forces towards the lower rings.

Insight 2: Collar width contacting the head was 20mm in this prototype and this was not sufficient to support the head and avoid the fulcrum effect. Additionally, the collar had a sharp edge which should be filleted for user comfort.
Action: Make collar wider ~ 30mm and with a smoother inner edge.

Insight 3: Force was being transferred to the clavicle as expected from the literature research.
Action: Expand front lower ends of the product and provide a clavicle relief area.

Detailing Test 3
In this test all the improvements from detailing test 2 were incorporated in the prototype. The goal was to check if there is still inward collapsing of the middle ring, even when the height of the soft rings is reduced and there are more hard rings. Additionally, collar and clavicle comfort were to be tested since there were adjustments made based on detailing test 2 to improve the comfort.

The prototype was made from TPU (see fig. 38) as in detailing test 2 with soft parts having gyroid infill (no outer wall) and hard parts having grid infill (with outer wall).

Figure 38. Detailing Test 3 Prototypes

Insight 1: 4 rings contact better than 3 rings between each other, but there is still some collapsing at the front (orange circle). Specifically, at the point where the second ring has to transfer the force to the first ring, which is lying on the torso. Instead of the second ring contacting the first ring it sinks down directly to the collarbone.
Action: Experiment what lattice can transfer force from downward to sideways motion.

Insight 2: Collar is now comfortable both in terms of width and gradual inner curve.
Action: On the sides right under the jaw the collar could be a bit wider, currently it's getting more narrow in this section.

Insight 3: Clavicle relief area is comfortable for the most part, it could only be trimmed on the side (dotted orange line), as it contacts the clavicle at this point.

Detailing Test 4.1
This test aimed at finding out what structure could facilitate the desired bending of the rings (most crucial between the first two base rings).
Five TPU samples were prepared (fig. 39).

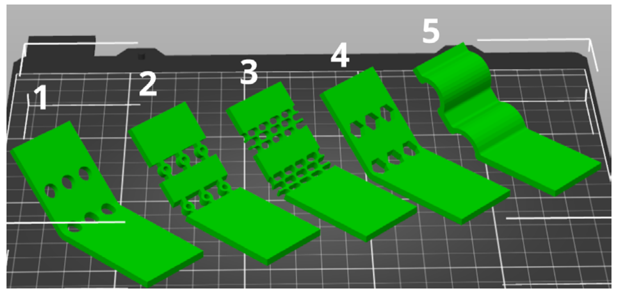


Figure 39. Detailing Test 4.1 Samples

Insight: Sample 5 provided the most desirable bending, therefore it was used to develop another prototype. An advantage of the bending of sample 5 was that the arches would flatten when compressed, thus forming a gradually formed dense structure that would stop the bending when it becomes extreme.

Detailing Test 4.2
A new 3D model incorporating arches instead of gyroid-based soft sections was developed to test whether the desired bending behaviour could be achieved (see fig. 40).

A 1:2 scale model was 3D printed with TPU to test the idea. The reason for scale model was that full-scale printing time took 20+ hours, support removal was time-consuming and material costs were higher.

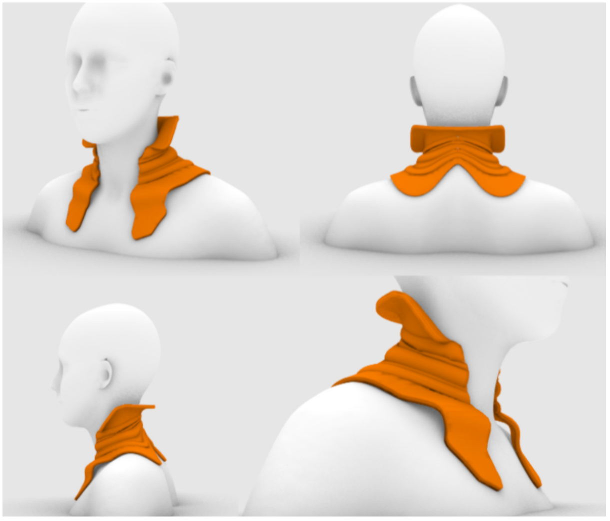


Figure 40. Detailing Test 4.2 3D Model

Insight: The product did not bend at all. Possible reasons for that are that the small-scale model made the structure stiffer, or that an arch in a simple shape is weaker and provides bending, but an arch in a more complex geometry could make the product stiffer. The latter suspicion is visible in the clavicle relief area, which is arched and is one of the toughest sections of the TPU prints.

Action: After a consultation with an experienced production designer, I was advised to use different thicknesses for varying hardness and bending facilitation, as this is a simpler approach than geometry adjustments.

Detailing Test 5
In this prototype the thickness was varied so that the softer parts were thinner (2mm) and bend and the harder parts were thicker (5mm) and stayed rigid. The clavicle piece was also trimmed on the side as discussed in detailing test 3 (refer to fig. 41 for prototype).

Figure 41. Detailing Test 5 Prototype

Insight: The product was again very stiff and did not bend at all in the desired thinner regions. Any bending was only due to the flexibility of the TPU and it was not at the intended locations.

Action: I cut out some of the softer sections to see if just a few strips holding the rings together were enough to provide stability and if the hollow cuts were enough to give it flexibility. The idea looked promising, therefore the next step was to build the protector in 3D with cuts where the soft pieces were. This meant also that the rings would have to be closer, because the ones in this test were too far apart to contact by bending. This is because I made the line cuts 5mm at the back for less compression at the back and 10mm at the side and at the front for more range of motion in those directions (lines shown in fig. 42).

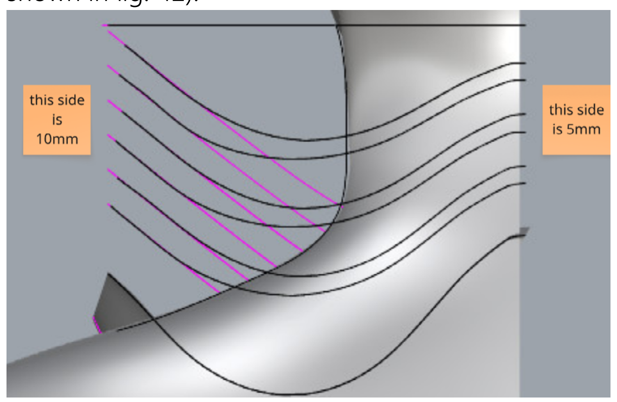


Figure 42. Detailing Test 5 Cutting Lines

Detailing Test 6
In this test the prototype (fig. 43) had cuts in the sections where I wanted to achieve bending. The rings were connected with three stripes - one at the back and two by the clavicles. The stripes consisted of gyroid-infill blocks between the rings. Additionally, I incorporated the spikes from detailing test 1.2. I added the spikes by all the stripes. At the front, so that the force is transfered from the second ring to the first base ring and at the back so that when the collar is pressed the protector cannot bend too far backward (extension). I also later added PLA to the base ring for more rigidity.

Figure 43. Detailing Test 6 Prototype

Insight 1: This was the first prototype where bending was happening as intended. The product was bending and allowing bigger ROM laterally than in extension and compression.

Insight 2: Compression force from ring 2 was successfully transferred to ring 1 (base ring) due to the spikes from detailing test 1.2.

Insight 3: The rings were a bit too thin and the prototype was a bit too flexible.

Insight 4: The stripes connecting the rings from gyroid-infill were too weak and some broke during support removal.

Action: Make rings thicker. The stripes should be solid and thin but with normal outer wall and grid infill, rather than the gyroid-infill blocks. The brace should be a bit wider because it is too tight at the front now. To make the rings' contact better, material should not be cut away between the rings but rather the upper surface of the lower ring should be shifted up and used for the lower surface of the upper ring (see fig. 44 below).

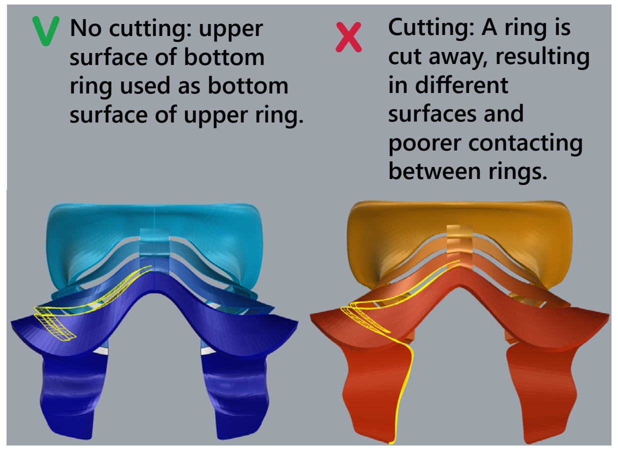


Figure 44. Detailing Test 6 Insights

The following lines as shown in fig. 45 were used to make the cutting surfaces, which define the shape and the ROM. In green are the back lines and in pink the side lines. These lines were crucial in shape definition and there were many iterations throughout the different prototypes to find the right curves.

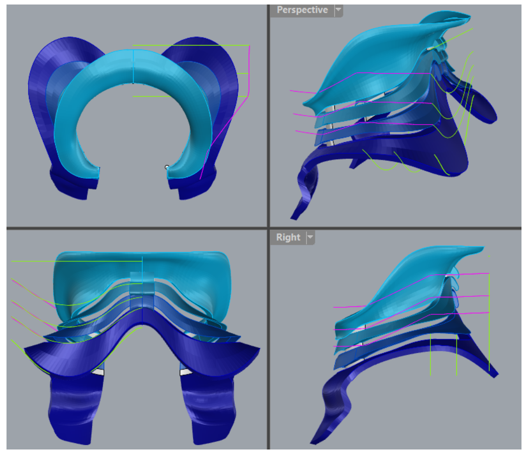


Figure 45. Detailing Test 6 Cutting Lines

Detailing Test 6.1
This test was very similar to test 6, with only a few adjustments as described in the actions above. This prototype was the foundation of the final concept. It was again printed from TPU. It was printed with 15% infill, organic support and it took 24 hours to print with PRUSA MK4.

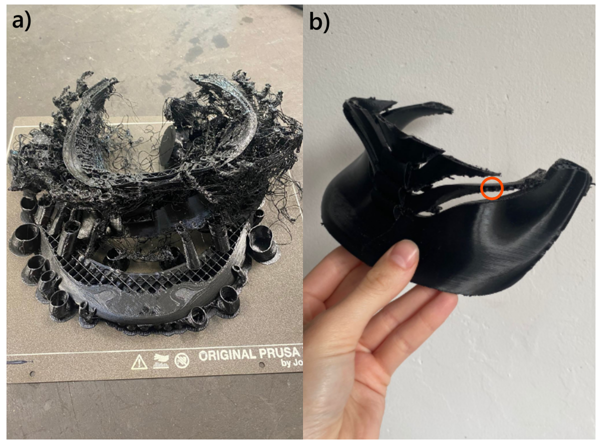


Figure 46. Detailing Test 6.1 Prototype

This print failed twice (fig. 46a)). Once due to failed y-axis calibration (fig. 46b)), the second time due to nozzle clogging problems. Nevertheless, the second print was able to give me some information:

Insight: Due to the alignment of the bottom and top rings' surfaces, some of the rings became too thin and weak.

Action: Thicken rings to make them stronger.

Detailing Test 6.2 (Final prototype)
An iteration of test 6.1 with thicker rings. This prototype was 3D printed successfully (fig. 47) and it was used as a **final detailing test prototype for user test (chapter 5.3) and range of motion evaluation (chapter 5.6)**.


Figure 47. Detailing Test 6.2 Prototype

Insights: The product worked as intended sizing was made for an individual with a neck base circumference of 400mm and neck horizontal circumference of 370 mm (see Appendix I). Next steps to prepare the prototype for user testing were to add foam padding and fabric cover.

Conclusion
- Ring contact is the main factor limiting movement.
- More rings improve strength and contact quality.
- Collar side cut facilitates head side rotation
- A wider collar improves comfort and impact distribution.
- For 3D printing, cutouts aid bending better than geometry or thickness changes; however, other manufacturing methods may favour different solutions.

5.2 Fabric Cover Development

Another aspect that I looked into during the detailing stage was sewing a fabric cover for the product. To add softness and integrate the product with the current SPINES back protector' vest two covers were needed. One cover with velcro attachment that will allow the product to be worn with the current vest and one product with stand-alone cover and strap system that will make it possible for users to wear the neck protector without the SPINES back protector' vest.

Detailing Test 7.1
The first step in creating the cover was finding the right cut. Initially, I tried making the cover from two pieces - one inner and one outer piece, inbetween which the protector would be inserted. With this first cut the fabric was not following the human shoulder and neck curve nicely. Material was stacking and wrinkling around the neck. To avoid this I thought I had to make the cut more extreme at the shoulder and neck area (orange dashed line in fig. 48).

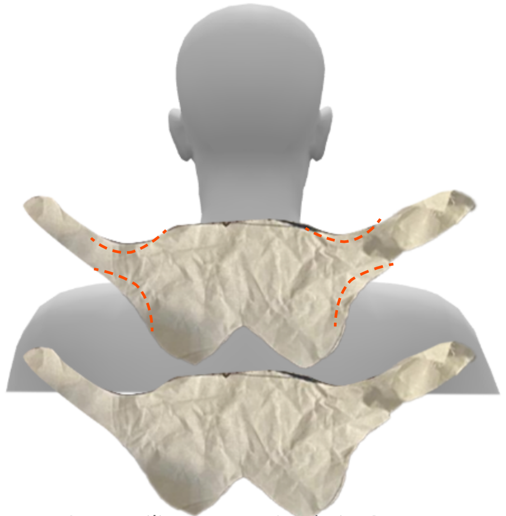


Figure 48. Detailing Test 7.1 Fabric Cut

Detailing Test 7.2
In the next iteration, I made the cuts more extreme, but it was still not sitting nicely on the neck (fig. 49). This led me to the conclusion that two whole pieces is not realistic and I need the fabric of the inner and the outer layers split into more pieces or at least with darts.

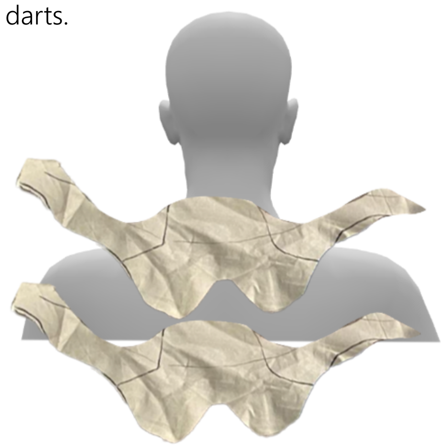


Figure 49. Detailing Test 7.2 Fabric Cut

Detailing Test 7.3
To find out where I need darts I used a vest with a collar. I made the front piece and the back piece, I laid them flat and got the dart shape and side cut I needed (orange dashed line fig. 50).

Figure 50. Detailing Test 7.3 Fabric Cut

This piece was then translated into one inner and one outer piece. The idea was to have the fabric cover as a pocket with elastic band so that the product can be accessible for replacement if it gets damaged. This would also make the sewing easier, as sewing the fabric closed with the product inside would be very difficult. The elastic band would be placed at the collar of the inner piece, therefore the inner piece is elongated by the collar (fig. 51).


Figure 51. Detailing Test 7.3 Fabric Cut 2-Piece

The final fabric cover should be made from breathable materials such as sports mesh, nylon, or lycra. At the clavicle area of the fabric cover there should be velcro for attachment to the SPINES back protector' vest, or sewn straps to allow wearing the product without the back protector vest. This was not developed during the prototyping process, but it will be part of the final solution (Chapter 6).

Detailing Test 7.4
I used the cut developed in test 7.3 and I made a fabric pocket for the protector from a sport mesh (fig. 52). I added an elastic band at the collar of the inner fabric which would wrap at the back of the protector collar.

Figure 52. Detailing Test 7.4 Fabric Cut & Fit

Insight 1: Mesh is very hard to work with and not stretching enough. Additionally, it was catching onto imperfections from the TPU 3D print and it was getting damaged.
Action: Use another material that is more sturdy (without holes) and more stretchy.

Insight 2: The fabric pocket was too small.
Action: All the pieces should be slightly bigger.

Insight 3: The fabric hides the back of the product which is the most unique and beautiful part of the product.
Action: The fabric could be only on the inner side of the product and sewn to the edge of the product. This would leave the back open, thus making the product look better, whilst reducing fabric material used and efforts to make the fabric cover.

Detailing Test 7.5
In this test, I increased the size of the pieces used for test 7.4. I used a different sports fabric which was more stretchy and instead of making a pocket I made only one layer of fabric for the inner side of the product (fig. 53).

Figure 53. Detailing Test 7.5 Fabric Cut & Fit

Insight 1: Size of the cuts was better and can be kept this way.

Insight 2: The fabric was getting very stretched and wrinkled in the middle (back of the neck), it was not following the product curve nicely.
Action: Keep the size dimensions, but make the collar a separate piece.

Detailing Test 7.6
To separate the collar correctly and ensure that it will take the shape of the product correctly this time I secured the fabric onto the neck protector and marked where I needed to make the splits for the different parts (fig. 54).

Figure 54. Detailing Test 7.6 Fabric Cut & Fit
Insight: Separating the collar worked well and the fabric was now following the curve of the protector well.

5.3 Final Prototype

The final prototype consisted of the TPU 3D printed neck protector from detailing test 6.2, the fabric cover from detailing test 7.6 and open-cell foam padding. The padding had a thickness of 5mm which reduced the neck base circumference to 370mm and the horizontal neck circumference to 340mm.

5.4 Sizing

Next to the concept detailing, I was researching the sizing I needed to make sure the product would fit different neck sizes. From the first cardboard prototype (Chapter 3.2) I found that neck circumference is one of the relevant sizes for the product development (fig. 55a)). Furthermore, during the field research I noticed that neck height is also very important particularly the length from the jaw corner - mandibular angle (Breeland et.al, 2025) to the shoulder, also known as lateral neck length (LNL) (Han et. al, 2015) and the neck height (fig. 55b)) from the spinous process of the C7 - cervical landmark to the base of the skull - nuchal landmark (Blackwell et. al, 1997).

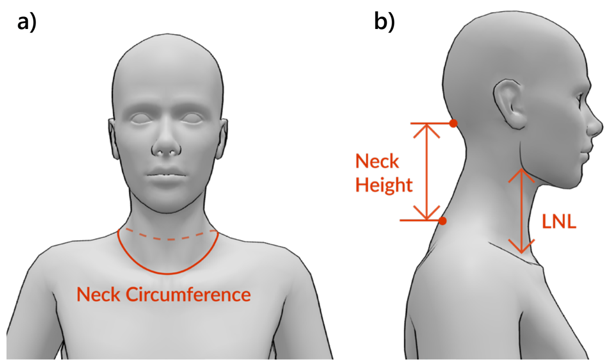


Figure 55. Needed Sizes for Product Fit

5.4.1 Neck Circumference

Neck circumference is a more common measure that is available at DINED as well as on clothing brands' sizing charts. The major challenge was that DINED as well as clothing brands have different ways of measuring the neck circumference, thus resulting in different sizes. Clothing brands and the EN13402 (Joint European standard for size labelling of clothes) measure the neck circumference 2cm below the Adam's apple, whilst DINED measures the neck base circumference with a steel rope that is left to rest on C7, around the shoulders and above the clavicles (Appendix I). This results in DINED having bigger values for neck circumference than the clothing brands and the EN13402. A limitation of using neck circumference data from clothing brands or EN 13402 is the lack of information on female neck sizes. This is why I used the DINED Ceasar database on mixed male and female 18-66 years old data as a foundation of the sizing research. To create a sizing guide it was important to understand what factors influence the neck circumference (NC). Through experimentation with mannequins in DINED I noticed that weight was the most important factor influencing the NC. This is further confirmed by Padilha et. al (2022), who suggest that bigger NC is correlated to obesity.

A starting point of the analysis was the alpha sizing of SPINES for their current back protectors (Table 3).

SPINES UNISEX SIZING

Size	Stature (mm) Min	Max
XXS	1100	1250
XS	1250	1400
S	1400	1680
M	1680	1780
L	1780	1880
XL	1880	1980

Table 3. Spines Unisex Sizing System & Stature

By using the DINED Ceasar 18-66 years old mixed adults database I found out what is the minimum, maximum, average, mean and standard deviation of the **weight** and NC corresponding to the S, M, L, XL body heights clusters (stature in DINED). Since the database was for adults, there was no sufficient data for sizes smaller than S (users shorter than 1400mm). Next, I did the same correlation for the alpha sizes and the **neck circumference**. This way I got the correlation between neck circumference and body weight. (See Appendix H for more detailed sizing information)
To make the boxes of the alpha sizing the average weight and neck circumference were used and the standard deviation for each alpha size (see fig. 56).

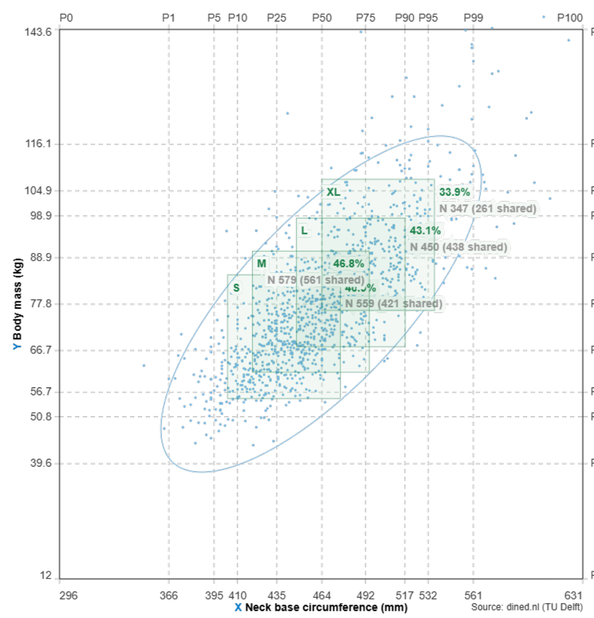


Figure 56. Neck Circumference and Body Weight. (DINED, 2025)

The limitation with Spines' uniform XS and XXS sizes is that they were made for children and the DINED database for children does not include neck base circumference. Nevertheless, in Appendix H it is estimated what would be the NC for XS alpha size.

5.4.2 Neck Height

The same database Ceasar 18-66 years old mixed adults was used for the neck height analysis. However, this measurement was not available directly through the DINED tool, but as an excel file (Dutch_Measurements_3D Measurements) from the repository on which DINED is based. Additionally, neck height was not measured for all the subjects in this Ceasar database. Nevertheless, there were 1145/ 1267 subjects, whose neck heights were measured and which data I used for the analysis. In contrast to neck circumference, where there was a correlation to body mass, neck height is linearly correlated to stature (Mahajan et. al, 1994). By using again SPINES' alpha sizing and stature clusters, I found out what is the minimum, maximum, average and SD of the neck height for those clusters.
Lateral neck length was not included in the analysis, because there is not enough data and it will be taken into account whilst modelling the protector in CAD based on mannequins created with the measurements from the neck base circumference, weight and body height.
With the data of the alpha sizing, corresponding neck height and body height a new ellipse was created (fig. 57) similar to the neck base circumference and body mass ellipse to see the relation between neck height, stature and SPINES' alpha sizing.

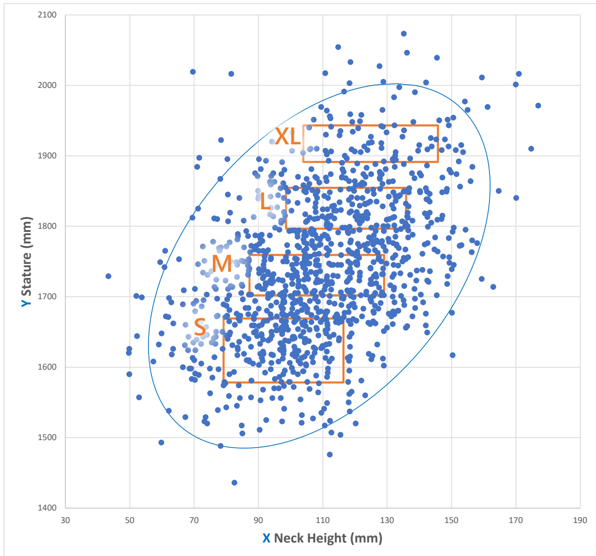


Figure 57. Neck Height and Stature

Another important factor was the ratio of the neck protector height to the total neck height. This is due to the fact that the protector has a smaller height, it starts above the C7 vertebra to avoid hurting this most pronounced part of the spine and finishes below the nuchal landmark because it contacts the helmet (see fig. 58). The final prototype was designed for a mannequin with a neck height of 103,9 mm and the protector had a height of 59,8mm meaning that the neck protector height is ~58% of the total neck height (C7-nuchal landmark).

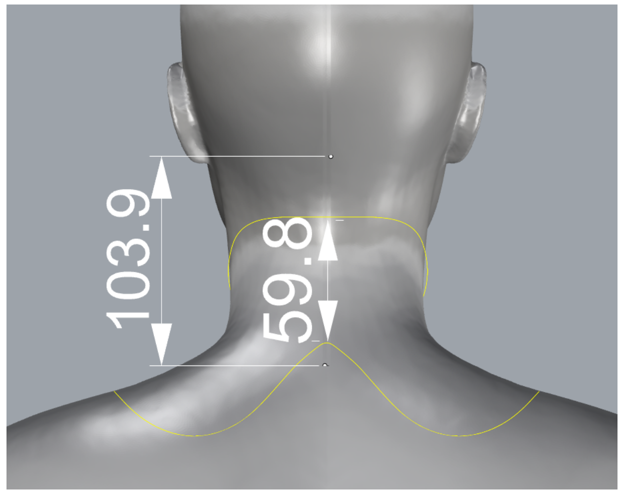


Figure 58. Product Neck Height and Body Neck Height

After the neck height - body height ratio and neck circumference - body weight circumference was established, the neck height and neck circumference were combined into one ellipse with the S-XL alpha sizing (see fig. 59). Again to define the alpha sizes the standard deviation of the average values within the SPINES height clusters were used.

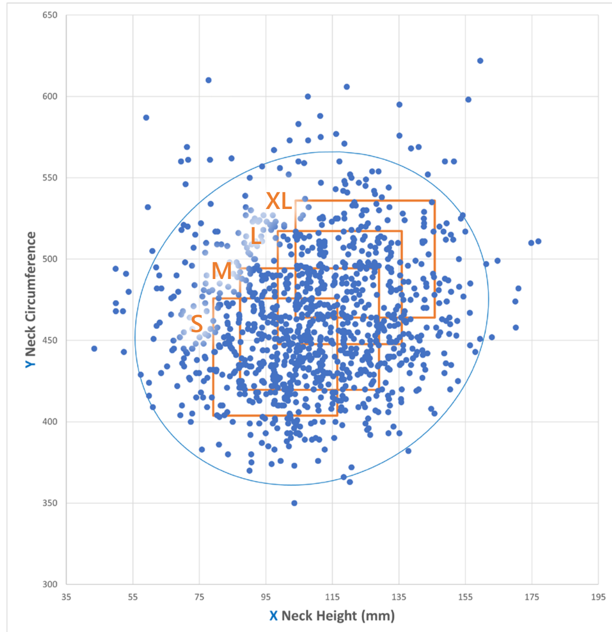


Figure 59. Neck Circumference and Neck Height

This ellipse showed a less steep linear relationship between the neck circumference and the neck height and a lot of overlap between the sizes. To create the dimensions of the product the average neck height and neck circumference was taken for each size.
The neck protector height was 58% of the average value for the neck height. For the product neck circumference the average NC value for each size was taken and 10mm offset was added to this value, due to padding and to make sure the product does not directly touch the skin of the user. Meaning the Product NC=Original NC+2 π×10mm.
These insights are summarized in the user sizing guide on the next page, which will be available to the users when purchasing their neck protectors.

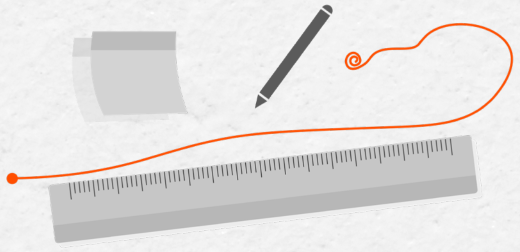
Users will be presented with this sizing chart when purchasing a neck protector. There will also be an explanation of how to measure their neck correctly on the webpage. This would look as presented below.

Clothing brands, EN13402 and medical braces sizing research can be found in Appendix G. The main limitation of this sizing system is that it does not provide children's sizes.

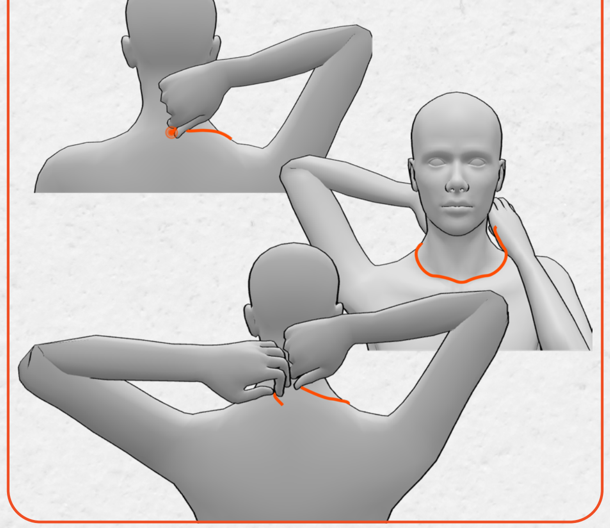
5.4.3 User Sizing Guide

1 To measure your neck you will need to collect a few measuring tools:

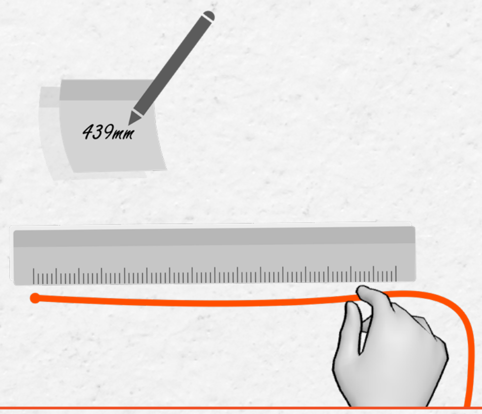
- necklace, rope, thread or something alike that you can wrap around your neck
- a long ruler or measuring tape on a table in front of you
- pencil or pen and paper to note measurements down



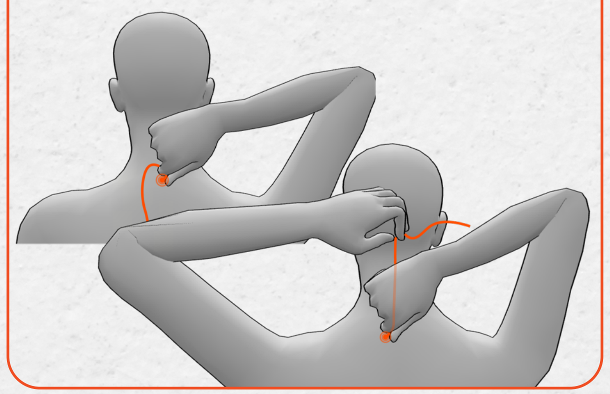
2 Take the rope and place it at your most pronounced point at the bottom back of your neck. Wrap the rope around your neck and let it fully rest on your clavicles. Connect the two ends at the back at the most pronounced point where you started measuring.



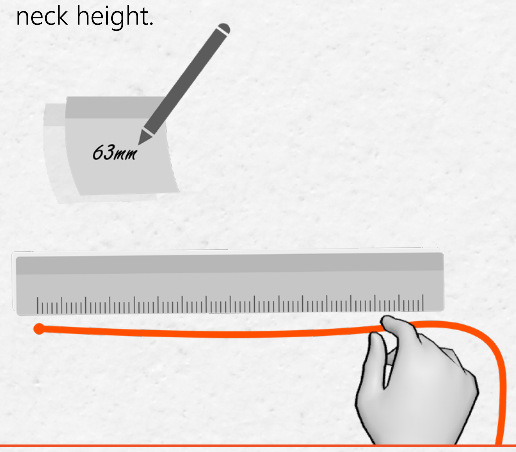
3 Keep your fingers at the end of the thread and lay it flat on the table right next to the ruler. Note down the length of the rope. This is your neck circumference.



4 To measure your neck height place the rope again at the most pronounced point at the back of your neck. Now slide your hand along the rope and hold the rope at the point where you feel the bottom of your skull.

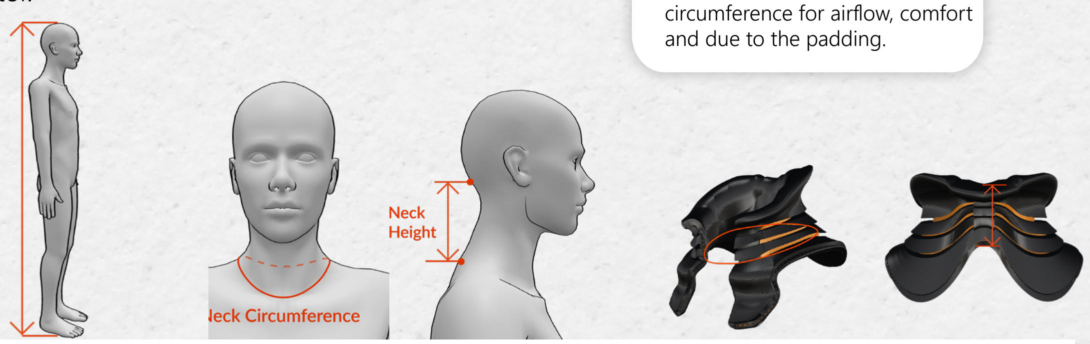


5 With your fingers holding the end of the rope lay it flat next to a ruler and note down the length of the rope. This is your neck height.



6 Based on the measurements check the sizing chart. Neck circumference is the leading factor.

Product circumference should be at least 6cm longer than your circumference for airflow, comfort and due to the padding.



SPINES UNISEX SIZING

Alpha Size	Stature (mm) Min	Stature (mm) Max	Neck Base Circumference (mm)	Neck Ht Range (mm)	Product Circumference	Product Height (mm)
S	1400	1680	440	98	503	57
M	1680	1780	457	108	520	63
L	1780	1880	483	117	545	68
XL	1880	1980	500	125	563	72

Table 4. User Sizing Guide

5.5 User Test

To test the final prototype a user test was done with 10 participants.

Goal:
Find out how users perceive the product.

Materials and equipment:
1) Neck protector prototype
2) Skiing helmet
3) Measuring tape
4) Printed consent form x10 (Appendix K)
5) Printed user survey x10 (Appendix L)
Test Set-up shown in fig. 61.

The user survey consisted of 11 questions:

Comfort related using Borg Scale 0-10

Figure 60. Borg Scale. From *Full Range Health*, (2020), https://fullrangehealth.org/rpe-covid/

Question 1: Mobility restriction
Question 2: Pressure on neck
Question 3: Thermal comfort

Looks & feel related using a 1-7 Likert scale
Question 4: Attractive - Unattractive
Question 5: Slim - Bulky
Question 6: Modern - Old-fashioned
Question 7: Sporty - Assistive
Question 8: Safe - Unsafe

3 open-ended questions
Question 9: What do you like most?
Question 10: What would you change?
Question 11: Does anything stand out as particularly good or bad?

6) Pen
7) Two markers
8) Phone camera

Methods:
1) Each user was given an introduction to the project and the purpose of the research. They were asked to read and sign the consent form agreeing that their anonymized data can be used for research purposes of this project.

2) The user was asked to put on the skiing helmet and then the protector. All users used the same skiing helmet.

3) A video was played with a first person perspective skiing and the users were asked to imagine they were skiing for 2 minutes (see fig. 62). Two markers were given to them to use as skiing poles.

4) After this the users were asked to rotate their head, extend it, flex it and laterally bend it. Whilst doing this they had to point out where there is discomfort and I took a picture of this.

5) In the end the users were asked to fill out a survey about the product.

6) Users were rewarded with a beverage.

Figure 61. User Test Set-up

Figure 62. User Test

Results:
Comfort related using Borg Scale 0-10
Only 2/10 subjects had a horizontal neck circumference smaller than 340mm, which was the circumference of the product. The rest of the subjects had bigger NC. The 2 subjects within the intended NC range found the mobility restriction to be weak (2) and moderate (3) and the pressure on the neck to be very weak (2)(see fig. 63).

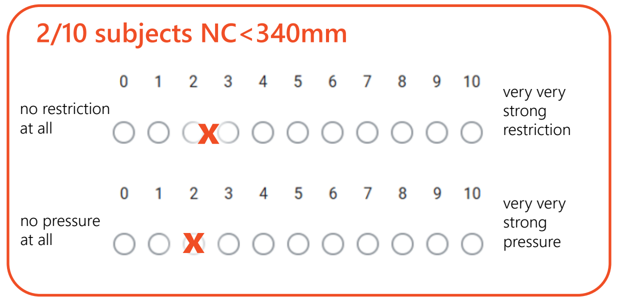


Figure 63. Survey Answers 2/10

For the rest 8/10 subjects (fig. 64) the average mobility restriction was strong (5) and the average pressure on the neck was very strong (6).

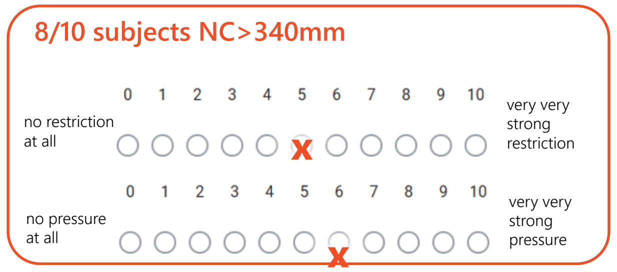


Figure 64. Survey Answers 8/10

It is interesting that during the tests most of the users indicated there is not much restriction. It is possible that pressure on the neck was interpreted also as mobility restriction. On average all 10 participants found the termal discomfort to be weak (2)(fig. 65). This was a harder question to assess taken the user did not wear the product in the expected environment temperature and did not wear ski gear.

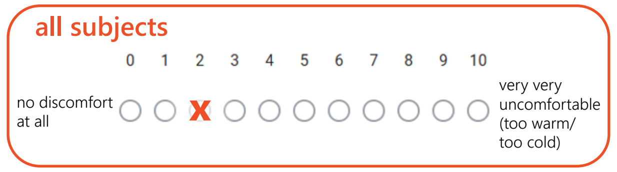


Figure 65. Survey Answers Termal Discomfort

Further, the product was generally perceived as attractive (3), slightly bulky (4,7), modern (1,2), neither sporty nor assistive (3,5) and safe (2,1) by all participants (see fig. 66 below).

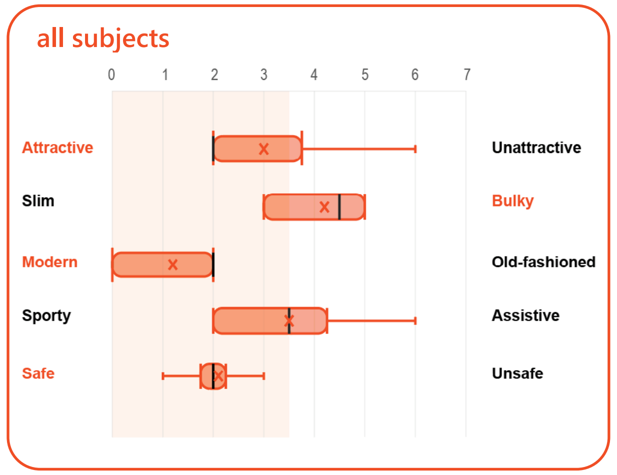


Figure 66. Survey Answers Product Perception

With the open-ended questions almost all participants indicated that the product *"looks cool"*, comfortable, especially the inner padding and that it looks like a safety product. The critical feedback was all regarding a better fit by the 8/10 subjects with NC>340mm. During the tests multiple users indicated that *"a strap adjustment system would be good to help keep the product in place"*. They felt like the product would slip backward during some movements. They also mentioned that an indication of correct placement would be nice. Pictures taken during the user test of the main pressure points can be found in Appendix N.

Take-aways:
Insight 1: The pressure was highest on the front two points touching the neck (fig. 67).
Action: Add more space by those points and try to lower them.

Figure 67. Front Pressure Points

Insight 2: The helmet adjustment system was putting pressure on the head by neck extension (fig. 68).
Action: Make a concave part of the collar where the neck adjustment system contacts the collar.

Figure 68. Adustment System Pressure Point

Insight 3: When rotating sideways the ear cover of the helmet was rubbing against the collar (fig. 69).
Action: Make the side collar even lower. However, in a real skiing scenario, skiers turn partially with their body and partially with their head, it is possible that this rubbing is not problematic.

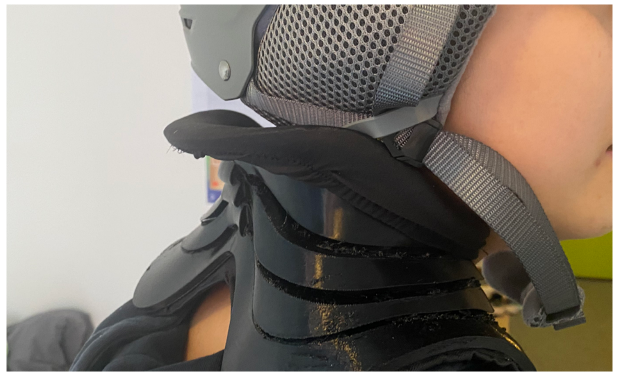


Figure 69. Helmet Ear Rubbing Protector

Insight 4: The product could look more sporty. Action: Look at sports apparel clothing. Possibly could be achieved through the fabric material, pattern and colour.

Insight 5: The helmet adjustment system was putting pressure on the head by neck extension. Action: Make a concave part of the collar where the neck adjustment system contacts the collar.

Insight 6: Users would like an indication they have placed the product correctly.
Action: Visual/ explanation in the product manual or on the product website about correct placement. If it's integrated with a vest possibly this is more straightforward.

Insight 7: Even the users with small NC, who the product was fitting well, said they would like a strap system to keep it in place.
Action: Add strap system for non-integrated in vest product.

Conclusion
The user test confirmed that neck circumferences is the leading factor in comfort. Users with bigger neck circumference found the product less comfortable. Generally, the product is perceived as attractive, modern and safe. On the other side, it is perceived as bulky and neither sporty nor assistive.

Limitations
All users in the test wore the same helmet. Testing the product with different helmets might give different results especially regarding helmet adjustment system pressure point, helmet ear covers rubbing against the collar and overall fit with the product. Ideally, only users with the intended horizontal neck circumference should have been sourced. This would help to evaluate the product's comfort with the intended user group. Restriction and pressure were perceived as similar questions, whilst with restriction the range of motion was implied. Alternatively, the users' ROM could have been measured instead of asking the users to answer this question themselves. A lot of the insights are regarding the shape of the product rather than the ROM. The shape of the product could have been tested with the users with an earlier prototype, meaning the whole user test could have been done earlier and some of the insights could have been implemented in the final prototype. Instead, the insights are now implemented in the final concept solution.

5.6 Range of Motion Evaluation

Based on the findings from the cervical neck range of motion Chapter 2.2.2, a test was conducted on cervical neck ROM with and without the neck protector prototype. This test was performed with one subject only, to validate that the product does not significantly restrict the range of motion. For lateral bending, sideways rotation, and flexion, the results for ROM with and without the protector were almost identical (differences were within 5°). Variations in angles could have been due to slight movements of the subject or partial involvement of the thoracic spine. For extension, however, the ROM with the prototype was 14° less than without it. Since the extension is one of the most harmful movements—particularly following compression—and is not commonly performed during skiing, this 14° reduction in ROM is considered acceptable and even potentially beneficial from a safety standpoint. Compression was not tested as it is an unnatural movement for the body to simulate without load and due to the fact that the prototype was not made from the intended final material - Polyurethane. Pictures from the test can be found in Appendix O.

5.7 Manufacturing & Materials

This was one of the most important topics during the detailing stage because it would define the shape of the product. During the detailing phase I was making the shape so that it works as intended when 3D printed, but if another manufacturing method is used the product shape might have to change. Multiple experts were consulted during this stage including Arjen Jansen, Gertjan Streefland, Willemijn Elkhuizen, Evren Uçar. All of which gave input on how the product could be manufactured. In this chapter, I have outlined the options for product manufacturing. The most important consideration was that injection molding should be avoided due to starting costs.

5.7.1 Vacuum Casting

Vacuum casting is one of the options for manufacturing the product. The mold could be 3D printed from PLA, PETG, ABS, or PA12 or CNC machined wood. The product could be made from a rigid (shore D) polyurethane (PUR) sheet and have a softer inner lining (shore A) PUR (Thompson, 2007, p.41). After the product is cast, it could be cut with a laser to achieve the desired geometry (e.g. bending movement). Additionally, the collar curve outward presents an undercut and it could not be achieved with thermoforming.

To achieve this bent, it would have to be heated and bent manually after casting, or placed in an oven with a jig that would guide the bending. The mold could look something like the torso shown in figure 70. After the product is vacuum cast in the torso mold the laser would have to go over the yellow lines and cut out the excessive material. The green line represents where the collar bent should be made later.

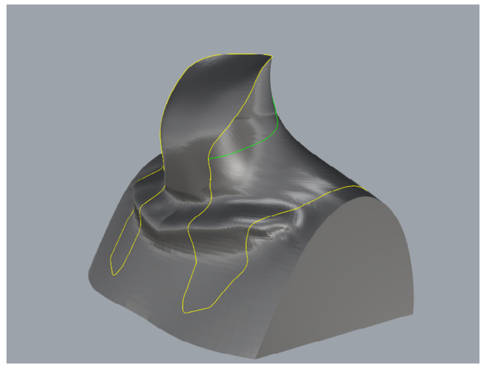


Figure 70. Vacuum Cast Mold Example

The main limitation of this manufacturing method is that the thickness cannot be controlled. This means the bending of the protector would have to fully rely on the material which was cut away.
Additionally, the spikes in the front by the clavicles and in the middle at the back would be very hard to form and would have to be hollow.

5.7.2 Compression Molding

Compression molding is another method that could be used for the production of the protector from PUR (Thompson, 2007, p.45). It is suitable for complex shapes such as the neck brace and tooling costs are moderate and less expensive than costs associated with injection molding - 3 to 4 times material cost. It is also conventionally used for thermosetting plastics such as PUR. The brace would have to be molded as a whole piece from PUR and the cutouts would again have to be manually processed afterwards. Alternatively, instead of having cutouts the product could use thickness variation as proposed in detailing test 5. The mold would have two halves. The lower half of the mold would have to be split into a few parts due to the collar shape which acts as an undercut. The separate parts would be brought together to form the die cavity.
The limitation of this method is that labour costs can be quite high.

5.7.3 Sillicon molding

This is a non-industrial production method for a low number of samples and it is suitable for creating new products, before investing in more expensive tooling and production methods such as compression molding and injection molding

This method will make it cheaper to create multiple molds for different neck sizes due to the low mold tooling costs. Additionally, the mold could be split into more than two parts, without significant cost increase which will facilitate the removal of the collar, which acts as an undercut. If the mold is flexible enough, it is possible that the product could be removed even without splitting the mold into more than 2 pieces. The product would be made from high shore PUR. It is the cheapest manufacturing method for low samples and it could help see the market need for this neck protector.
The main limitation is that the mold is not nearly as durable as molds by compression and injection molding, but that is justified with low-volume production.

5.7.4 Selective Laser Sintering (SLS)

This technique is a suitable alternative to achieve the intricate shape of the product, whilst avoiding high tooling costs. The only disadvantage is that PUR is not an option with SLS, instead, thermoplastic polyurethane (TPU) would have to be used, the same as the FDM 3D printed prototypes. After researching, I found out that Oceanz could SLS print the product from TPU 88A shore hardness for 900EUR. This is a very high cost for a single product and the 88A shore hardness is softer than the TPU 98A shore hardness used for FDM printing, which was already a bit too flexible. This makes SLS printing a less desirable option.

5.7.5 Other Options

The other low-cost alternatives are creating molds with SLA and SLS printing, which will be more durable than the silicon mold and casting hard shore PUR in them. The biggest cost associated here would be the manual labour.

Conclusion
After consultations with specialists and research, it is evident that there is no one right answer as to what production method should be used. The current manufacturer of SPINES shall be consulted as a next step to find out which process they could best facilitate and at what cost. After consideration of their facilities and pricing comparison of the different options one production method shall be chosen. This is, however, not further looked into here due to the time-consuming process of creating molds for the different techniques and getting the indicative price quotations from manufacturers.

06

Final Solution

The final concept solution included adjustments based on the user test, such as helmet adjustment knob clearance, fitting system to the body and integrated solution with the SPINES back protector. The shape of the front was adjusted so that the two pressure points in the throat were avoided. The main features of the product are presented, together with the fitting system and conclusion and recommendations of the whole master's thesis are summarized.

6.1 Final Concept Solution

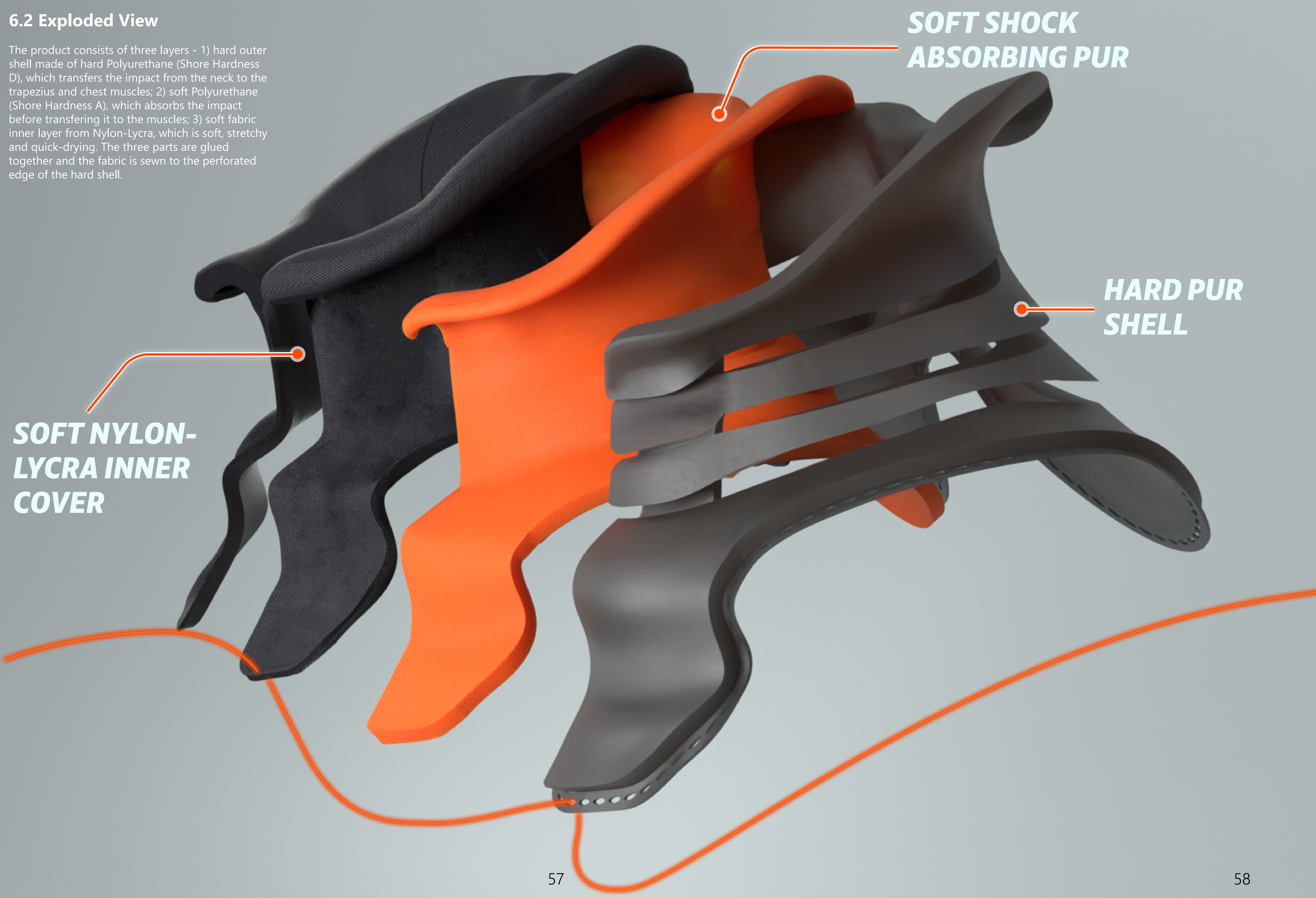
WEAR STAND-ALONE WITH STRAPS

OR INTEGRATED WITH BACK PROTECTOR

EASY VELCRO ATTACHMENT

6.2 Exploded View

The product consists of three layers - 1) hard outer shell made of hard Polyurethane (Shore Hardness D), which transfers the impact from the neck to the trapezius and chest muscles; 2) soft Polyurethane (Shore Hardness A), which absorbs the impact before transfering it to the muscles; 3) soft fabric inner layer from Nylon-Lycra, which is soft, stretchy and quick-drying. The three parts are glued together and the fabric is sewn to the perforated edge of the hard shell.



6.3 Conclusion & Recommendations

The goal of this thesis was to design a cervical neck protector for winter enthusiasts. This protector is meant to guard it's wearer from the main biomechanics of a forward fall, which is the most severe injury-prone type of fall. The design assignment was very open due to the novelty of the design idea. Most inspiration was drawn from motocross sports, as a field where injuries are more frequent than winter sports and protection is one step ahead. Existing solutions were taken as a starting point for the quick prototyping and ideation and insights from those were collected and developed until a novel, winter sports unique product was shaped.

Ergonomics & Safety
The main challenge was to enhance user safety by reducing the risk of cervical spine compression, extension, and lateral bending (requirement ES1-4). The product's shape effectively prevents compression using three structural strips—one at the back and two at the front near the clavicles—which connect the rings and prevent them from collapsing inward.
Extension is restricted by 14° compared to the typical comfortable neck ROM, due to the overlapping spikes on the strips between the rings. Lateral bending and flexion remain within the comfortable range of motion, with less than a 5° deviation from normal values when wearing the protector.
Other requirements such as ES5 stated that the user should be able to put on their skis.This is possible due to the freedom of flexion. It was tested during the field research with an earlier prototype and there were no challenges in this process since the action of putting on skis mostly involves bending forward from the lower waist. The skier should also be able to turn their head whilst skiing. This is possible as tested in Chapter 5.6 Range of Motion Evaluation. The skier should also have no discomfort from the adjustment system and have the adjustment system hold the protector in place. The adjustment system is only incorporated in the final concept solution, so it is still to be tested in terms of comfort and sturdiness. Finally, the skier should be able to pick up something from the floor by bending forward. Similarly to putting the skis, picking up something from the floor should also be possible, since there is no restriction on neck flexion.
Requirement ES6 stated that fulcrum effect should be avoided from the helmet going over the edge of the collar. This is currently, fulfilled due to the wide collar shape, which extends beyond the helmet. The protector also guards the clavicle area with the clavicle relief shape, thus fulfilling ES8.

Furthermore, the product shape successfully transfers force from extension and compression into the chest and trapezius muscles, addressing requirement ES9. Regarding ES8, which ensures the product facilitates sliding: on one hand, the protector will be worn under the ski jacket, which provides a smooth surface; on the other hand, the collar sticks out of the jacket and may protrude, hence potentially act as a latch against the snow.

Safety Recommendation
To make sure the product is safe to use the exact forces by a forward ski fall should be further researched. This would ideally be done with a crash test dummy such as Hybrid III or THOR, whereby sensors in the mannequin itself can be used, or optical motion capturing to measure the speed of the fall and calculate the impact based on the mass of the subject. The mannequin could be swung forward simulating the curve of a skiing forward fall. Once the product is produced from polyurethane, it could be placed on the mannequin and the same forward fall situation could be simulated. Then it will be possible to measure compression and compare if the protector is reducing the forces acting on the neck during an impact.

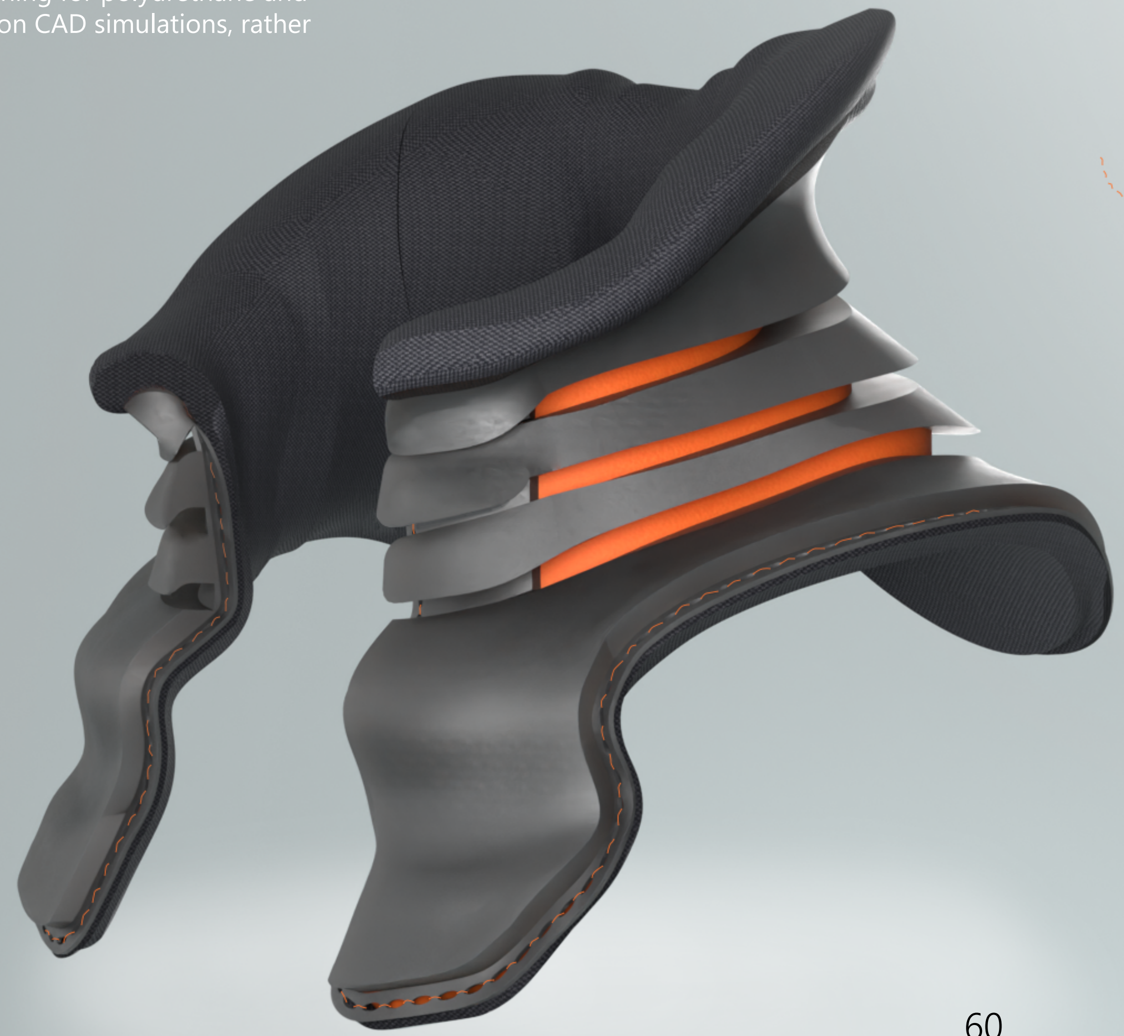
Comfort & Desirability
The product offers different sizing fitting adult neck sizes from 440-500mm neck base circumference (CD3). The users will be instructed to buy the size by adding 6cm to their neck circumference, thus assuring there is an offset between the product and their neck, hence sufficient heat dissipation (CD1). The prototype currently weighs 0,1kg but once the final product is made from the intended material it would be heavier (CD2). The final solution suggests an integration with the back protector through the use of a velcro attachment between the two.

Comfort & Desirability Recommendations
The soft polyurethane foam insert could have a hole pattern similar to that of the back protector to allow for better heat dissipation (CD1). Data on children's neck sizes should be collected and the product should also be made available in children's size. Integration with the back protector could be detailed through. It would be good if the back protector's soft PUR insert could follow the shape of the cervical neck protector, so that they fit nicely together. Furthermore, it should be tested if velcro attachment is enough to keep the neck protector in place or if its better to sew buckle straps onto the back protector vest which attaches to the neck protector.

Manufacturing & Cost
The exploration of the market and current winter sport back protectors helped to base material choice for the neck protector and assure that the manufacturing will be compatible with current production methods (MC2). The fabric used is Nylon-Lycra, a moisture-wicking material commonly used in sports gear, and the soft PUR insert is also standard. The main cost lies in mold-making for the outer hard PUR shell. Chapter 5.7 Manufacturing & Materials offers low-cost mold-making processes suitable for low-volume starting production. The design has been optimised to minimise stitching and manual labour: instead of full fabric coverage, the fabric now only lines the interior. It is sewn to the edges of the perforated hard PUR shell, with an elastic band at the top that wraps around the collar (MC1).

Material & Costs Recommendation
The design process and shape development were strongly influenced on insights from 3D-printed prototypes. In reality, with different production techniques and materials, the design could have taken a different direction and it is worth exploring in the future how could this protector functionality be achieved when designing for polyurethane and basing decisions based on CAD simulations, rather than 3D prints.

Opportunities
Whilst originally designed for skiing, further research could explore how the product might be adapted for snowboarding and other high-impact sports such as kite surfing and mountain biking.



To conclude, this thesis proposes a solution for winter sports neck and cervical spine protection. The protector restricts extension and compression, but allows side bending and flexion. It is inspired from articulated joints which restrict movement in one direction, whilst allowing it in another direction. The solution aims to bridge the gap in current protective equipment and raise awareness that such equipment is much needed.

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Figures

Tables

Appendix A
Project Brief

DESIGN FOR our future — TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Iva Hristova **Student number** 5,890,470

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Enhanced Winter Sports Spine Protection

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Winter sports such as skiing and snowboarding, are known for their risk of injuries, with spinal column injuries being some of the most severe. As a result protection is becoming an increasingly important part of the skiers' and snowboarders' routine. Helmets are now worn by almost everyone on the slopes, back protectors, knee pads, wrist guards and impact pants are also becoming more popular. This is due to technology advancements, access to information, awareness about safety and possible consequences.

The primary stakeholders are thus the regular winter sport enthousiasts whose main interest is staying safe and, secondary, looking good. Next, are the major sports goods brands and their interest in developing innovative protective gear that is both effective and stylish.

The opportunity here is that there is no product on the market designed for winter sport which protects the cervical spine of skiers and snowboarders.

However, there are several challenges and limitations. First, making sure the product provides the necessarily protection and freedom of movement. Second validating the product with the corresponding safety regulations and testing for efficiency. Finally, the product has to be aesthetically appealing for people to wear it and it should blend in the style of existing sports equipment.

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DESIGN FOR our future — TU Delft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

The problem which I want to solve is how can a cervical spine protector provide the desired protection, but also not restrict the freedom of movement. There is some degree of freedom which is important not only for the enjoyment in the sports, but also for the safety of the user to orientate themselves on the slopes and know what is going. Additionally, the product should be stylish and blend in existing sports equipment, without looking like an assisstive medical device.

The value for the primary stakeholders - winter sports enthusiasts is that this product will make it possible to go on the slopes with neck protection.

By motosports there are already neck protectors, due to the fact that those sports were recognised as dangerous earlier than wintersports. By wintersports protection is much more recent, which gives room for improvements.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design a solution to protect the cervical spine area of winter sport enthusiasts, which prevents injuries whilst skiing or snowboarding and fits in the style of existing winter sports products.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

Project Phase 1 Desk Research (Literature Research on norms & protectors on the market, source products and analyze them, survey on what protectors people wear, list of requirements, reframed design goal)

Project Phase 2 Field/User Research (Explore what is the minimum needed freedom of movement and minimum restriction for protection by falls)

Project Phase 3 Ideation (Generate ideas, converge ideas into few concepts, develop concepts & select one)

Project Phase 4 Concept Detailing (Design according to norms and regulations, design functionality, design product shape and components, specify materials and find/source components, make prototype, pricing & business plan)

Project Phase 5 Product Evaluation (Test product on norms and regulations, evaluate with user)
Project Phase 6 Deliverables (Report, Poster, Presentation)

Appendix A
Project Brief

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	31 Jan 2025
Mid-term evaluation	17 Apr 2025
Green light meeting	2 Jun 2025
Graduation ceremony	27 Jun 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

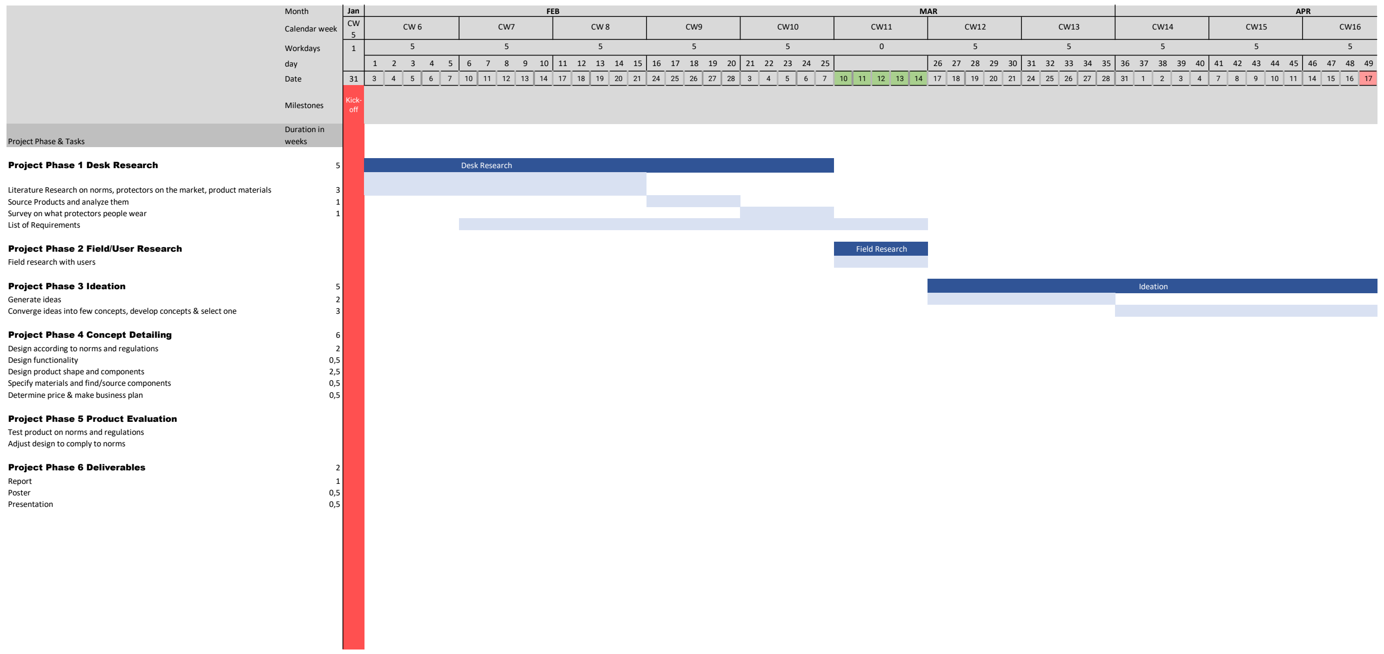
Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

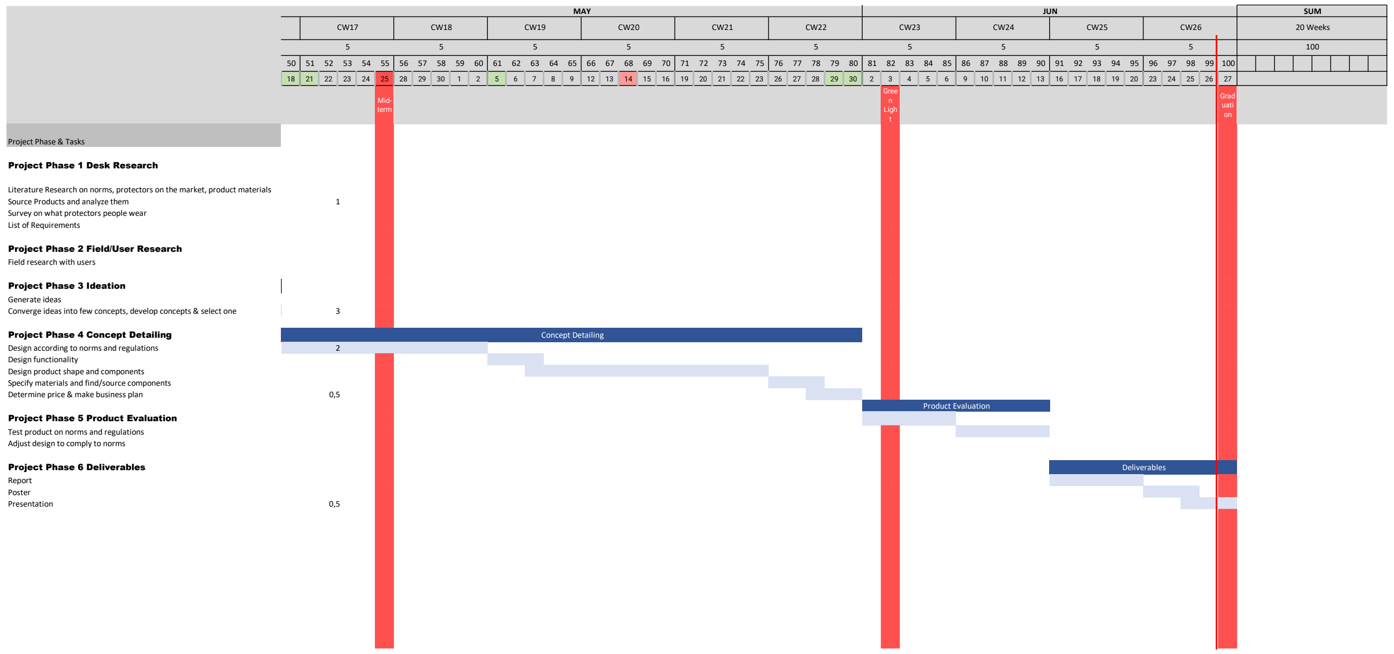
Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

I want to make a winter sport protector which protects the neck and the back, because I myself have a back injury and when I have searched for suitable protectors I have not been able to find a protector which has this function.
During this project I want to develop the following competencies:

1) Comply product to norms and regulations
2) Design for Manufacturing
3) Prototyping (3D modelling, sewing, 3D printing)
4) Making market-ready product

Appendix B
Project Plan





Appendix C
Market Research

	Product Name	Product Image	Manufacturer	Materials Fabric	 Protector	Price [€]	Ceritifcation	Protection type advantage	 disadvantage	Other funcions
	DBCK 500		Dreamscape	12% Elastane 60% Polyamide 28% Polyester	100% Polyurethane	59.99	EU Regulation 2016/425 on PPE tests on shock absorption, impact tests according to EN1621-2 level 1 standard			Attachment of trousers, attachments of crash pants, can be tightened around the waist, material become flexible through body heat
Winter sport	DBCK 100		Dreamscape	Main 13% Elastane 87% Polyamide Back: 100% Polyester Wasitband 100% Polyester	43% Polyvinyl Chloride 27% Ethylene Vinyl Acetate Dry Nitrile Butadiene Rubber	34.99	EU Regulation 2016/425 on PPE tests on shock absorption, impact tests according to EN1621-2 level 1 standard	minor fall or collision shock absorption capacity: average residual force less than 18kN following 50J impact	injury caused by twisting/compression	
	Cairn Proride D30		cairn	60% Polyester 40% Nylon	12,5% PU 12,5% Rubber 75% D3O®	109.99	EN 1621-2 standard			tightening straps under the vest, activated under impact
	Komperdell Pro Vest Light		Komperdell		Cross flex	193.14	EN 1621-2	shock absorption capacity: 5,93kN residual force value		chest and upper body protection (ribs)
	SAFETY VEST Slim-fit Frontzip		Komperdell		Cross flex	289	EN 13158:2018– LEVEL 3	shock absorption capacity: 4kN residual force value		360 all round protection
horse riding	Helite Airshell Vest Outer		Airvest	83% Polyester 14% Elastane 4% Polyurethane	CO2	160	CE certified airbag ALIENOR CERTIFICATION laboratory.	due to not constantly being		Attachment from CO2 canister

Appendix C
Market Research

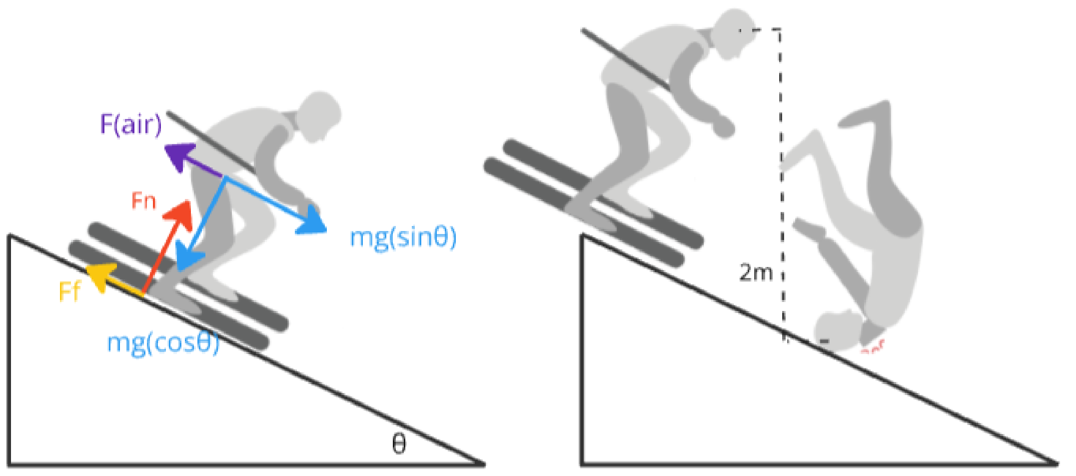
	Helite Zip'In 2 Airbag		Airvest	Polyurethane	CO2	450	[illegible] checks and approves personal protective equipment (PPE) for horse riders.	inflated, it does not restrict freedom of movement, limiting the risk of hyper-flexion	new air canister is needed after one time use	to saddle, when falling from the horse the attachment is stretched and activates the CO2
hockey	Interceptor BIB		aegisi	Stretch Nylon Spandex Body: 100% Micro Polyester Lining: 100% Aramid Cut Resistant Fiber	D3O®		BNQ Certified	shock absorption, cut protection	insert is not washable	
racing	REV Head and Neck Restraints		necksgen		Carbon Fiber Composite		SFI 38.1 certified			
	Bodyprotector voor ruitersport		FOUGANZA	Main fabric: 95% Polyester 5% Polyurethane Net: 100% Polyester	74% Polyurethane 14% Nitrile Butadiene Rubber 9% Polyvinyl Chloride 3% Ethylene Vinyl Acetate	63	EN13158	impact and fall protection		
	Bodyprotector voor ruitersport		WALDHAUSEN	Nylon Polyester	4 layer High density foam	145	EN13158 Niveau 3 BETA standard 3	washable	should be replaced after every severe fall or collision	if the red velcro patches are covered, then its properly adjusted

Appendix C

Market Research

Schouderbeschermers IH 500 kinderen		OROK	Polyester	100% Polyethylene	30	
Dainese D-Air Ski		Dainese				absorbs up to seven times more energy than traditional hardshell protective gear
Workair		Dairlab			760	
		Dainese	Liner in thermoformed polyethylene foam, External polypropylene plates	aluminium Honeycomb frame		

Appendix D
Force Calculation



Given:
height=1,75m m= 75kg Falling height=2m
average skeer speed = 48,2km/h=13,4m/s
g=9,81m/s

Calculation:
According to momentum theory
Ft=mv
t=2s

Force at impact
Ft=mv/t=(75kg)*(13,4m/s)/(0,1s)=10050N=10,05kN (in EN1621-2 the product is tested for 10,5 kN)

Impact Energy
PE=mgh=75kg*9,81*2=1471,5 J (in EN1621-2 the product is tested for 50J)

Appendix E
Biomechanics Consultation with Prof.dr. H.E.J. Veeger

- Find out at what force is there a fracture.
- The material should be deformable, no spring effect.
- Deformation range is the most important.
- Ideally you want to restrict the movement before you reach the maximum range of motion and then have some more deformation.
- Crash test softwares-> SIEMENS, MADYMO, MATLAB
- You know the forces are high, the best way to check is to test with a setup in practice
- It is very unlikely you fall perfectly on your head, I suggest removing the chin padding, the chin can tuck in all the way in
- If you absorb the energy then it will not travel back up in the head
- If the energy is absorbed it can travel back up and you can break the jaw
- Least harmful thing to break if something has to be broken is the clavicle

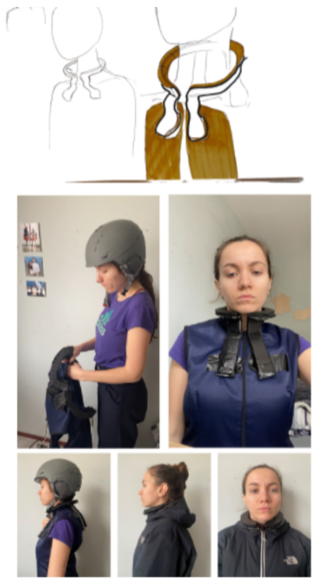
Appendix F
Quick Prototyping

Quick test 1
Goal: Quick prototype to see if sketched idea has potential
Insights:
- Tight neck closure chokes the user.
- If its not tight around the neck then the whole protector moves or the head turns and the protector stays still.
- Foam deforms under the chin when head rotates.
- Foam makes noise from rubbing against the user's head
- Support backward is comfortable.

Take-away:
- More rigid structure that's not touching the neck directly might be a better direction. Allow head rotation, prevent compression.

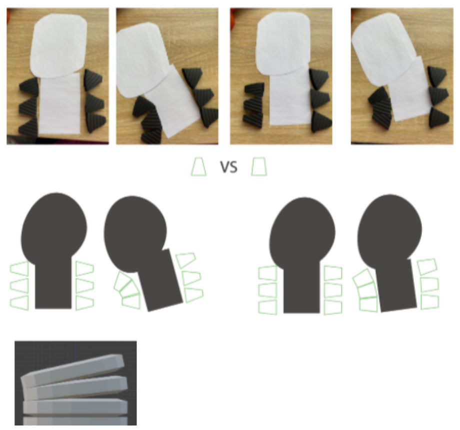
Quick test 2
Goal: Quick prototype to see if sketched idea has potential
Insights:
- Straps pull on vest
- Straps should be integrated in the vest and go under the arms to provide the needed fixation
- Once fully fixated they work well and do not obstruct the vision
Take-away:
- Good direction to restrict head rotation and lateral flexion to allowable range of motion. Some semi-rigid collar might be needed to prevent compression.

Quick test 3
Goal: Quick prototype to see if sketched idea has potential
Insights:
- Upper surface shouldn't be flat but in a cone shape for a more comfortable fit -> flat surface in mottocross braces is due to helmet bottom shape
- The brace in front should be lower.
- Front closure should be adjustable to allow for different neck sizes.
- Protector should not touch the user around the neck and chin area, elsewise it gets annoying.
- Impact transferring piece should be in two pieces and go around the spine. (transfer impact to muscle and not to spine)
Take-away:
- Good direction, would have to figure out connection to the vest and the right material. But its very good that it transfers the impact to trapezius muscle and chest muscles rather than a collar like test 1.
- Inspiration atlas tyke.



Quick test 3.1
Goal: See if cone shape is better than flat
Insights:
- Overall cone shape feels nicer than flat one, only under the chin it should be flat.
- Back support should be directly under hinge.
Take-away:
- Has potential in terms of protection, but bulkiness might be a challenge.

Quick test 4
Insights:
- Likely to stop compression without restricting flexion and rotation.
- les sharp edges of trapezium restrict more the range of motion.
Take-away:
- Interesting direction in terms of cost and effectiveness.



Quick test 4.1
Insights:
- Works as expected.
- There should be more than 2 rows of the trapezium to have a smoother restriction.
- Trapezium could be less bulky.
- Cloth should be a bit stiffer to hold the pieces in place.
- The pressure goes onto the clavicles and it causes discomfort.
- Shape of the top and bottom surface should be a bit different to follow the chin and the body.
Take-away:
- Interesting direction in terms of cost and effectiveness.

Appendix G
Neck Sizing Market Research

brand/standard	Size	Neck Circumference (mm)		Neck Height (mm)				Description of measurement	Origin
		Unisex							
	1	22-48		6					
Brace ID	2	28–49		8				**Neck Height** - edge of your	
	3	28–52		10				chin and the top of your	
	4	28–52		12				sternum	Belgium
		Unisex							
	XS	38		6,4	9			**Neck Circumference**-below	
	S	43		6,4	9			adam's apple and add 5cm to	
Standard Foam Cervical Collar	M	46		6,4	9			measurement for air	
	L	51		6,4	9			ventilation and blood flow	
	XL	56		6,4	9			circulation	
	XXL	61		6,4	9			**Neck Height**-same as brace	UK
		Unisex							
	S	25-33		5,7	8,3	10,8	13,3		
e-life brace	M	33-41		5,7	8,3	10,8	13,3		
	L	41-48		5,7	8,3	10,8	13,3		
	XL	>48		5,7	8,3	10,8	13,3		Taiwan
		Male							
	S	36,5-38,5							
EN13402	M	38,5-40,5						**Neck Circumference**-with	
	L	40,5-42,5						the tape measure passed 2	
	XL	42,5-44,5						cm below the Adam's apple	Europe
		Male	Female						
	XS	36	30,6					**Neck Circumference**-	
	S	37-38	31,6					measured at 2 cm below the	
Dainese	M	39-49	32,6-33,6					Adam's apple in the front, and	
	L	41-42	34,6					at the 7th cervical vertebra in	
	XL	43-44	35,6					the back	Europe

Stifneck is the brace used by the Dutch Ambulance and its an example of medical brace with critical sizing. Unfortunately, there is no exact data on the neck circumference range and height range that the brace can suit. It is designed to be used in urgent scenarios so the measurements are taken very quickly with the hand of the paramedic. There are four increments for height adjustment - No neck, Short, Regular, Tall. Neck circufmerence adjustment is not specified, but there are separate braces for kids and adults. Some adjustment is provided through the use of a strap. (Laerdal Medical, 2016)

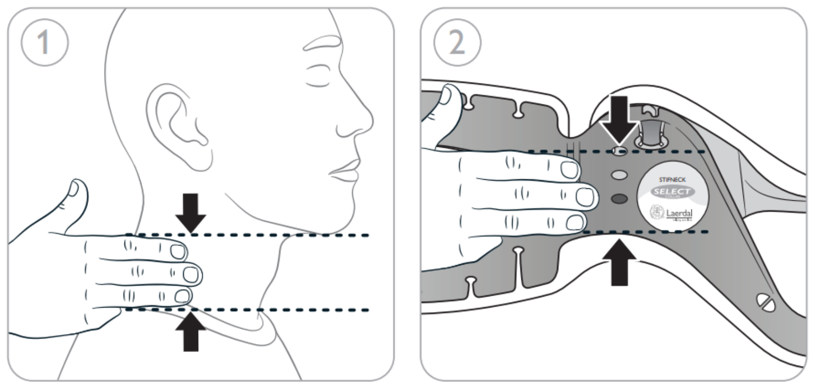


Image Source: Stifneck Select. From *Laerdal*, n.d., https://cdn.laerdal.com/downloads/f6969/dfu_stifneck_select__americas.,

Appendix H
Sizing

Neck Circumference

A starting point of the analysis was the alpha sizing of SPINES for their current back protectors.

SPINES UNISEX SIZING

Size	Stature (mm) Min	Max
XXS	1100	1250
XS	1250	1400
S	1400	1680
M	1680	1780
L	1780	1880
XL	1880	1980

By using the DINED Ceasar 18-66 years old mixed adults database I found out what is the minimum, maximum, average, mean and standard deviation of the weight and NC corresponding to the S, M, L, XL body heights clusters (stature in DINED). Since the database was for adults, there was no sufficient data for sizes smaller than orter than 1400mm).

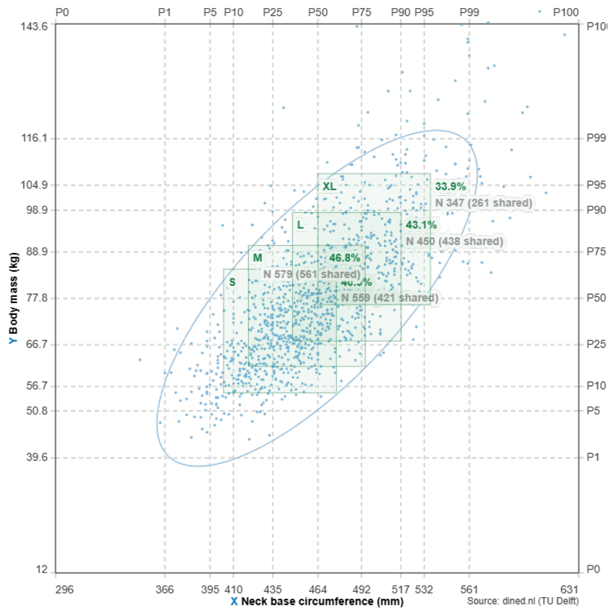
Size	Weight (kg) Min	Max	Median	Average	SD
XXS					
XS					
S					
M	37,3	143	67	70	14,8
L	49	130	73,5	76	14,5
XL	55,8	143,9	80,3	83	15,4
	64,4	149,7	90	92	15,7

Important to note, there were no major differences between the median and the average. Next, I did the same correlation for the alpha sizes and the neck ci nce.

Size	Neck Base Circumference Range (mm) Min	Max	Median	Average	SD
XXS					
XS					
S					
M	350	587	434,0	439,7	36,1
L	372	610	451,0	456,9	37,4
XL	404	600	481,0	482,5	34,8
	430	612	499,0	500,0	36,0

Table 4. Spines Unisex Sizing System & NC

These two tables helped me to relate body weight and NC to unisex alpha sizing of SPINES. Figure 50 shows how body weight and NC relates linerally to each other. To determine the range of the S, M, L, XL size of the body weight and the NC the SD of each parameter was used.



The limitation with Spines' uniform XS and XXS sizes is that they were made for children and the DINED data base for children does not include neck base circumference. Nevertheless, to accommodate smaller neck sizes I decided to use the same Ceasar 18-66 mixed adult data base and use the assumption that XS size represents 0-5th percentile of the population, S size 5-25th percentile, M size 25-50th percentile, L size 50-75th percentile and XL 75-95. By using this approach I got very similar neck base circumference as to using the Spines alpha sizing and height ranges. This is visible in the average results in the table below and the average results in table 5. The biggest difference is by size XL - 12mm. This shows that the percentile assumption gives fairly accurate results and it could be used for defining size XS for adult necks which is 350-388mm.

Percentile		Size	Neck base circumference (mm) Min	Max	Average
0	5	**XS**	350	388	369
5	25	**S**	395	495	445
25	50	**M**	435	464	449,5
50	75	**L**	464	492	478
75	95	**XL**	492	532	512

Lateral neck length was not included in the analysis, because there is not enough data and it will be taken in account whilst modelling the protector in CAD based on mannequins created with the measurements from the neck base circumference, weight and body height.

Neck Height

The same database Ceasar 18-66 years old mixed adults was used for the neck height analysis. However, this measurement was not available directly through the DINED tool, but as an excel file (Dutch_Measurements_3D Measurements) from the repository on which DINED is based. Additionally, neck height was not measured for all the subjects in this Ceasar database. Nevertheless, there were 1145/ 1267 subjects, ,whose neck heights were measured and which data I used for the analysis. In contrast to neck circumference, where there was a correlation to body mass, the neck height is linerally correlated to stature (Mahajan et. al, 1994). By using again Spines alpha sizing and stature clusters, I found out what is the minimum, maximum, average and SD of the neck height for those clusters.

Size	Neck Ht Range (mm) Min	Max	Median	Average	SD
XXS					
XS					
S	49,8	150,4	98,3	97,8	18,6
M	43,3	163,0	107,0	108,1	20,9
L	69,5	170,2	118,1	117,2	18,7
XL	70,9	176,9	124,3	124,8	20,9

With this data and the stature information from the database I could create an ellipse similar to the neck base circumference and body mass ellipse to see the relation between neck height, stature and Spines alpha sizing. This ellipse was not available in DINED and it was created manually, based on the information from Ceasar 18-66 years old mixed adults database excel sheet (Dutch_ Measurements_3D Measurements) .

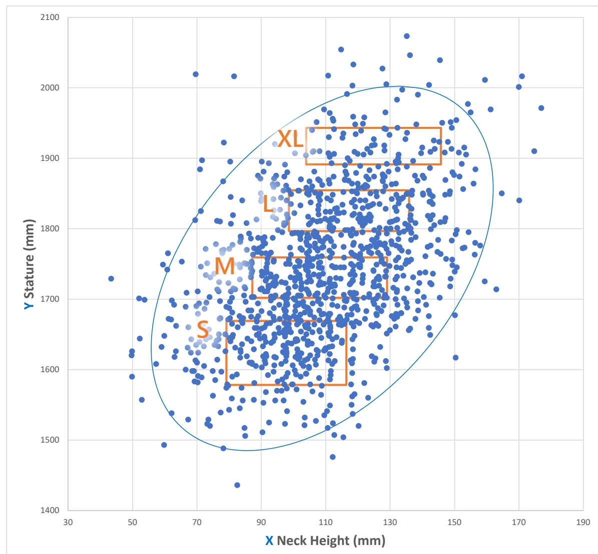


Figure 51. Neck Height and Stature

Table below represents the summarized findings from the neck base circumference, body weight, stature and neck height and how they correspond to Spines unisex alpha sizing.

SPINES UNISEX SIZING

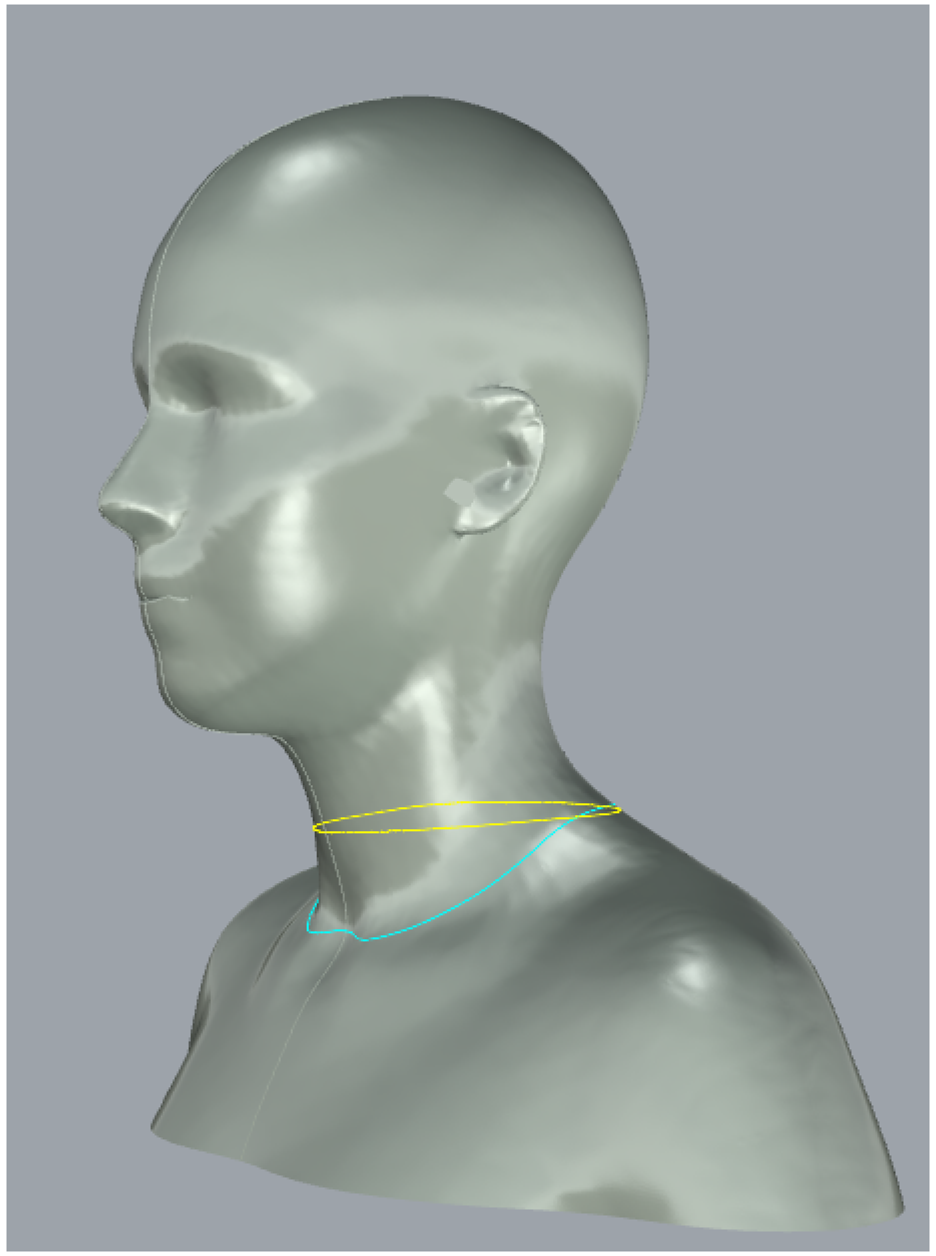
Size	Stature (mm) Min	Max	Median	Average	SD	Weight (kg) Min	Max	Median	Average	SD	Neck Base Circumference Range (mm) Min	Max	Median	Average	SD	Neck Ht Range (mm) Min	Max	Median	Average	SD
XXS	1100	1250																		
XS	1250	1400									350	388	369							
S	1400	1680	1633	1624	45,4	37,3	143	67	70	14,8	350	587	434,0	439,7	36,1	49,8	150,4	98,3	97,8	18,6
M	1680	1780	1730	1731	28,6	49	130	73,5	76	14,5	372	610	451,0	456,9	37,4	43,3	163,0	107,0	108,1	20,9
L	1780	1880	1822	1826	29,0	55,8	143,9	80,3	83	15,4	404	600	481,0	482,5	34,8	69,5	170,2	118,1	117,2	18,7
XL	1880	1980	1910	1917	25,8	64,4	149,7	90	92	15,7	430	612	499,0	500,0	36,0	70,9	176,9	124,3	124,8	20,9

Excel Document with all Data

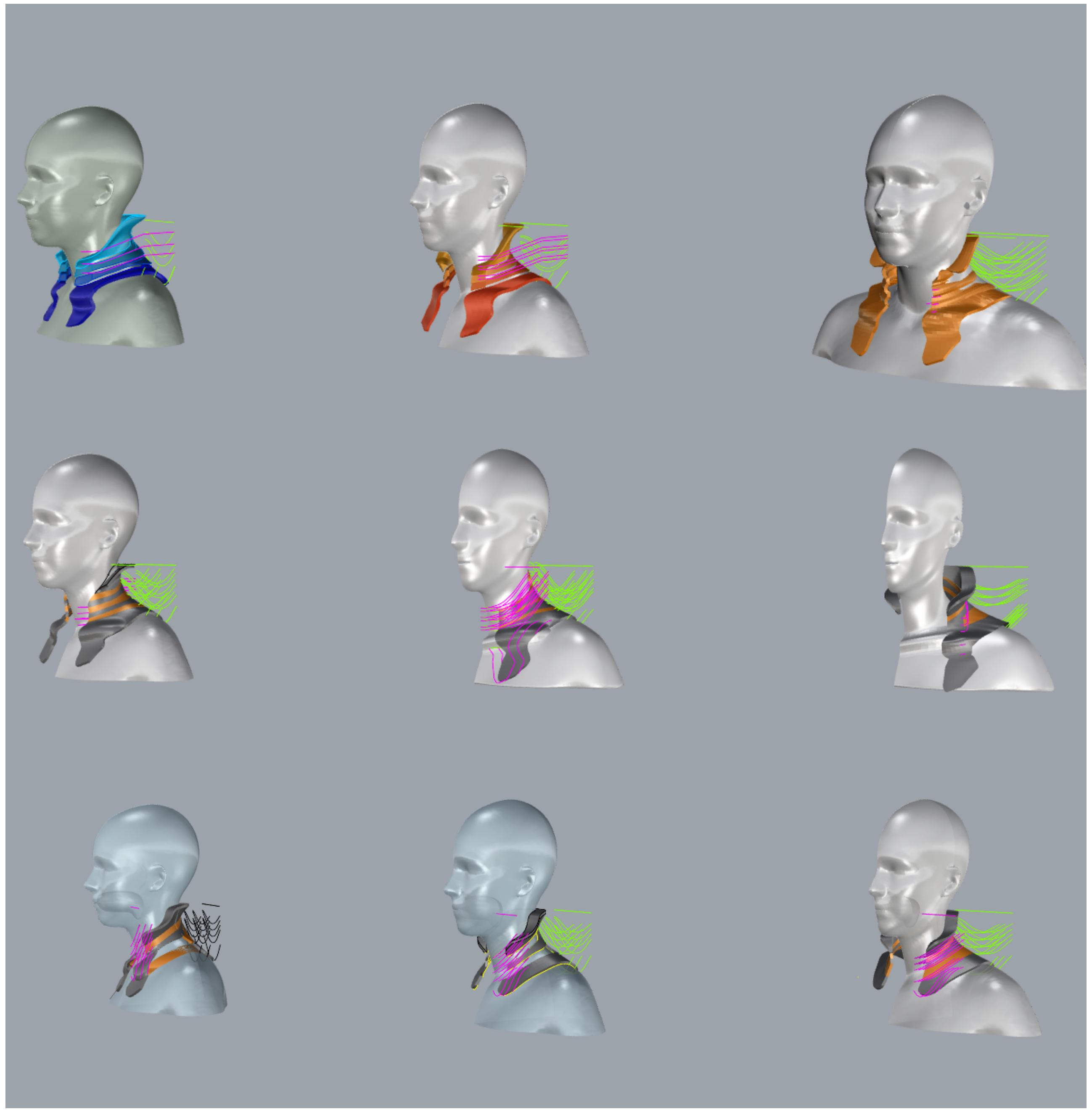
https://docs.google.com/spreadsheets/d/1SYHfc7TAJqHJvHqtcXDg6JddwgMZpJkU/

Appendix I
Neck Circumferences

DINED female mannequin used for creation of prototype. Parameters used for creation of the mannequin were weight-58kg and height-1680mm.
In yellow horizontal neck circufmerence -370mm.
in blue neck base circumference-400mm.



Appendix J
Prototype Iterations



Appendix K
Consent Form

You are being invited to participate in a research study titled Neck Protector for Winter Sports. This study is being done by Iva Hristova from the TU Delft in collaboration with SPINES.

The purpose of this research study is to see how people perceive the comfort, safety and looks of a neck protector developed for winter sports during a Master's Thesis. This will take you approximately 20 minutes to complete. The data will be used for evaluation of the design, re-designing of the product, argumentation for design choices and it will be included in the final report of the Master's Thesis. We will be asking you to **share your height, weight, size, neck circumference & height, wear the product for 5 minutes and answer 12 questions related to the product**.

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by **keeping the survey anonymous**.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions.

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated [ ], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: [*see points below*]	☐	☐
• *Wearing a product which is under development* • *Completing a survey* • *Having pictures taken, where my face is not identifiable*		
4. I understand that I will be compensated for my participation by […]	☐	☐
A chocolate		
5. I understand that the study will end […]		
in 20 minutes		
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the following risks […]. I understand that these will be mitigated by […]	☐	☐
• *physical discomfort from wearing a product which is under development, which will be mitigated by the product having a fabric cover for comfort*		
7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) […] and associated personally identifiable research data (PIRD) […] with the potential risk of my identity being revealed […]	☐	☐
• *Height, weight, clothing size, neck circumference and height*		
8. I understand that some of this PIRD is considered as sensitive data within GDPR legislation, specifically [*see points below*]	☐	☐
List the relevant issues: eg: • *religion, political views* • *Data concerning criminal activities will/may be collected and processed* • *Research has a Data Processing Impact Assessment (DPIA) in place*		
9. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach […]	☐	☐
• *anonymous data collection*		
10. I understand that personal information collected about me that can identify me, such as [*e.g. my name or where I live*], will not be shared.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
11. I understand that after the research study the de-identified information I provide will be used for [*see points below*]	☐	☐
• *design development* • *Thesis final report*		
12. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
13. I give permission for the de-identified [*photos, body height, weight, neck circumference and height*] that I provide to be archived in [*TU Delft Graduation report repository*] so it can be used for future research and learning.	☐	☒
14. *If relevant please add:* I understand that access to this repository is [*open*]	☐	☐

Signatures

______________________ ______________________ ________

Name of participant [printed] Signature Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

______________________ ______________________ ________

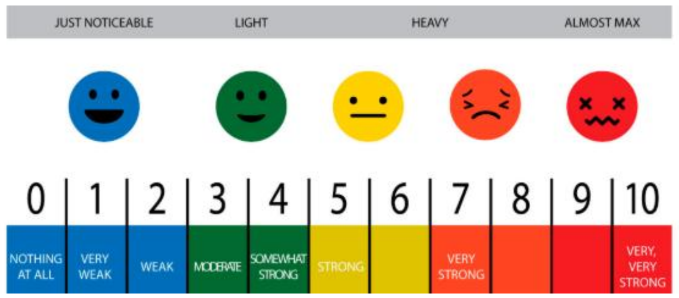
Researcher name [printed] Signature Date

Study contact details for further information: [*Name, phone number, email address*]

Appendix L
User Survey

Neck Protector for Winter Sport

Participant:
Age:
Height:
Weight:
Clothing size:
Neck circumference:
Neck height:



Question 1:

	0	1	2	3	4	5	6	7	8	9	10	
no restriction at all	○	○	○	○	○	○	○	○	○	○	○	very very strong restriction

Question 2:

	0	1	2	3	4	5	6	7	8	9	10	
no pressure at all	○	○	○	○	○	○	○	○	○	○	○	very very strong pressure

Question 3:

	0	1	2	3	4	5	6	7	8	9	10	
perfect fit	○	○	○	○	○	○	○	○	○	○	○	very very bad fit

Question 4:

	0	1	2	3	4	5	6	7	8	9	10	
no discomfort at all	○	○	○	○	○	○	○	○	○	○	○	very very uncomfortable (too warm, too cold))

How would you describe the product?

Question 5:

	1	2	3	4	5	6	7	
Attractive	○	○	○	○	○	○	○	Unattractive

Question 6:

	1	2	3	4	5	6	7	
Slim	○	○	○	○	○	○	○	Bulky

Question 7:

	1	2	3	4	5	6	7	
Modern	○	○	○	○	○	○	○	Old-fashioned

Question 8:

	1	2	3	4	5	6	7	
Sporty	○	○	○	○	○	○	○	Assistive

Question 9:

	1	2	3	4	5	6	7	
Safe	○	○	○	○	○	○	○	Unsafe

Question 10:

What do you like most about the look or feel?

____

Question 11:

What would you change?

____

Question 12:

Does anything stand out as particularly good or bad?

____

Appendix M
User Survey Answers

Participant	Gender	Age	Height (mm)	Weight (kg)	Clothing Size	Horizontal Neck circumference (mm)	Neck height (mm)	Mobility restriction	Pressure on neck	Thermal comfort	Attractive-Unattractive	Slim-Bulky	Modern-Old-fashioned	Sporty-Assistive	Safe-Unsafe	What do you like most?	What would you change?	Particularly good/bad?
1			1630	60	S	350	130	3 Weak	6 Strong	0 no discomfort	2 Attractive	3 Slim	2 Modern	2 Sporty	2 Safe	feels really comfy around the sides & back	Pressure points in the front	good:the look bad: too much science fictiony
2			1730	70	M/L	370	140	4 Somewh	7 Very strong	3 moderate	2 Attractive	5 Bulky	2 Modern	4 Neutral	2 Safe	its a bit flexible and it looks cool because its not fully closed	no pressure on my throat	bad: the pressure on my throat
3			1730	62	S/M	370	150	6 Strong	7 Very strong	0 no discomfort	3 Attractive	5 Bulky	2 Modern	2 Sporty	1 Safe	It feels sturdy and smooth, looks like a proper safety product	its not very fashionable, better sizing and alignment with the helmet	has a similar look as other protective clothing and therefore feels trustworthy, its immediately reconisible as such
4			2020	89	XL	400	170	3 Moderat	5 Strong	2 Weak	6 Unattractive	5 Bulky	2 Modern	6 Assistive	1 Safe	It makes you feel robust/safe	make it closeable/movement at the back of the head	the fit was very comfy;its not super big
5			1700	61	M/L	350	160	7 Very stro	7 Very strong	4 Somewhat stror	2 Attractive	5 Bulky	0 Modern	3 Sporty	2 Safe	looks really cool and fashionable	the front of the protector is a little bit tight	difficult to turn back when wearing the helmet and the neck protector
6			1600	50	S	320	160	2 Very wea	2 Very weak	3 Moderate	2 Attractive	4 Neutral	0 Modern	3 Sporty	2 Safe	looks cool	make it tighter	-
7			1800	63	M	350	140	7 Very stro	7 Very strong	4 Somewhat stror	3 Attractive	3 Slim	0 Modern	2 Sporty	3 Safe	Cloth on inside and padding	less tight, more padding	Good: Could protect neck, Bad: Could restrict movement/breathing
8			1580	52	XS	320	135	3 Moderat	2 Very weak	1 Very weak	2 Attractive	5 Bulky	2 Modern	4 Neutral	2 Safe	gives a secure feeling, i like the exoskeleton look	the back edge so it doesnt clash with the helmet	-
9			1730	83	M/L	410	160	6 Strong	6 Strong	3 Moderate	6 Unattractive	3 Slim	0 Modern	4 Neutral	2 Safe	Yes, except the back which I associate with a medical supportive product (spine)	The front points.	I like the idea in general. The attachments would make it feel even safer.
10			1910	90	XL	440	160	6 Strong	8 Very strong	1 Very weak	2 Attractive	4 Neutral	2 Modern	5 Assistive	4 Neutral	the ribs/joints	make it bigger	the spikes in the middle at the back the foam is also very comfortable, tightness is bad
								5 Strong	6 Strong	2 Weak	3 Attractive	4 Neutral	1 Modern	4 Neutral	2 Safe			

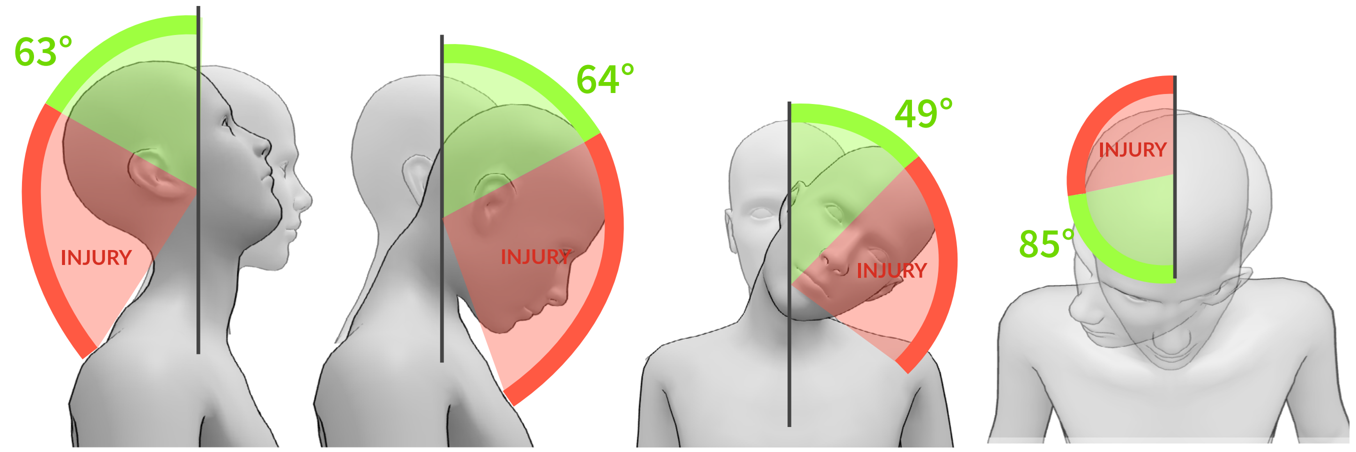
Appendix N
User Test Pictures

Front pressure points:

Helmet adjustment system pressure:

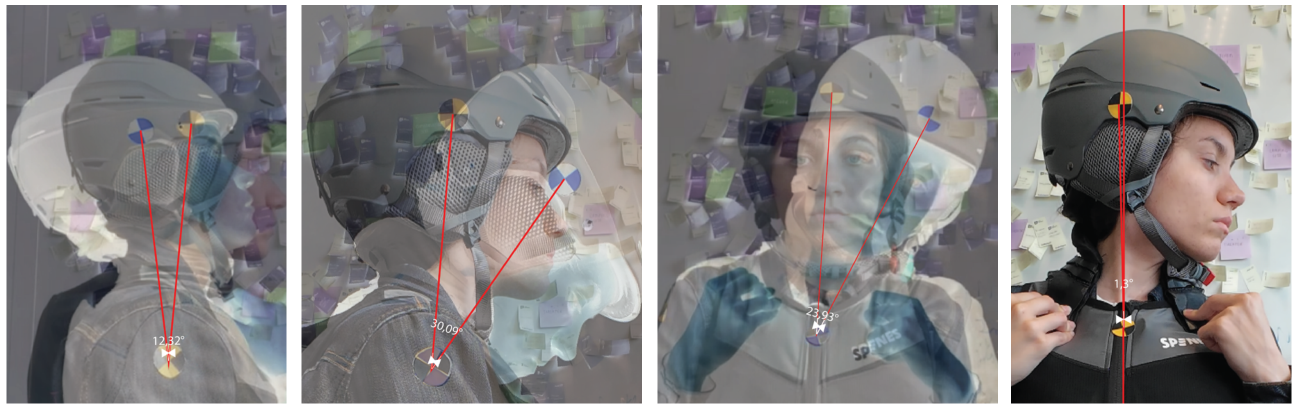
Mobility restriction, helmet ear against collar:

Appendix O
Neck ROM with Prototype



Without protector:

With protector:



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