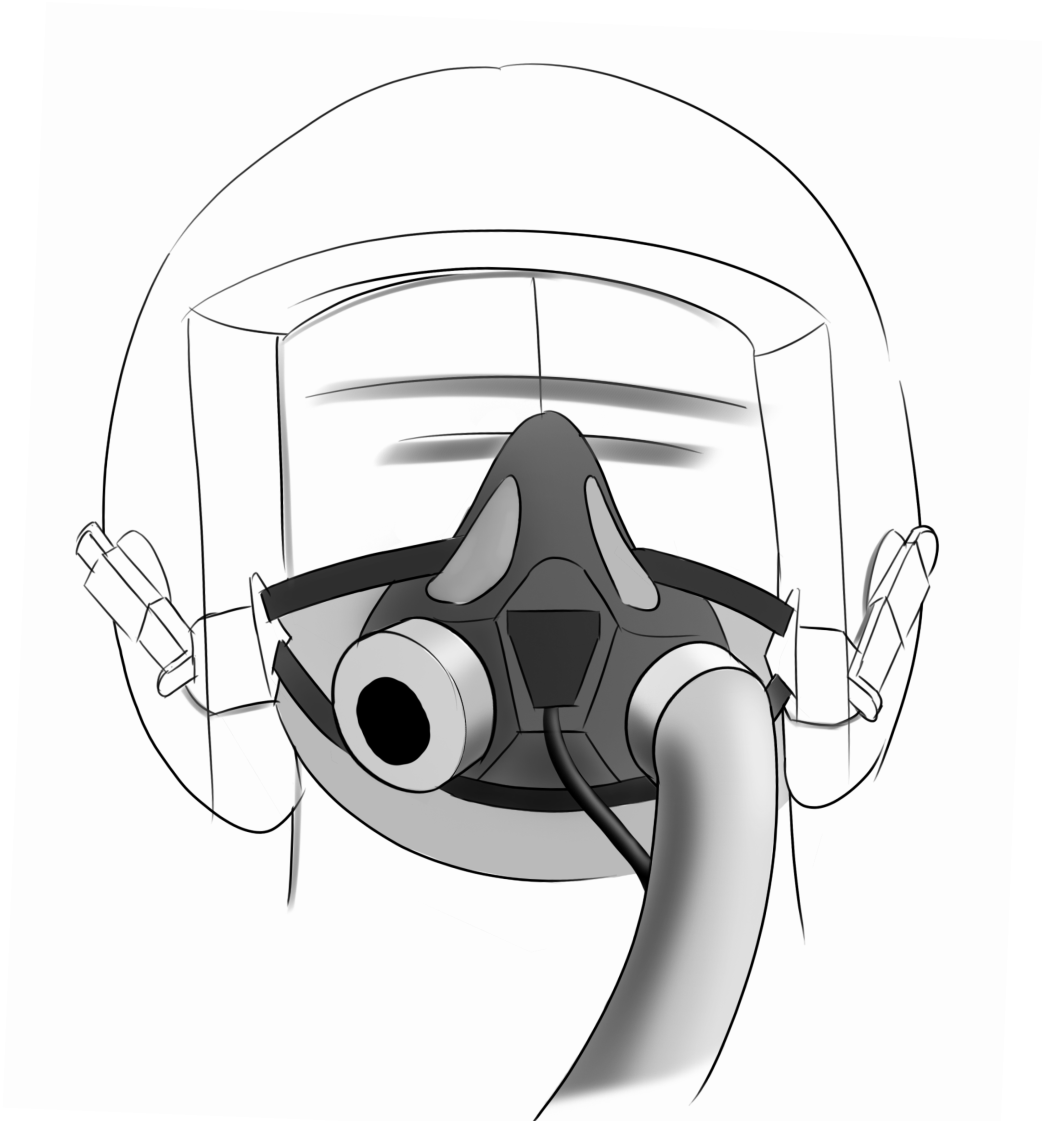
Ergonomic redesign of oxygen masks for fast jet pilots

A case study for the Royal Netherlands Air Force



MASTER THESIS

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Ergonomic redesign of oxygen masks for fast jet pilots

A case study for the Royal Netherlands Air Force

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TU Delft

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Glossary

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ACM- Air combat manoeuvre

BFM- basic fighting manoeuvre

CMA – Centre for Man in Aviation (Nederlands: CML - Centrum voor Mens in Luchtvaart)

DFS – Dutch Female Subset

DMS – Dutch Male Subset

DTS – Dutch Target group Subset

HCD – Human-centered design

HMD – helmet mounted display

Hypoxia- low levels of oxygen in bodily tissues

Nasal root – beginning of the nose from the face between the eyes

MBU- Mask Breathing Unit

NVG – Night Vision Goggles

PDT – Pressure Discomfort Threshold

RNLAF – Royal Netherlands Air Force (Nederlands: Koninklijke Luchtmacht)

STT – Soft Tissue Thickness

UMP – USAF Male Personnel

USAF – United States Air Force

Valsalva – clearing the pressure difference in the ear canal by pinching the nose and exhaling through the nose.

VUT – Vlieger Uitrusting Technicus

Zygomatic region – cheekbone

Summary

Summary

This design study aims to reduce the discomfort and facial trauma seen with the use of the MBU-20/P oxygen mask for fighter pilots of the Royal Netherlands Air Force. To achieve this, the following research questions are answered:

- Are the reported issues with F-16 pilot oxygen mask usage still present with current F-35 fighter pilots?
- Are there differences in facial features between Dutch and American fighter pilots and does this influence the fit?
- Is it possible to design a better fitting mask with digital fabrication tools?

The current shape of the oxygen mask is based on anthropometric research on American male fighter pilots from 1967. Since the introduction of the current oxygen mask used by the Royal Netherlands Air Force in the 1990's, the design has not changed. No anthropometric research has been conducted on how this mask shape fits European or Dutch male and female pilots.

To answer the research questions, various methods were used. Semi-structured interviews and questionnaires were conducted with F-35 pilots to identify their issues. Anthropometric research was conducted to analyze facial differences in Dutch and American fighter pilots. A virtual fit analysis algorithm was created to better understand the relationship between mask shape, facial features and discomfort. Based on these analyses a new oxygen mask design was proposed using digital fabrication techniques and the design was evaluated in flight like conditions.

The results of the study showed that current F-35 pilots still experience discomfort and, in some cases, facial trauma from using the oxygen mask. The greatest discomfort was experienced on the nasal root, which is in line with literature. High G-forces and prolonged time of wearing the mask increased this discomfort, leading to adverse behavior and possible unsafe situations.

Significant differences in facial features were found between Dutch fighter pilots and the American fighter pilots, on which the design is based. The current sizing system of the oxygen mask does not cover the Dutch fighter pilot population properly. The differences facial features and improper sizing system were considered to be a main contributor of the discomfort experienced by Dutch fighter pilots.

The virtual fit analysis showed how the current design's shape does not fit the facial features of Dutch fighter pilots well. By considering the pressure discomfort threshold and soft tissue thickness, better insights were generated on the fit and associated discomfort of oxygen masks.

The virtual fit analysis was used together with a parametric model to quickly and iteratively redesign the oxygen mask, based on anthropometric data. These models enabled the creation of redesigns which are better suited for the facial features of Dutch fighter pilots.

The redesign was evaluated through physical evaluation, production cost estimation and a reflection on requirements and wishes. The physical evaluation showed a significant decrease in pressure at the nasal root, an overall reduced pressure on the face, an improved pressure distribution and increased comfort of the redesign.

The redesign showed more stability and less shifting of the mask during high G-forces, indicating a better fit for Dutch fighter pilots. However, an increase in discomfort was observed at the chin, which could not be explained by the physical evaluation.
All requirements in scope of the project were met and most wishes were satisfied. The redesign shows it is a viable alternative for the Royal Netherlands Air Force.

In conclusion, this design project demonstrated the potential of designing better fitting and more comfortable oxygen masks for the Royal Netherlands Air Force, using anthropometric methods and digital fabrication tools.

Further research with more participants is needed to evaluate the redesign and identify additional issues that need to be resolved in future oxygen mask designs. This research will help to further validate the desirability, feasibility and viability of the proposed redesign.

Samenvatting

Samenvatting

Dit ontwerpproject heeft als doel het verminderen van discomfort en trauma in het gezicht van straaljagerpiloten van de Koninklijke Luchtmacht, tijdens het gebruik van het MBU-20/P zuurstofmasker. Om dit te bereiken worden de volgende onderzoeksvragen beantwoord:

- Zijn de gerapporteerde problemen met het zuurstofmaskergebruik van F-16 piloten nog steeds aanwezig bij huidige F-35 piloten?
- Zijn er verschillen in gezichtsmaten tussen Nederlandse en Amerikaanse straaljager piloten en heeft dit invloed op de pasvorm?
- Is het mogelijk om een beter passend masker te ontwerpen met digitale fabricagemiddelen?

De huidige vorm van het zuurstofmasker is gebaseerd op een antropometrisch onderzoek naar Amerikaanse mannelijke piloten uit 1967. Sinds de introductie van het huidige masker bij de Koninklijke Luchtmacht in 1990, is het ontwerp niet veranderd. Er is geen antropometrisch onderzoek gedaan naar hoe de vorm van het zuurstofmasker past bij Europese of Nederlandse mannelijke en vrouwelijke straaljagerpiloten.

Om de onderzoeksvragen te beantwoorden zijn verschillende methoden gebruikt. Er zijn semigestructureerde interviews en vragenlijsten afgenomen bij F-35 piloten, om hun problemen met het zuurstofmasker in kaart te brengen. Antropometrisch onderzoek werd uitgevoerd om verschillen in gezichtsmaten tussen Nederlandse en Amerikaanse straaljagerpiloten te analyseren. Een algoritme is gemaakt voor een digitale pasvormanalyse, om de relatie tussen maskervorm, gezichtsvorm en discomfort beter te begrijpen.

Op basis van deze analyses werd een nieuw zuurstofmaskerontwerp gemaakt met behulp van digitale fabricagemiddelen. Dit ontwerp werd geëvalueerd in vluchtachtige omstandigheden.

De resultaten van het onderzoek toonden aan dat de huidige F-35 piloten nog steeds discomfort en, in sommige gevallen, trauma in het gezicht ervaren bij het gebruik van het zuurstofmasker. De hoogste discomfort werd ervaren op de neuswortel, wat overeenkomt met de literatuur.

Hoge G-krachten en het langdurig dragen van het zuurstofmasker verhoogden de discomfort, wat leidde tot ongewenst gedrag en mogelijk onveilige situaties.
Er werden significante verschillen in gezichtsmaten gevonden tussen de Nederlandse piloten en de Amerikaanse piloten, waarop het zuurstofmaskerontwerp is gebaseerd.

Het huidige maatsysteem van het zuurstofmasker dekt de Nederlandse populatie van straaljagerpiloten niet goed. De verschillen in gezichtsmaten en het onjuiste maatsysteem werden beschouwd als een belangrijke oorzaak van de discomfort die wordt ervaren door Nederlandse straaljagerpiloten.

De digitale pasvormanalyse liet zien dat de vorm van het huidige ontwerp niet goed past bij de gezichtsmaten van Nederlandse straaljagerpiloten. Door rekening te houden met de druk discomfort drempel en zacht weefsel dikte werd een beter inzicht verkregen in hoe de pasvorm van het masker zich verhoud met de bijbehorende discomfort van het zuurstofmasker.

De digitale pasvormanalyse werd samen met een parametrisch model gebruikt om het zuurstofmasker snel en iteratief te herontwerpen op basis van antropometrische gegevens.
Met deze modellen konden herontwerpen worden gemaakt die beter passen op de gezichtsvormen van Nederlandse straaljagerpiloten.

Het herontwerp werd geëvalueerd door middel van een fysieke evaluatie, productiekosten inschatting en een reflectie op eisen en wensen. De fysieke evaluatie toonde een significante afname van druk bij de neuswortel, een algehele afnamen van de druk op het gezicht, een verbeterede drukverdeling en een verhoogd comfort van het herontwerp.

Het herontwerp toonde meer stabiliteit en minder verschuivingen van het zuurstofmasker tijdens hoge G-krachten, wat duidt op een beter pasvorm voor Nederlandse straaljagerpiloten. Er werd echter wel een toename in discomfort bij de kin waargenomen, wat niet verklaard kon worden door de fysieke evaluatie.
Aan alle eisen binnen de scope van het project is voldaan en de meeste wensen zijn behaald. Het herontwerp toont aan dat het een haalbaar kan zijn voor de Koninklijke Luchtmacht.

Concluderend heeft dit ontwerpproject aangetoond dat het mogelijk is om beter passende en comfortabelere zuurstofmaskers te ontwerpen voor de Koninklijke Luchtmacht, met behulp van antropometrische methoden en digitale fabricagemiddelen.

Verder onderzoek, met meer deelnemers, is nodig om het herontwerp te evalueren en bijkomende problemen te identificeren die moeten worden opgelost in toekomstige zuurstofmaskerontwerpen. Dit onderzoek zal helpen om de wenselijkheid, haalbaarheid en uitvoerbaarheid van het voorgestelde herontwerp verder te valideren.

Chapter 1

Introduction

1 Introduction

1.1 Introduction

The Royal Netherlands Air Force (RNLAF) uses several types of fixed wing aircrafts. These fixed wing aircrafts include the F-16 and F-35 fighter jets. To safely operate such fighter jets, oxygen masks are required when flying above 8.000 to 10.000 feet, or 2.4 to 3 km (American Lung Association, 2022). Oxygen masks are used to breath oxygen normally at higher altitudes, but also in case of cabin pressure loss to prevent hypoxia and loss of consciousness (Schreinemakers, 2014). The oxygen mask is therefore seen as one of the most important parts of the aircrew life support system (Carey, n.d.).

However, the oxygen masks currently in use raise safety and health concerns. Pilots experience varying levels of discomfort while wearing the mask, leading to adverse use of the oxygen masks to decrease the discomfort. They can also cause (soft) tissue trauma in the face, varying from irritated skin (erythema) or small wounds (stage two pressure ulcers) to non-cancerous bone tumours (exostoses) in the nose, due to the pressure of the mask on the face. In extreme cases, this extra bone tissue has to be surgically removed for the pilot to experience less discomfort and pain to continue flying (Schreinemakers, 2014). A tight seal between the oxygen mask and the face of the pilot is required to prevent oxygen leakage. It is suspected that the problems are caused by a mismatch between the shape of the oxygen mask and the facial features of pilots (Schreinemakers, 2014), increasing pressure on the face.

The current shape is based on anthropometric research of male United States Air Force pilots from 1967 (Churchill et al., 1977). The design of the mask was evaluated for American male and female pilots in 1997, however, no design changes were proposed as the mask fit was seen as adequate. Since the introduction of the current masks in the 1990s for the RNLAF, the design has not changed and no anthropometric research has been conducted previously on how this mask shape fits European or Dutch male and female pilots.

This design project aims to investigate the influence of facial anthropometry on the fit and discomfort of the current oxygen mask with the ultimate goal of decreasing the discomfort and facial trauma seen in fighter pilots of the RNLAF, by answering the following research questions:

- Are the reported issues with F-16 pilot oxygen mask usage still present with current F-35 fighter pilots?
- Are there differences in facial features between Dutch and American fighter pilots and does this influence the fit?
- Is it possible to design a better fitting mask with digital fabrication tools?

1.2 Methods and structure

To design a solution for a problem it is important to (fully) understand and identify this problem to come to the solution. When designing a new product, the desirability, viability and feasibility of the proposed solution are important to keep in mind, Figure 1

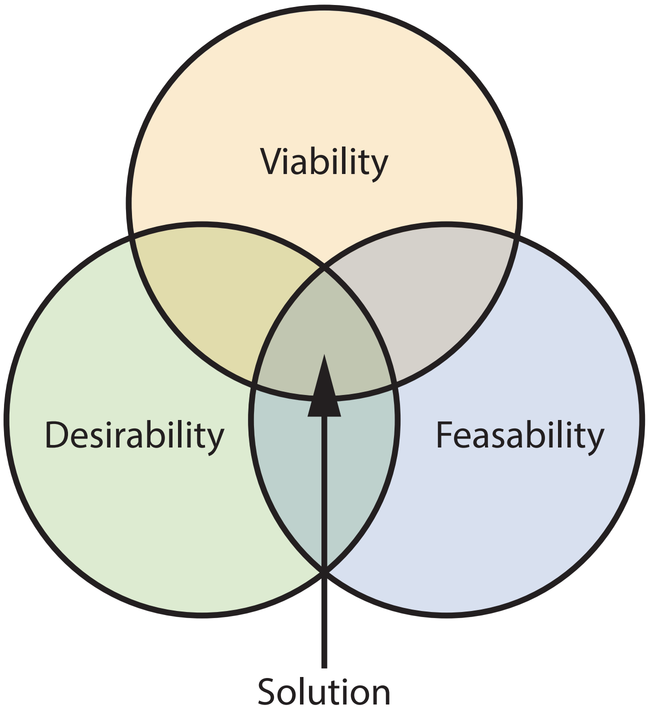


Figure 1: *Desirability, Viability and Feasibility of a design solution*

- Desirability refers to if the product meets the needs and desires of the users.
- Viability refers to if the product is financially sustainable.
- Feasibility refers to if the product is technically feasible.

If all three aspects are considered, it is more likely that the proposed solution can be implemented.

To answer the research questions various methods were used during the design project. A human-centred design (HCD) approach was used for the design process and can be broken down into 4 distinct steps (International Organisation for Standardization, 2019):

- Step 1 is to understand and specifzy the context of use.
- Step 2 is to specify the user requirements.
- Step 3 is to produce design solutions.
- Step 4 is to evaluate the design with users.

Figure 2 shows the redesign process, the HCD steps and what the role of the research questions was in this process.

Chapter 2 describes the literature and background research used to create a basic understanding of earlier reported problems with fighter pilot oxygen masks and how the design changed over time.

Chapter 3 describes the semi-structured interviews and questionnaires about product interactions and discomfort used to research if the reported issues with F-16 pilot oxygen mask usage were still present, or to what extent, in current F-35 pilots. The semi structured interview focussed on 4 topics and the questionnaire contained Likert scale questions to understand product behaviour and questions about the pilot anthropometry.

Chapter 4 describes how the differences in facial features of Dutch and American fighter pilots were researched and how these facial features influence the fit. First a statistical database with facial measurements representing the Dutch fighter pilot population was created. Afterwards the current sizing system could be analysed with this database. Afterwards a selection of important facial measurements was used to research facial differences in Dutch and American fighter pilots. Foam milled faces were used to investigate oxygen mask deformation with varying facial features in Dutch fighter pilots. Lastly, a virtual fit analysis algorithm was created to simulate static fitting of the mask, to better understand how the shape of the oxygen mask and facial features interact with each other.

Chapter 5 describes how all the findings with importance to the redesign resulted in a framework with requirements and wishes.

Chapter 6 describes how the redesign framework and the virtual fit analysis algorithm for an iterative design approach was used to quickly develop better performing redesigns. When a possible better redesign was found, the design was further developed into a physical prototype.

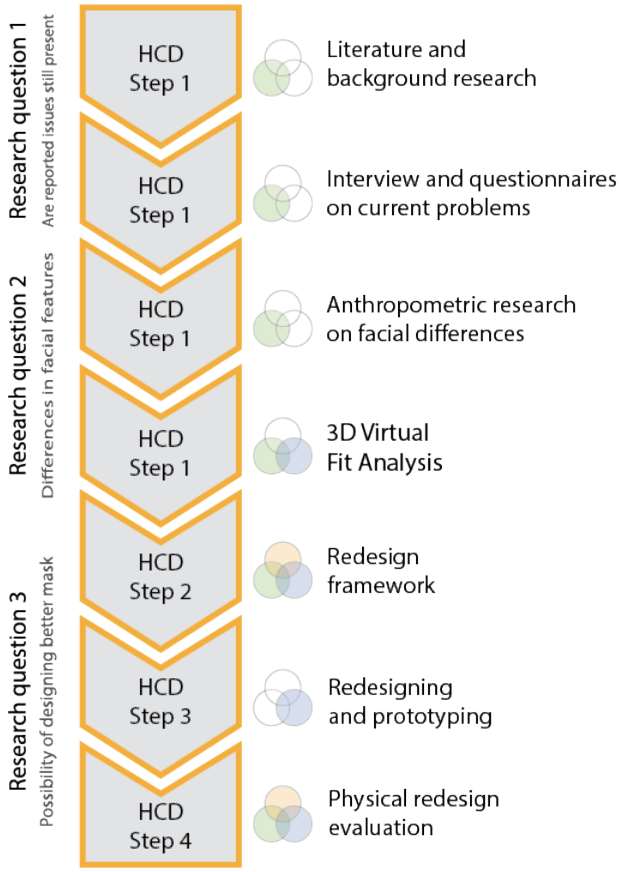


Figure 2: *Redesign process and methods used*

Chapter 6 describes how the redesign framework and the virtual fit analysis algorithm for an iterative design approach was used to quickly develop better performing redesigns. When a possible better redesign was found, the design was further developed into a physical prototype.

Chapter 7 describes how the final design was evaluated with F-35 pilots in flight-like conditions, to asses if previously identified problems were mitigated. In a balanced research the new design was tested against the original design. The pilots had to perform certain communication tasks, freedom of head movement tasks and a dynamic test in the human centrifuge to evaluate the masks, afterwards a questionnaire with Likert scale questions was filled in.
Pressure distribution and pressure hotspots on the fighter pilots' faces were measured with specialized pressure-measuring film.

As described in Figure 1, the first step of the redesign process is to do literature and background research.

Chapter 2

Military oxygen masks

2 Military oxygen masks

A brief history of the product development is given to understand previous problems. First the product and the instability of the product system are described. After which an overview of known facial trauma and discomfort is given. This information is important to keep in mind when redesigning.

2.1 The product

The oxygen masks currently in use by the RNLAF are from the Mask Breathing Unit (MBU) family and of the type MBU-20/P (F-16) and MBU-23/P (F-35), by American manufacturer Gentex Corporation. The main components of the two masks are the same and can be seen in Figure 3.

The facepiece is a silicone rubber part which is pressed into the face of the pilot. The facepiece is held in place by the hardshell. The microphone, in- and outlet valves are attached through the hardshell to the facepiece. The oxygen supply hose is connected to the inlet valve. The bayonets are attached to the hardshell via straps, which can be adjusted when fitting the mask to the pilot. The whole mask assembly is attached to the helmet of the pilot via the bayonets of the mask and bayonet receivers attached on the helmet.

Figure 4: *Angled pull (F-16) and straigh pull (F-35) bayonet*

The MBU-20/P and MBU-23/P mask differ in the type of bayonets (Figure 4), valves and microphone used. The overall shape and layout of the masks is the same.
Focusing on the facepiece when redesigning could increase the fit for the MBU-20/P and MBU-23/P, as this component is the same for both masks and presses directly in the face.

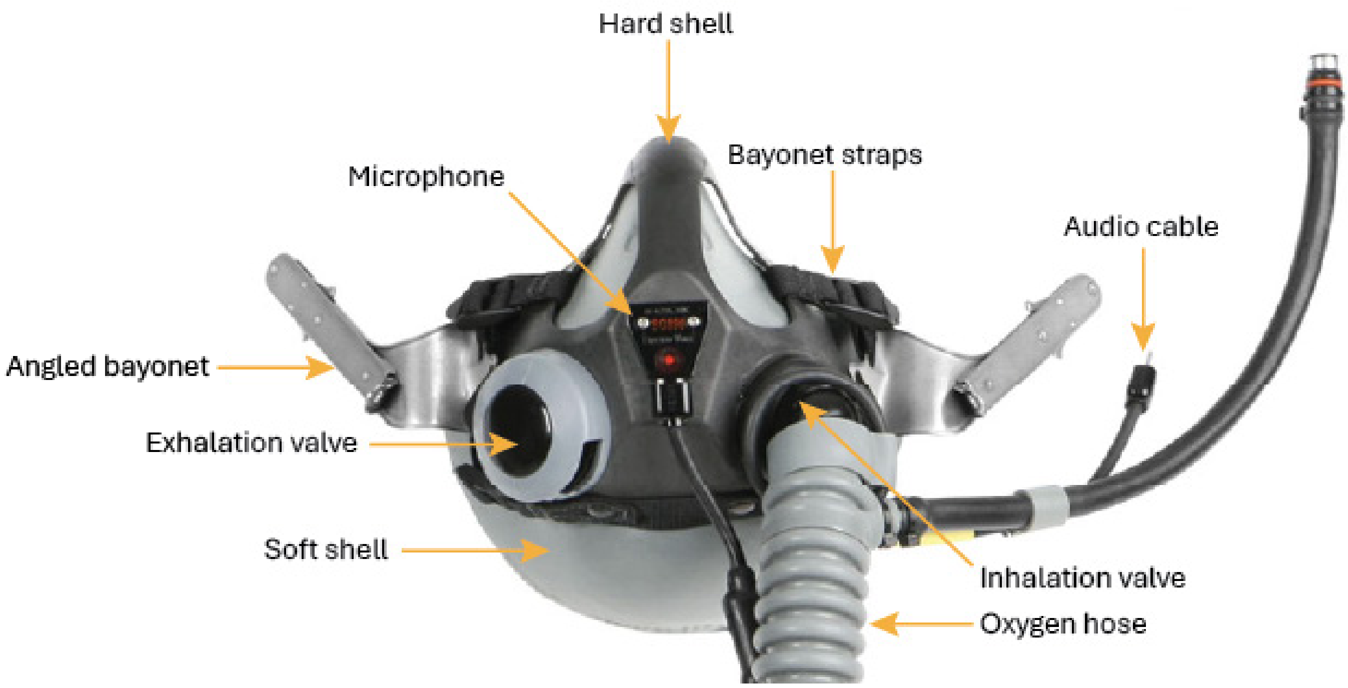


Figure 3: *Overview of components of the MBU-20/P oxygen mask*

2.2 Instability of the mask and helmet system

The oxygen mask is attached to the helmet via the bayonets and bayonet receivers.
The bayonet receiver can be adjusted in placement and has three detents. When fitting the mask, the bayonet is always set in the second detent and the straps are used for final adjustments. This leaves room to loosen or tighten the mask, if necessary.

For a good fit of the oxygen mask, it is essential that the helmet of the pilot is fitted properly. Because of the way the mask is attached to the helmet, any rotation or displacement of helmet will exert a force on the mask and thus on the face. The mask needs stability on the face when the pilot performs their tasks. However, due to the unstable nature of the design uneven pulling forces on the mask and pressure on the face is seen. This unstable nature is caused by the shape of the facepiece, angle of the bayonets and the attachment of the straps to the bayonets. The straps attached to the bayonets create a pivot point for the mask, this could cause the mask to pivot away from the face.

When pilots pull high G forces, these forces and pressures are increased. The mask hangs mostly on the nose with high G forces and the rotational forces are increased.

The use of angled or straight pull bayonets have an influence on the force direction acting on the mask and face. Gravitational forces are shown in red, forces attaching the mask to the helmet are shown in green, Figure 5.

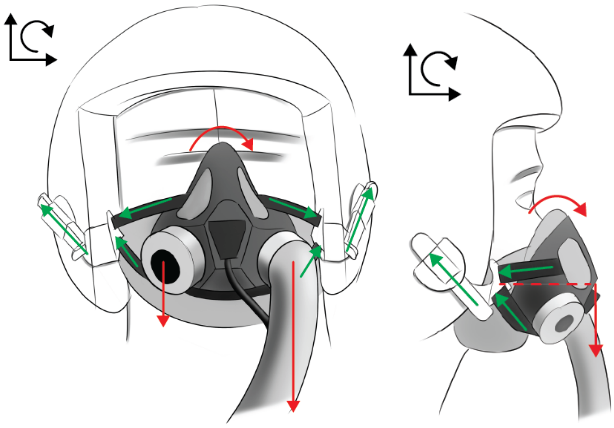


Figure 5: *Front and side view of forces acting on the mask*

All these variables differ for each pilot and make it hard to model and account for all these variables in this research. When redesigning the oxygen mask, the pulling force and rotation of the mask should be kept in mind.

2.3 History

2.3.1 The first oxygen systems

The first flight of an aircraft with a purpose-provided oxygen system was in 1913 by French aviator Georges Lagagneux (Carey, n.d.),
With the start of World War I in 1914, it became increasingly important to operate military aircrafts at higher altitudes to fly beyond the reach of ground fire. With these increasing altitudes, the need for breathable oxygen became important to safely operate above 15.000 feet (Carey, n.d.).

These first oxygen systems used a pressurized oxygen bottle and delivered oxygen to the pilot using a “pipe stem” held between the teeth (Posselt et al., 2018), Figure 6. This design was changed for a rubber facemask connected to the oxygen bottle to address the freezing conditions seen at high altitudes. Making it hard to grip the pipe at longer sorties, this oxygen mask was issued to all aircrew of the RAF by 1918 and marks the first standardized use of a half-face oxygen mask in military aviation (Posselt et al., 2018), Figure 7. An American version was adapted from this British design (Carey, n.d.).

Figure 6: *Pipe stem oxygen supplysystem*

Figure 7: *First rubber half-face mask in avation*

Since this first oxygen mask, a lot of research and development contributed in the improvement of oxygen mask designs, most of these developments occurred during wartime.

2.3.1 Difficulties through the years

Declassified research reports from the United States Air Force (USAF) highlighted ongoing issues with sizing, comfort and fitting of the MBU family oxygen masks.

When the MBU-5/P (Figure 8) was developed in 1961, sizing has been problematic. The MBU-5/P had four sizes, but 1 in 100 pilots could not wear them due to facial variations. Straps often had to be tightened significantly to create a proper seal (Seeler, 1961).

Figure 8: *MBU-5/P*

The MBU-12/P (Figure 9) mask was introduced in 1974 and was found a well-functioning and fitting mask after four years of testing. However, 5% of pilots reported excessive pressure on the cheek and/or nasal bridge from the mask (Alexander et al., 1979).

Figure 9: *MBU-12/P*

The MBU-20/P was developed to better accommodate the higher G forces seen in the newer fighter jets.
A study on the MBU-20/P (Figure 10) highlighted the mask had challenges with comfort, fitting and the creation of a proper seal. These problems were increased under high G loading (Bitterman, 1991). One of the reasons mentioned was the fact that masks were often tested on mannequins and not taking the differences in facial features of users into account.

Figure 10: *MBU-20/P*

Both the MBU-12/P and MBU-20/P used the anthropometric research of (Churchill et al., 1977) from 1967 as input for the design of the mask shape. Piccus et al. (1993) observed that sizing systems used for mask design have not kept pace with advances in mask design. The use of traditional anthropometric data, methods and testing on mannequins have led to poor fit and discomfort, which could lead to unsafe situations.

Throughout the years, sizing and comfort have proven difficult to design for. A new way of using anthropometric data could help improve the sizing and comfort of the mask design.

2.4 Discomfort and facial trauma

Research highlighting facial trauma and discomfort has been very limited. However, the available research showed that the reported problems can be quite severe.

2.4.1 Facial trauma in Dutch F-16 pilots

Research conducted by Schreinemakers (2014) highlighted nasal issues among fighter pilots of the RNLAF. The research investigated the development of nasal deformities in fighter pilots (Figure 11), attributing the issues to the pressure exerted by oxygen masks during flight. Some of these pilots required surgery, in extreme cases, to remove these deformities and decrease their discomfort with the mask

Figure 11: Pre- and post-operative side view of F-16 pilot showing dorsal hump which increased in size during his flying career *(Schreinemakers, 2014)*

The deformities ranged from minor to major, redness caused by injury or inflammation (erythematous skin) to noncancerous bone tumour (exostoses) of the bony pyramid of the nose over time, Figure 12 and Figure 13. It was noted that extreme external pressure from the oxygen mask in flight is one of the causes of these deformities

Figure 12: *Persistent erythema on the bridge of the nose in the contact area of the oxygen mask (Schreinemakers, 2014)*

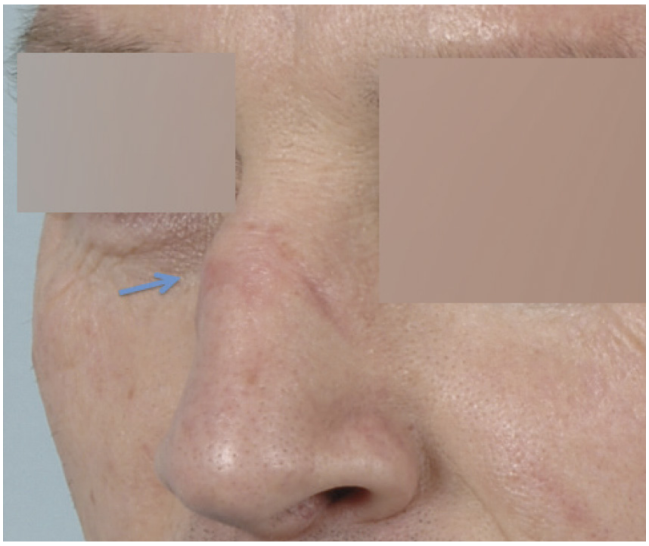


Figure 13: *Exostosis on the bony pyramid of the nose (Schreinemakers, 2014)*

Some pilots developed wounds on the nose, which could be classified as a stage 2 pressure ulcer (Edsberg et al., 2016). The four stages of pressure ulcers can be seen in Figure 14.

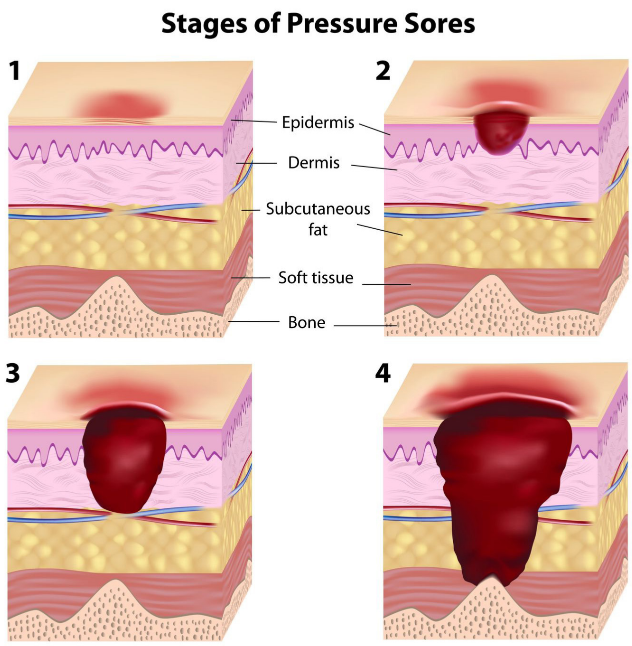


Figure 14: *Four stages of pressure ulcers. Stage 1: the skin is unbroken, but red and inflamed. Stage 2: Skin is broken on the top layers of skin only. Stage 3: Injury extends down to the tissue under the skin. Stage 4: Loss of skin and tissue, exposed bones, cartilage or tendon (Hayward et al., 2021)*

When the pilot undergoes a high G load, the mask could shift and flip inside out on the nose. This causes the mask to effectively “dig” into the skin of the user (Figure 15).
Shearing of an object on the skin are also causes of pressure ulcer development (Edsberg et al., 2016). The pressure, in combination with the shear of the mask, could cause these pressure ulcers to occur.

Figure 15: *Folding inside out of the MBU-20/P mask without and with pulling force*

Further research, involving the CMA, revealed that a majority of RNLAF F-16 pilots wore ill-fitted masks (Schreinemakers, 2014). The research raised concerns that the design of the helmet and mask could increase nasal problems, citing issues like high pressure on the nose bridge and the impact of equipment placement on the helmet, such as Night Vision Goggles (NVG’s) as shown in Figure 16.

Figure 16: *Pilot wearing MBU-12/P mask with NVG’s*

Schreinemakers (2014) noted pilots attempting to address the problem themselves, such as using band aids to decrease the pressure on the nose. The usage of the MBU-20/P mask caused minor to severe problems around the nasal area of Dutch F-16 pilots. It is important to look at the pressure on the nasal area when redesigning.

2.4.1 Facial discomfort in Korean pilots

Research conducted by Lee (2013) looked into the discomfort, oxygen leakage and mask slippage of Korean Air Force (KAF) pilots wearing the MBU-20/P oxygen mask. 68% of KAF pilots reported experiencing a moderate to high (3 to 5) discomfort of wearing the MBU-20/P. The highest discomfort was seen at the nasal root and nasal side (Lee, 2013), Figure 17.

41% of KAF pilots reported moderate to excessive oxygen leakage of the mask. This was also most severe at the nasal root and nasal side areas (Lee, 2013), Figure 18.

88% of KAF pilots experience some form of mask slippage, from slight to excessive, during use. 53% of KAF pilots have contact between the microphone in the oxygen mask and their lips (Lee, 2013).

An example of the excessive pressure on the nasal side and cheekbone (zygomatic region) and oxygen leakage at the nasal root of a pilot wearing the mask can be seen in Figure 20. The highest discomfort was seen around the nasal area. Confirming the importance of this area when redesigning the facepiece.

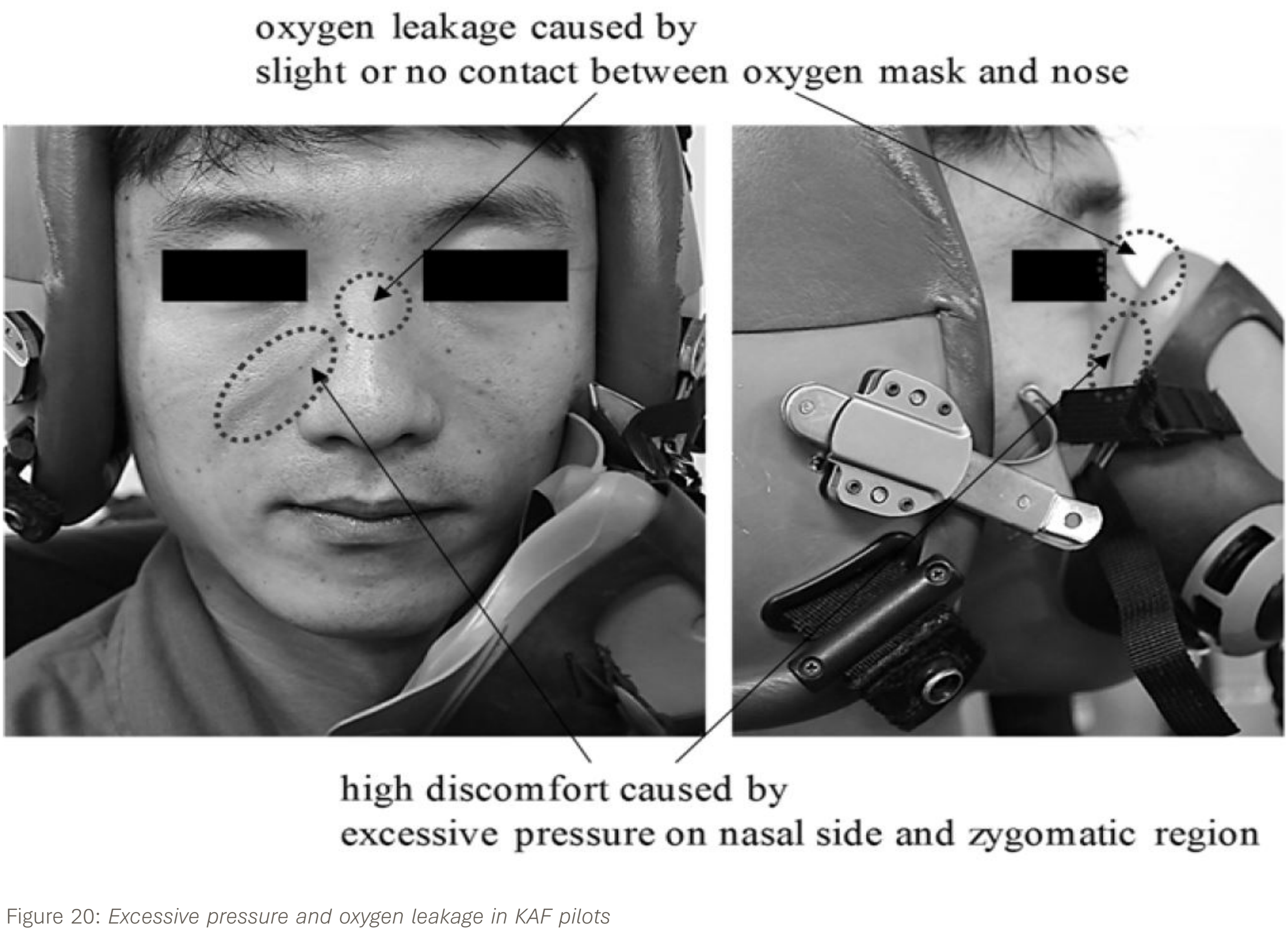
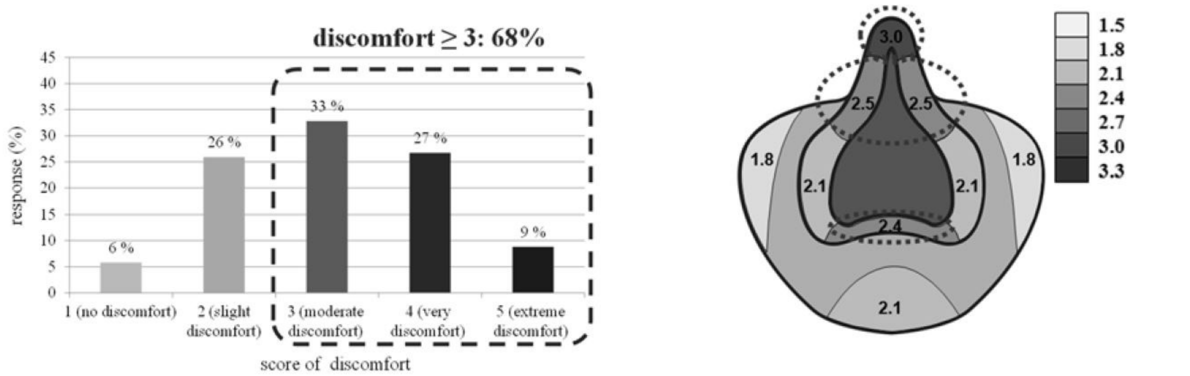


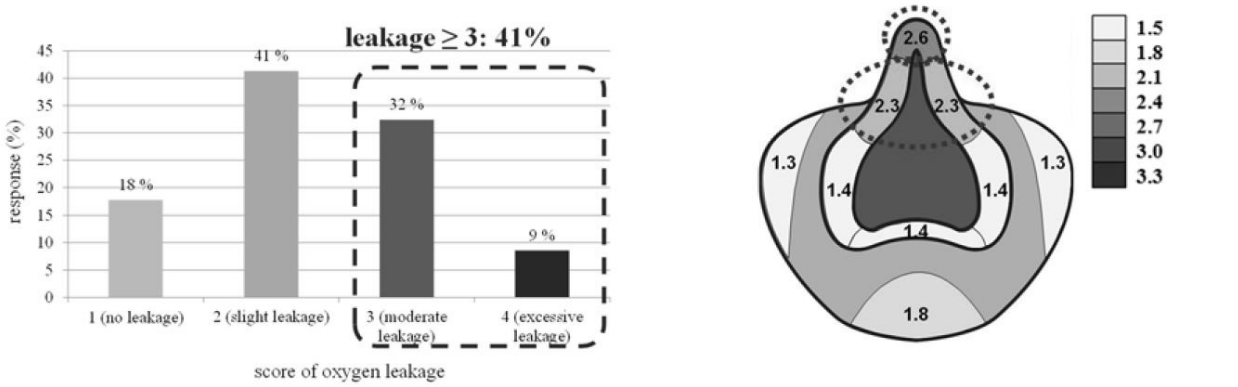
Figure 20: *Excessive pressure and oxygen leakage in KAF pilots (Lee, 2013)*



(a) Distribution of the highest score

(b) Average discomfort score by facial area

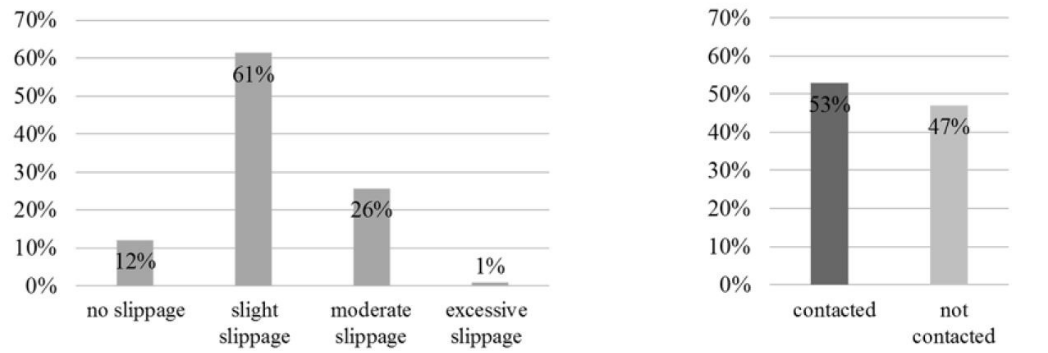
Figure 17: *Discomfort score and distribution of the MBU-20/P mask by KAF pilots (Lee, 2013)*



(a) Distribution of the highest score

(b) Average oxygen leakage score by facial area

Figure 18: *Oxygen leakage and distribution of the MBU-20/P mask by KAF pilots (Lee, 2013)*



(a) Result of slippage

(b) Result of microphone-lip contact

Figure 19: *Slippage and microphone-lip contact of the MBU-20/P mask by KAF pilots (Lee, 2013)*

2.5 Conclusion

Over the years, military oxygen masks have seen significant improvements, starting from the pipe stem systems to more complex designs. Despite these improvements, challenges in mask sizing, fitting and comfort proofed difficult to overcome. The fit and comfort of an oxygen mask is influenced by multiple factors, such as head and helmet movement, but also G-forces increasing pressure of the mask on the face.

The MBU2-/P oxygen mask has been reported to cause discomfort in the face of pilots, especially around the nasal area. Pilots reported issues from modest to severe discomfort and facial trauma, highlighted by an uneven pressure and discomfort distribution on the face. Mask slippage, overall discomfort and contact between the microphone and pilots' lip suggest that the current mask shape does not fit the user correctly.

The need for improved anthropometric methods in mask design is critical for better performing masks and safe aircrew operations. Focus should be on the nasal area during redesigning. More advanced anthropometric techniques could help design a better fitting oxygen mask. A desirable design should minimize discomfort and risk of injury, whilst ensuring safe aircrew operations.

Chapter 3

Problems experienced by F-35 pilots

3 Problems experienced by F-35 pilots

To answer the first research question "Are the reported issues in literature with oxygen mask usage still present with current fighter pilots?" semi-structured interviews and questionnaires were conducted with F-35 fighter pilots currently in service with the RNLAF. The research was conducted at Volkel Air Base with the 313 "tiger" squadron.

The questionnaire included items to gather information about their demographic, oxygen mask usage and experienced (dis) comfort and was answered by 14 pilots. An example question where the mask is rated can be seen in Figure 21. Each question had a control question to validate the answers.
The semi-structured interviews focused on 4 main topics:

1. When is discomfort explicitly felt, and where on the face?
2. What causes discomfort to increase or decrease?
3. Are there ways to improve the fit and reduce discomfort?
4. How is the ideal mask described?

A total of 22 F-35 pilots were interviewed with their age ranging from 23 to 50. Some pilots had prior flight experience with the F-16. All subjects of the questionnaire and interviews were male pilots.
The most relevant results will be discussed per these 4 topics. The questionnaire and all results can be found in appendix A.

3.1 When is discomfort explicitly felt and where on the face?

In the interviews 68% (N = 22) of pilots experience discomfort caused by the mask during long flights. From 1.5 to 2 hours onwards a flight is considered long. 20% (N = 15) of the pilots experience discomfort on longer flights also experienced discomfort on shorter flights. The questionnaire highlighted that this is also the case when wearing the mask for a very long time, Figure 22.
87% (N = 15) of the pilots who experienced discomfort attributed the discomfort to a pressure point of the mask on the nose.

Figure 21: *Example Likert scale questions from the*

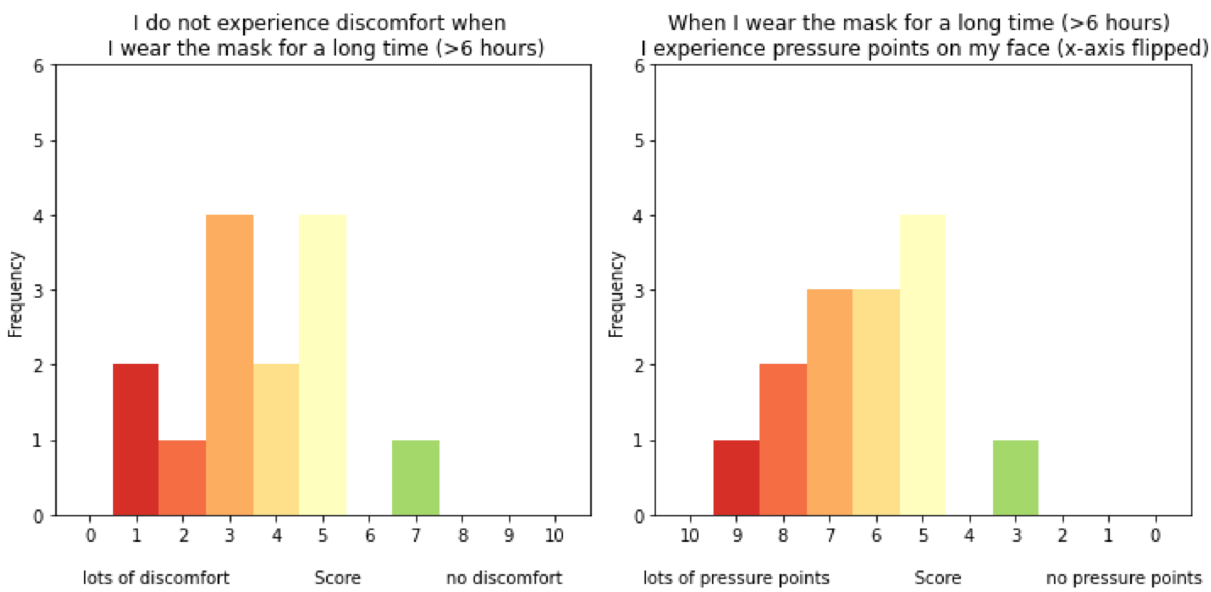


Figure 22: *Histogram of pilot discomfort when wearing the mask for a long time from questionnaire*

Of which 23% (N = 13) developed wounds on the nose due to the pressure point. This could indicate grade 2 pressure ulcers (Edsberg et al., 2016).

The pressure point was also seen in the questionnaire responses. Pilots were asked to rate the discomfort on a scale of 0 - 10 (no discomfort to highest discomfort respectively) of the mask in 6 locations:

1. Nasal root
2. Right side of nose
3. Left side of nose
4. Right cheek
5. Left cheek
6. Chin

The nasal root had the highest discomfort level, with an average of 7,1 out of 10, Figure 23 & Figure 24. The chin had the second highest discomfort level, with an average of 2,6 out of 10.

> *"You see with all pilots, they actually have a bump here. The longer they fly, the bigger the bump becomes."*
>
> -Pilot 4

> *"When I look at photos from that time, I see everyone has a big red bump on their face every day, even if they didn't fly. It's still there on Thursday."*
>
> -Pilot 22

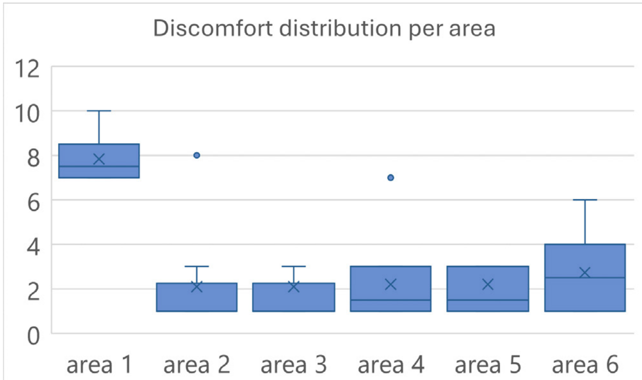
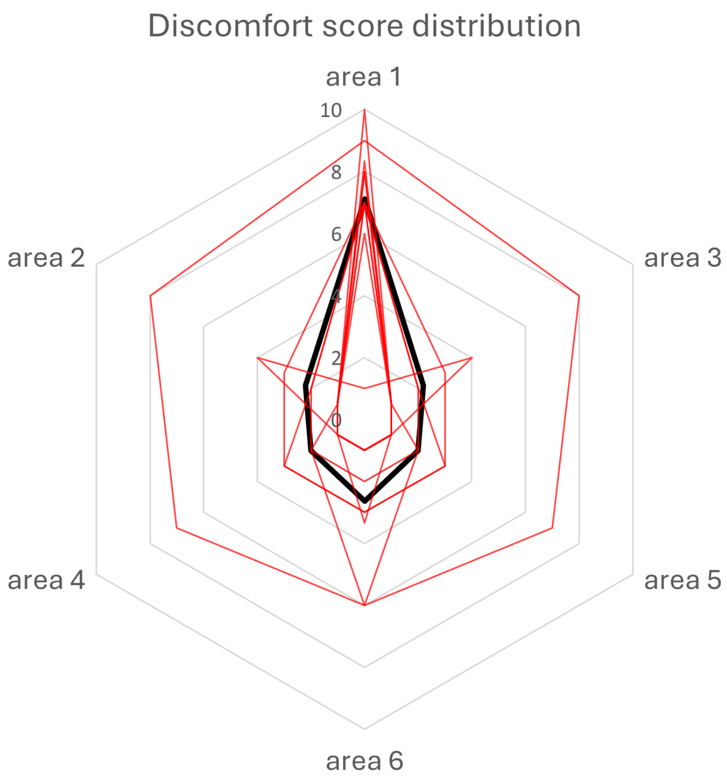


Figure 23: *Discomfort distribution inter subject (n=14)*



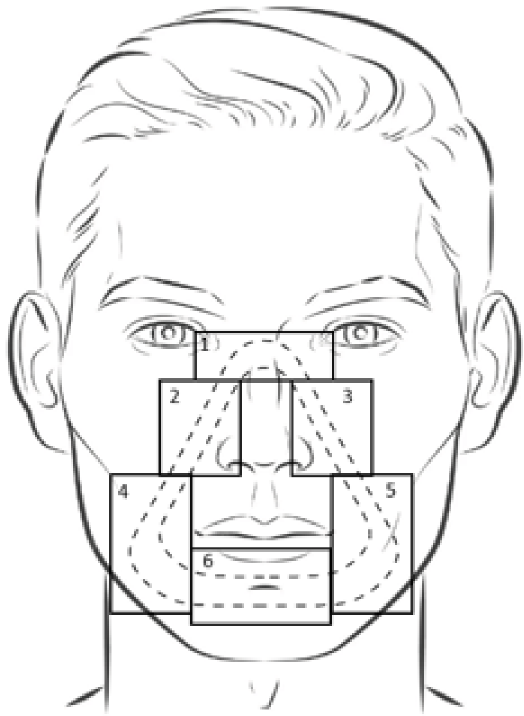


Figure 24: *Discomfort distribution on the face of F-35 pilots, showing average and individual scores (N=14)*

The discomfort at the nasal root was however contradicted when the pilots were asked if they felt an equally distributed pressure on their face (Figure 25). This could be explained by the fact that the soft tissue around the nasal area is thinner compared to the rest of the face where the masks applies pressure (De Greef et al., 2006).

A product which fits the user well should not cause major discomfort or other problems.
However, when asked to the fighter pilots they seem to agree that the shape of the mask fits their face well

The highest pressure and discomfort is still experienced on the nasal root and some pilots develop wounds on their nose. This confirms that attention should be given to the nasal area when redesigning. The cheekbone areas scored the lowest overall in discomfort levels, this could indicate that little pressure is on this part of the face.

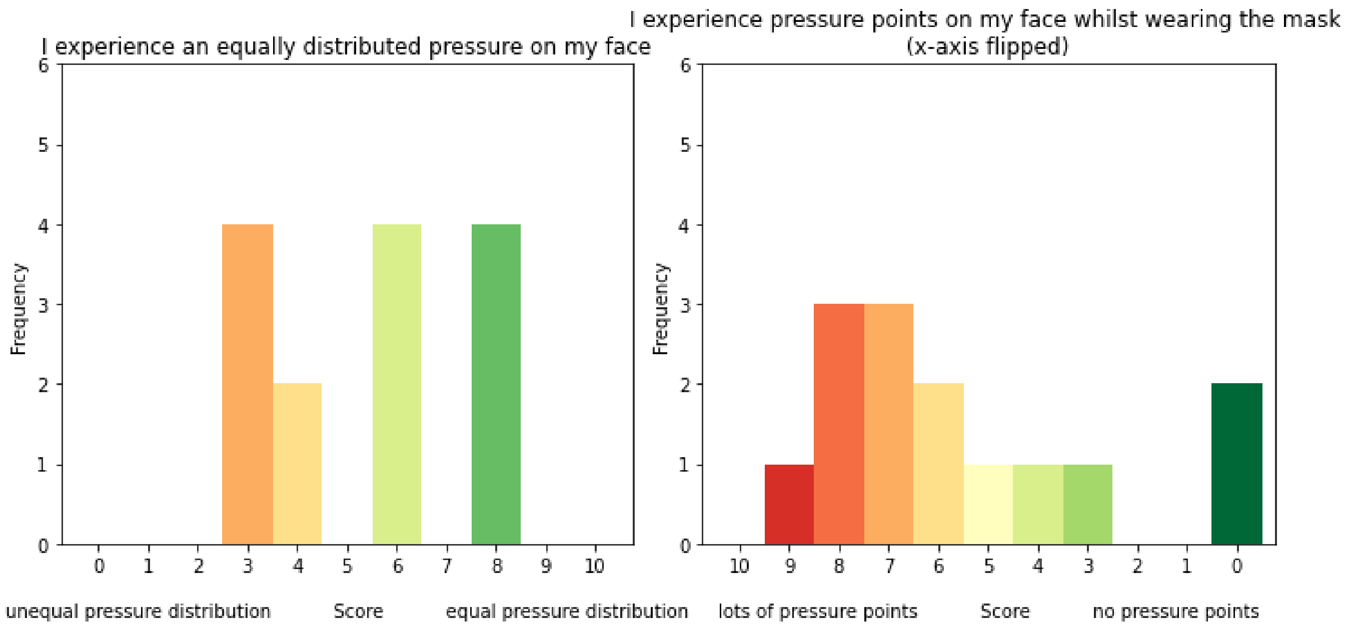


Figure 25: *Histogram of pressure distribution in the face of pilots from questionnaire*

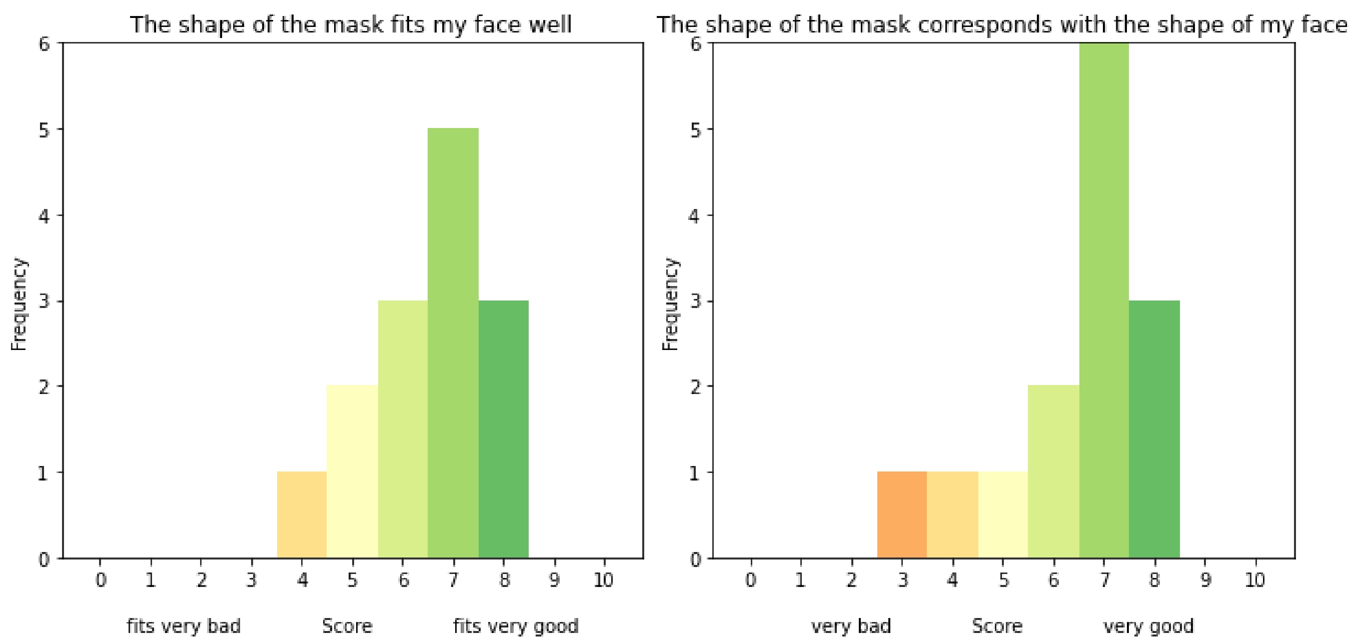


Figure 26: *Histogram of how the shape fitting the face of pilots from questionnaire*

3.2 What causes the discomfort to increase of decrease?

3.2.1 Increasing discomfort

The time of mask wearing has an effect on the experienced discomfort. The longer the mask is worn, the higher the discomfort will be eventually. Other factors also influence the experienced discomfort. 73% (N = 22) of the pilots indicate that they need to tighten the mask during BFM/high-G manoeuvres. This increases the pressure and discomfort on the face.

As explained in chapter 2.2, the mask tends to tilt and shift away from the face when a high-G is exerted on the pilot and mask, Figure 28. 38% (N = 16) explicitly mentioned they experienced the mask shifting away from their face during high-G manoeuvres. This can also be seen in Figure 27.

High-G loading increases discomfort experienced by pilots, as they have to increase the pressure of the mask on the face to decrease the mask shifting from their face. Even though this pressure is increased, mask shifting can still occur.

What causes a lot of problems for me on my nose over time. During higher G-loading, the mask must be tighter. Otherwise, the helmet will sag, falling downward. Which is actually not comfortable

-Pilot 3

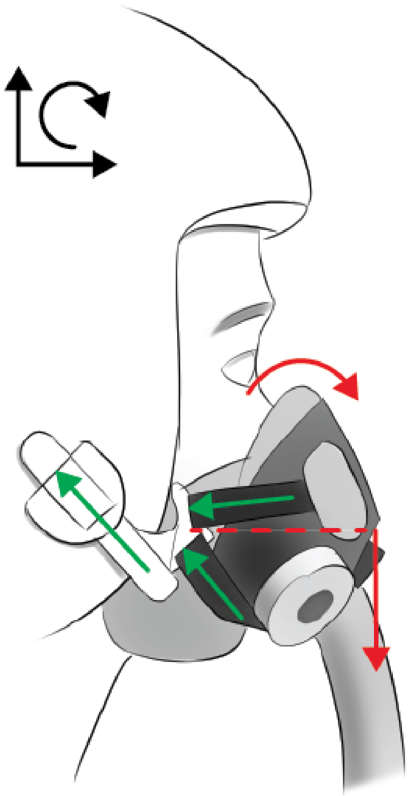


Figure 28: *Side view of forces acting on mask*

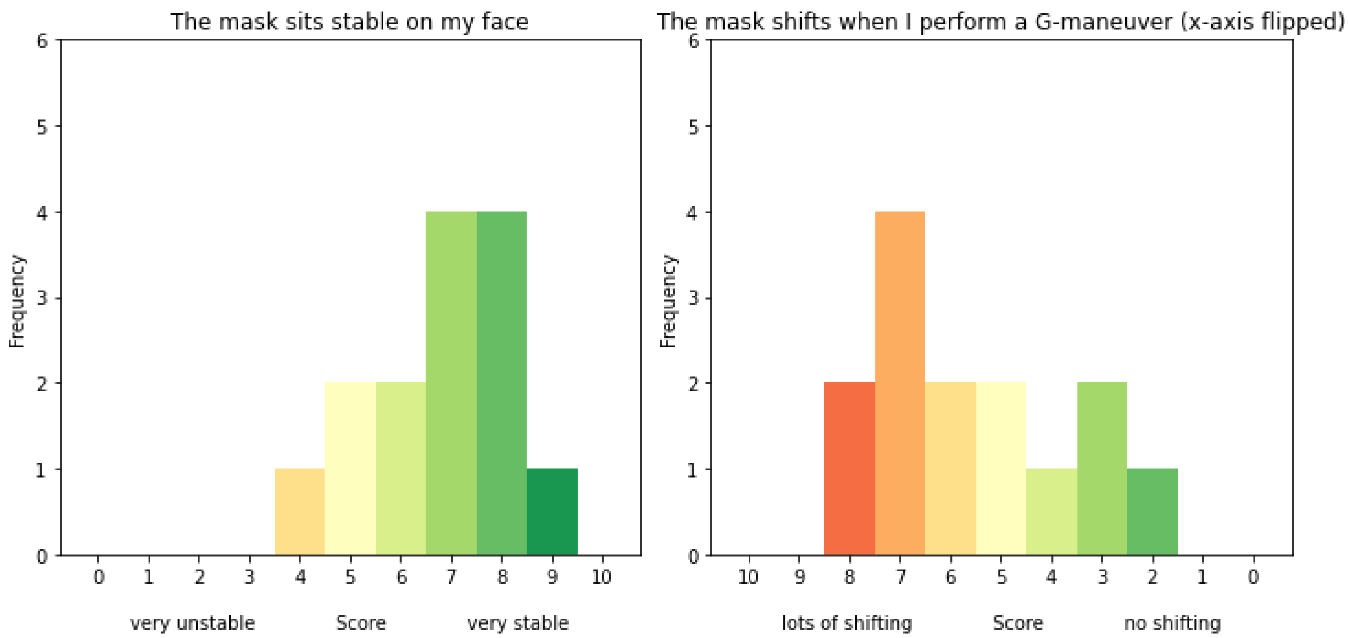


Figure 27: *Histogram of mask stability from questionnaire*

3.2.2 Decreasing discomfort

Pilots mentioned multiple ways to decrease the discomfort. 79% (N = 14) of the pilots remove their mask during certain periods in flight. This practise is not described in protocols and could lead to unsafe situations. 64% (N = 11) of the time, the main cause mentioned was discomfort to remove the mask. Eating and drinking were also often mentioned reasons to remove the mask. However, this is not possible with the mask fitted. 50% (N = 22) of pilots mentioned flying with the bayonets in first detent to decrease the pressure, but for the proper functioning of the mask the bayonets should be in the second detent.

Of the pilots experiencing a pressure point on the nasal root 31% (N = 13) use band aids to decrease the pressure and discomfort. 33% (N = 15) of the pilots experiencing discomfort mentioned experiencing less discomfort compared to flying in the F-16. This could be explained by the integration of NVG's into the helmets of F-35 pilots and the decrease in long missions flown, compared to the missions in Iraq and Afghanistan.

> *But I know people, if they flew a lot for a whole week. They needed to do something with band aids, because the skin has chafed off. But... Well... You can see it with everyone, after every flight, if they flew, purely by their nose. That should tell you something. Of course it's always red for everyone.*
>
> -Pilot 13

Pilots have found ways to decrease the amount of discomfort experienced. However, some of these practises could lead to unsafe situations because of unsafe use of the oxygen mask. The usage of band aids to decrease pressure, as described by (Schreinemakers, 2014), is still seen. The integration of NVG's has possibly decreased some experienced discomfort.

3.3 Are there ways to improve the fitting and reduce discomfort?

Material of the hardshell can be removed around the nasal root area to create more space for the nose, if necessary for increasing comfort. When a mask cannot create a seal on the face of the user, a smaller mask size must be fitted. One pilot mentioned he needed a smaller mask size to create a good seal. This is a standard procedures described in the technical order MD 5901-00001 (Gentex & CMA, 2017) for the fitting of an oxygen mask.

55% (N = 22) of pilots had material removed from their hardshell. Reducing discomfort was the main reason to remove material. From 2024 onwards, the maximum amount of material allowed to be trimmed away will be standard on all hardshells (Gentex, personal communication Steinman, 2024). 9% (N = 22) of pilots deliberately increased pressure on the chin during the fitting process, to decrease pressure on the nose.

> *I fitted my mask to have the bottom a bit tighter, so it sits more on my chin, which is less annoying for the skin, in my opinion. However, during flight, it's still not nice to have pressure on one of the two spots*
>
> -Pilot 12

9% (N = 22) of pilots flew with a larger mask size than originally fitted to increase their comfort.

> *I actually have a larger mask than prescribed by the protocol. When it was fitted, I needed to have a medium, but that just felt crappy. So, in the end, I have a large mask*
>
> -Pilot 10

The need to use smaller than originally fitted to create a seal indicate that improvements in the sizing of the masks could be needed. The usage of larger masks than originally fitted for increased comfort and deliberately increasing pressure on the chin indicate that the shape and size of the mask could help improve comfort of wearing the masks.

3.4 How is the ideal mask described?

When asked how pilots would describe an ideal mask, several improvement points were mentioned. 27% (N = 22) of the pilots thought the mask would be more comfortable if the silicone rubber of the facepiece would be softer. This was also seen in the questionnaire responses, Figure 29.

14% (N = 22) of pilots mentioned personalizing masks as a method to decrease comfort. Some other improvements mentioned included; decreasing the weight, increasing the contact area, changing the shape and improve the pressure distribution of the masks on the face.

Earlier research in combination with CMA by de Vette (2013), suggested decreasing the hardness of the silicone facepiece from 65A to 45A to decrease the discomfort. As per 2024, all new masks produced will have a hardness of 45A (Gentex, personal communication Steinman, 2024). The softness of the mask is thought to have a big influence on the experienced discomfort by pilots. Personalizing masks of pilots is also seen as a way to decrease the discomfort.

3.5 Conclusion

The interviews and questionnaire responses confirm that the problems discussed in Chapter 2 are still present, with most discomfort still seen around the nasal root.
This confirms that focus should be on the nasal area during the redesign process.
The duration for which pilots wear the mask has an influence on their perceived discomfort. High-G forces have a negative impact on mask behaviour and stability, increasing discomfort. As a result of this discomfort, pilots may show adverse behaviour with the mask to decrease the discomfort which could lead to unsafe situations.
The current oxygen mask fails to meet the needs of fighter pilots. A more comfortable mask is necessary to reduce the adverse behaviour and enhance safety. The mask sizing and shape have an influence on the experienced discomfort and therefore need to be kept in mind during the redesign process, to design a more desirable solution.

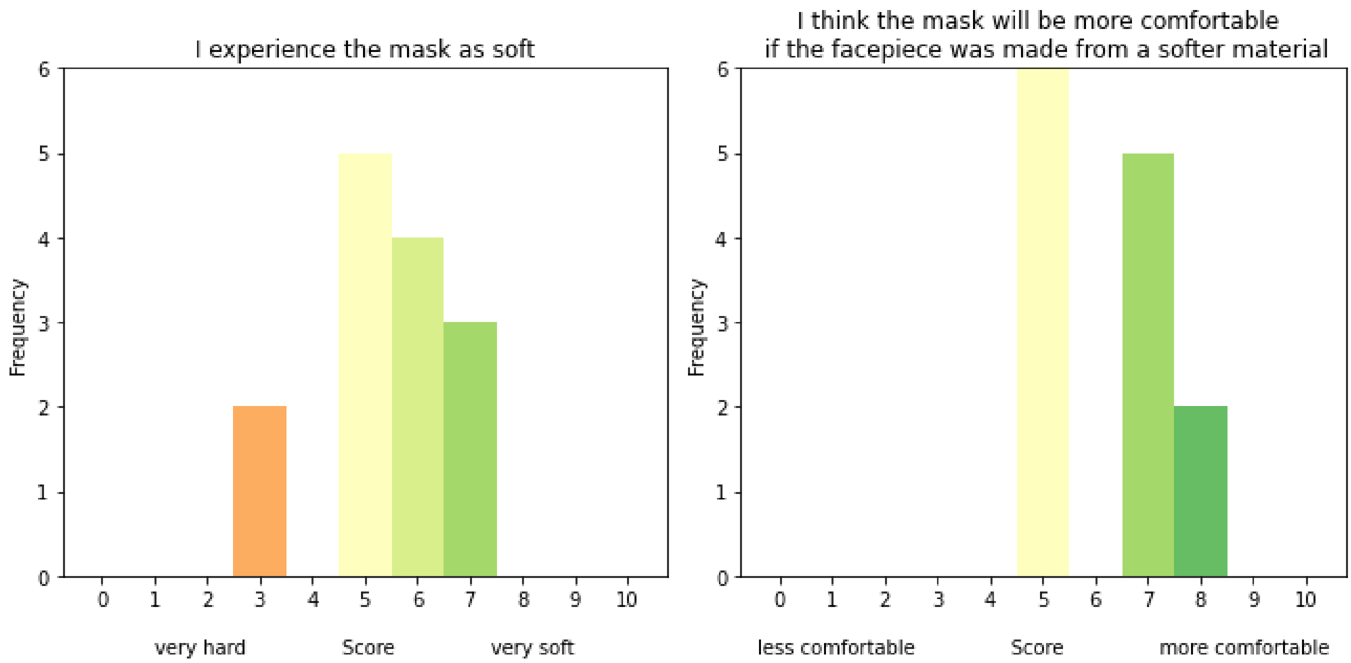


Figure 29: *Histogram of mask softness of questionnaire*

Chapter 4

How does the mask fit Dutch fighter pilots

4 How does the mask fit Dutch fighter pilots

To answer the second research question: “Are there differences in facial features between Dutch and American fighter pilots and how does this influence the fit?”, the question was divided into three separate parts.
In the first part, a statistical database of facial measurements of the RNLAF fighter pilot population needed to be made. Afterwards the current mask sizing system could be evaluated and facial measurements of importance to mask design were compared with the AMRL database (Churchill et al., 1977), used for the development of the MBU-20/P mask, to evaluate the current sizing system and identify significant facial differences.
Lastly, a system was developed to better understand how the 3D shape of the masks interacts with Dutch faces. This system helped better understand the fit of the masks.

4.1 Statistical database of RNLAF facial measurements

To create a statistical database of the facial measurements of the RNLAF fighter pilot population, 3D scanning was seen as an option for data gathering. The RNLAF has around 50 fighter pilots in active duty. However, due to logistical hurdles only a few pilots (N = 10) were 3D scanned for data gathering.

This sample was too small for statistical analysis, compared to the 2420 subjects of Churchill et al. (1977). So another method was needed. It was decided to use one of the most recent anthropometric surveys of the Dutch population instead. In order to best represent the RNLAF fighter pilot population the database was filtered on some criteria.

4.1.1 CAESAR database

The Civilian American and European Surface Anthropometry Resource (CAESAR) study (Robinette et al., 2002) is a large scale anthropometric study conducted on population of three NATO member states. This study contains traditional 1D measurements, such as weight and stature, as well as 3D body scans of subjects. The CAESAR data set contains three distinct databases:

- North America (N = 2400)
- The Netherlands (N = 1250)
- Italy (N = 800)

The 1250 subjects of the Netherlands database of CAESAR represent the entire population and cannot directly be used as a stand in for the target population, as fighter pilots might have a different physique compared to the average citizen.

To create a subset of the Dutch civilian database which represents Dutch fighter pilots more accurately, the database was filtered on the following criteria:

- Age between 18 and 50 years old
- Stature between 1620 and 1930 mm
- A BMI between 18.5 and 27.5

Age

The age criterium was based on the youngest age a person can enter the pilot training program and after 50, pilots are not in active fighting duty anymore with their squadron.

Stature

The stature criterium was based on the pilot selection requirements for the pilot training program (Ministerie van Defensie, n.d.) An (aspiring) pilot cannot be smaller than 1620mm or larger than 1930mm.

BMI

BMI was chosen as a criterium to evaluate fitness of subjects, as a better BMI score has been linked to physical fitness in west European adults (Tittlbach et al., 2017) and it was assumed all fighter pilots have a good fitness. A healthy BMI range is between 18,5 and 25 (James & François, 1994).
The BMI range from questionnaire responses was between 21,1 and 27,1. To prevent exclusion of mostly women from the subset the 18,5 value was chosen as the lower limit. As European women tend to have a lower BMI compared to their male counterpart (Eurostat, 2019).
To include all fighter pilots in the subset, the upper BMI value of a fighter pilot was chosen with a margin added to prevent edge cases. This set the upper limit to 27,5. Combined, this created the BMI criterium of 18,5 to 27,5.

High BMI and facial fat tissue build-up

The highest fighter pilot BMI (27,1) belonged to a fighter pilot with a stature of 1920mm.
The pilot had a good physical shape, a lot of muscle tissue and would not classify as unhealthy. This high BMI value could be explained by the fact that muscle tissue has a higher density compared to fatty tissue. Muscle tissue density is around 1,06kg/L (Méndez, 1960) and fatty tissue density is around 0,92kg/L (Farvid et al., 2005).

The upper limit of the BMI criterium will include more subjects which would classify as overweight, as a BMI value above 25 is seen as overweight (James & François, 1994).
However, facial features do not accumulate fatty tissue as severely as other parts of the body. The ratio of facial fat to abdominal fat buildup is 1:5 (Levine et al., 1998). It is suspected that the inclusion of these overweight subjects will not have a significant effect on the facial feature data of the subset.

Evaluating filterin criteria

The three filtering criteria were applied to the Netherlands database of CAESAR in SPSS (IBM, 2023), resulting in 528 subjects. An almost equal male-female ratio was achieved, Table 1.

subjects per group	
All subjects	528
Male subjects	259
Female subjects	269

Table 1: *Subjects per group after filtering*

The filtered male subjects were plotted on BMI and age against the fighter pilot replies from the questionnaires, to evaluate if the filtered data could represent the fighter pilot population of the RNLAF, Figure 30.

Keeping the BMI range of fighter pilots (21,1 - 27,1) and the BMI filter criterium (18,0 - 27,5) in mind, a good distribution of filtered male subjects is seen compared to the fighter pilots. This provides evidence to assume that the filtered male subjects could represent current male fighter pilots. Hence, we assume that filtered women subjects could represent future female fighter pilots as there are no female fighter pilots represented in the questionnaire data to confirm.

The three datasets based on all subjects and gender were classified as follows:

- Dutch Target group Subset (DTS) for all subjects
- Dutch Male Subset (DMS) for male subjects
- Dutch Female Subset (DFS) for female subjects

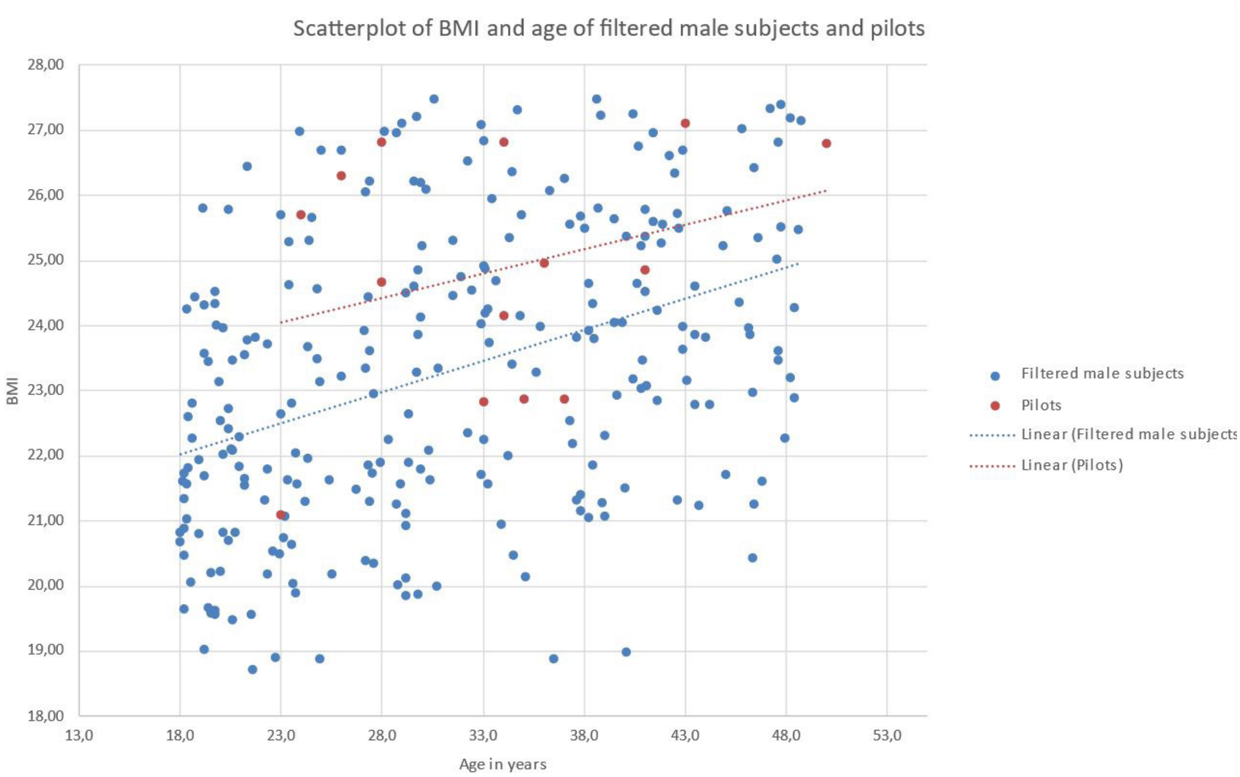


Figure 30: *Scatterplot of BMI and age of fighter pilots and filtered males*

4.1.2 Conclusion

The three filtering criteria based on available data shows the possibility to create a more accurate dataset representing the target population, compared to the dataset of the whole Dutch population. A good distribution of filtered male subjects compared to fighter pilots was seen. It was assumed that the filtered female subjects could represent future female fighter pilots.

The filtered subjects can provide more insights in possible sizing issues and facial differences between current fighter pilots of the RNLAF and fighter pilots of the USAF influencing the fit of oxygen masks.

4.2 Current sizing system

Based on the AMRL databank (Churchill et al., 1977) the MBU-20/P oxygen mask was originally designed with four sizes: Small-Narrow, Medium-Narrow, Medium-Wide and Large-Wide. A later study by Gross, et al (1997) suggested an additional mask size, Extra-Small-Narrow, to better fit female pilots who have a relatively smaller face and head. The sizes differ in the length and width of the mask.

The manufacturer claims on their website that the five available sizes are designed to fit the 97th percentile of the pilot population (large male) to 3rd (small female) percentile (Gentex Corporation, 2021), this should result in a coverage of 94% of the population. Technical order MD 5901-00001 (Gentex & CMA, 2017) describes the size assignment and fitting procedure. The current sizing system of the MBU-20/P can be seen in Figure 31.

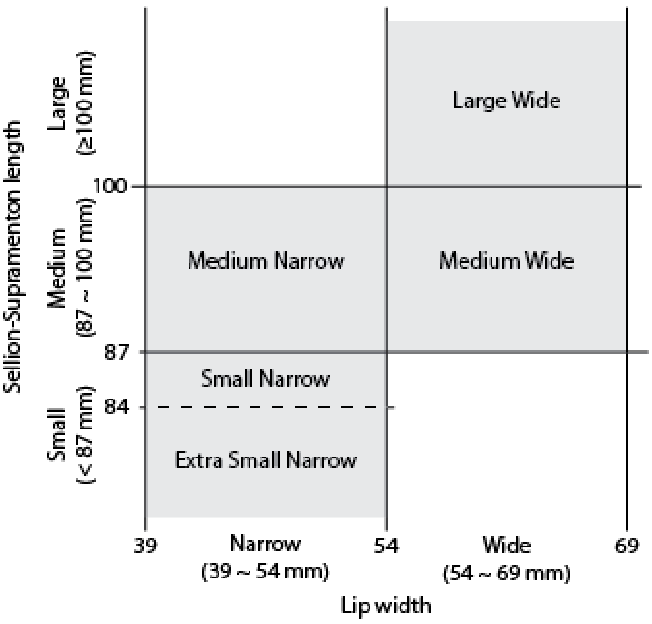


Figure 31: *Current sizing system of the MBU-20/P (Gentex Corporation., n.d.)*

To determine the mask size for the pilot First the sellion-supramenton length is measured with a calliper, to determine the main size (Small, Medium and Large), Figure 32.

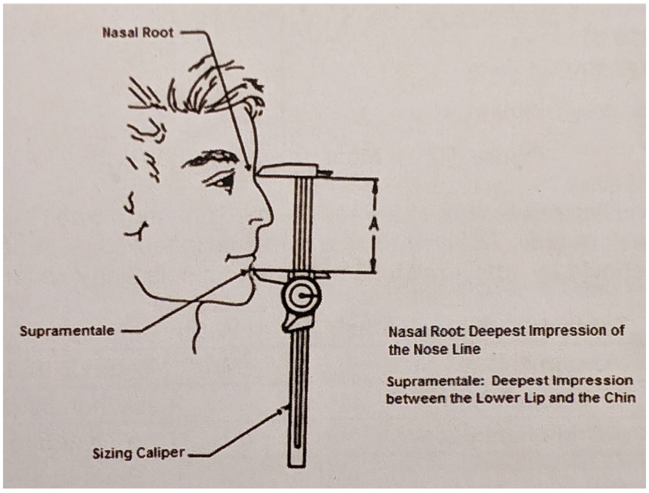


Figure 32: *Measuring of sellion-supramenton length*

Second, the lip width is measured to determine if a narrow or wide mask is needed if the pilot, Figure 33. The definition of these measurements can be found in appendix B.

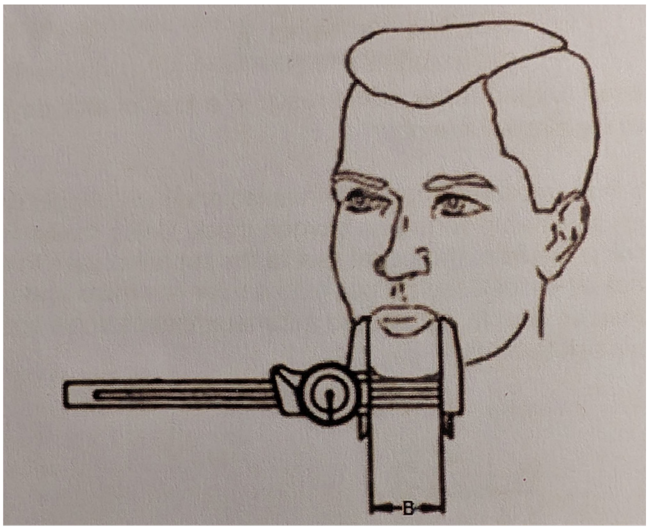


Figure 33: *Measuring of lip width*

The sellion-supramenton length and lip width do not correspond to the physical size of the mask in a 1:1 ratio. A margin is seen between the maximum facial measurement and dimension of the mask. The physical dimensions of the masks were measured by Lee (2013) and can be found in appendix C.

It should be noted that the sellion-supramenton measurement was not present in the AMRL databank, yet is used for assigning the right mask size. This could be a cause of the discomfort experienced by pilots. The Extra-Small-Narrow size is not currently used by the RNLAF.

4.2.1 Evaluation of current sizing system for the DTS subjects

To evaluate the current sizing system and it's claimed coverage, a scatter plot of lip width and sellion-supramenton length was made with the DTS data. The current sizing system was overlaid and the coverage was calculated, Figure 34.

The current sizing system does not cover the population from the 3rd to 97th percentile. The figure shows that a large part of the DTS population isn't accommodated by a mask size and could therefore have an inappropriate fit, which could lead to discomfort and other complications. An actual coverage of 77% was seen.

Expert fitters of Collins Aerospace and CMA confirmed this underserved population. As they often need to fit a mask to an individual whose face is too long for a Medium-type mask, but too narrow for the Large-Wide mask (Culley, personal communication, 2024).

The percentage of fighter pilots experiencing discomfort (68%) is larger than the percentage of unaccommodated subjects of the DTS data (23%). This suggests that the discomfort could be caused by more than an improper sizing system alone.

4.2.2 Conclusion

The current sizing system of the MBU-20/P oxygen mask uses the sellion-supramenton length and lip width to determine the correct size mask for a pilot. The sellion-supramenton length is not present in the AMRL databank, on which the oxygen mask design is based, yet is used for the sizing.

Based on the assumption that the filtered data could represent the fighter pilot population of the RNLAF, a coverage of 77% of the current sizing system is seen. This coverage does not reflect the suggested coverage of 94%.

The lower coverage of the current sizing system probably contributes to the experienced discomfort of pilots. However, the percentage of pilots experiencing discomfort is higher than the unaccommodated subjects, which suggests that the discomfort is not caused by the improper sizing system alone.

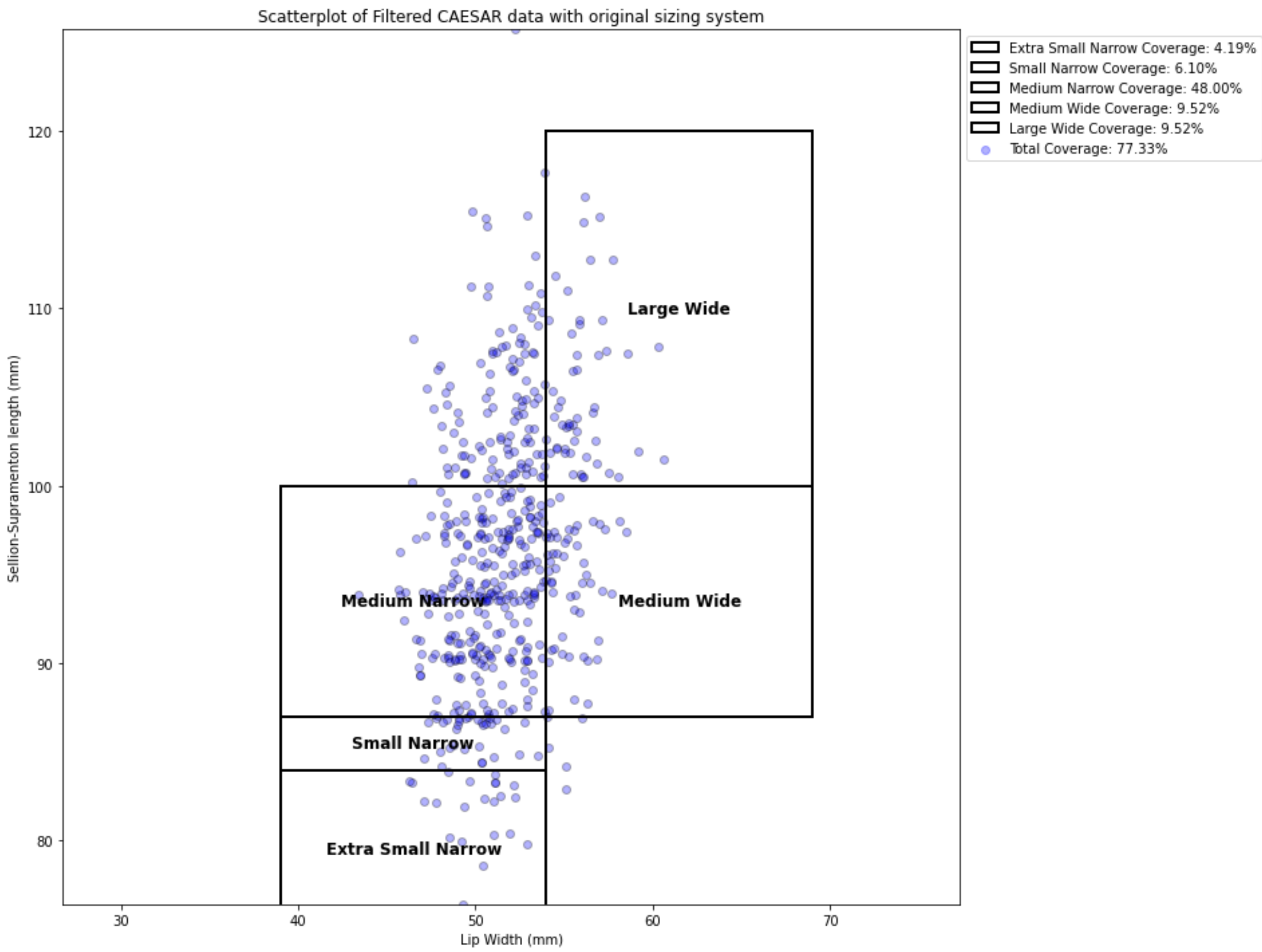


Figure 34: *Scatterplot of lip width and sellion-supramenton length of the DTS subjects with current sizing system*

4.3 Facial anthropometrics

To further investigate the causes of discomfort, the facial measurements of fighter pilots should be looked into. To understand how Dutch fighter pilot faces differ from their American counterpart, important facial measurements had to be identified first.
Afterwards these facial measurements could be compared to the values of the USAF Male Personnel (UMP) from the AMRL databank (Churchill et al., 1977), used for the design of the MBU-20/P oxygen mask. To better understand facial differences, the most significant differences are compared and evaluated how this could influence the fit of the oxygen mask.

4.3.1 Selection of facial measurements

A study by (Jeong et al., 2011) identified 22 facial measurements and their importance to the design of an pilot oxygen mask, Table 2.

The 22 facial measurements were selected by a panel of ergonomics experts and clothing experts, who also rated their importance to the design of an oxygen mask.
Not all these measurements were available in the AMRL or CAESAR data, so a selection was made of available measurements for the comparison, Table 3.

A visual overview of the selected facial measurements can be seen in Figure 35. The definition of all these measurements can be found in appendix B.

Most of the facial measurements used for the design of the oxygen mask were from Volume II – The 1967 survey of USAF flying personnel (Churchill et al., 1977).
Except for the following measurements:

- Nose length
- Nose protrusion
- Nasal root breadth

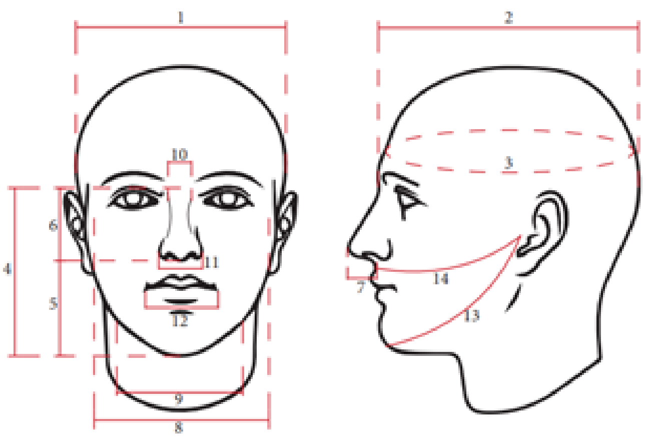


Figure 35: *Visualisation of selected facial measurements*

nr.	facial measurement	level of importance
1	head height	L
2	head breath	L
3	head length	L
4	head circumference	L
5	face length	H
6	lower face length	M
7	sellion-supramentale length	M
8	supramentale-menton length	L
9	rhinion-menton length	M
10	rhinion-promentale length	H
11	promentale-menton length	L
12	nose length	M
13	nose protrusion	M
14	face width	M
15	chin width	L
16	nasal root breadth	H
17	maximum nasal bridge breadth	H
18	nose width	H
19	lip width	H
20	bitragion-menton arc	L
21	bitragion-subnasale arc	L
22	bizygomatic-menton arc	L

Table 2: *Facial measurements and their importance to the design of a pilot oxygen mask (Jeong et al., 2011)*

nr.	facial measurement	level of importance
1	Head breadth	L
2	Head length	L
3	Head circumference	L
4	Face Length	H
5	Lower face length	M
6	Nose length	M
7	Nose protrusion	M
8	Face width	M
9	Chin width	L
10	Nasal root breath	H
11	Nose width	H
12	Lip width	H
13	Bitragion-chin arc	L
14	Bitragion-subnasale arc	L

Table 3: *Selection of facial measurements and their importance, based on available data*

4.3.2 Traditional and digital measurements

The AMRL databank (Churchill et al., 1977) consists of only traditional hand measurements. The CAESAR database consists of a combination of traditional and 3D measurements, based on 3D scans of the subjects. Not all measurements from Table 3 were present as traditional measurements.
(Huysmans et al., 2020) developed a method to digitally augment the CAESAR data, by measuring 3D scan digitally. Table 4 shows which of the selected measurements were measured traditionally (1) or digitally (2).

It is expected that the digital measurements will differ slightly from their traditional counterpart.
The traditional measurement was used in the comparison if both types of measurement were available.

It is also expected that traditional measurements will vary between the studies, as the ISO 16976 norm was not introduced at the time the (Churchill et al., 1977) did their research.
This ISO norm standardized the definition of landmarks and measurements for better research.

nr.	facial measurement	Measurement type
1	Head breadth	1, 2
2	Head length	1, 2
3	Head circumference	1, 2
4	Face Length	1
5	Lower face length	2
6	Nose length	2
7	Nose protrusion	2
8	Face width	1, 2
9	Chin width	2
10	Nasal root breath	2
11	Nose width	2
12	Lip width	2
13	Bitragion-menton arc	2
14	Bitragion-subnasale arc	2

Table 4: *Measurement type per selected facial measurement of the CAESAR database*

4.3.3 Differences in facial measurements of subsets compared to UMP data

A comparison in facial measurements of the DTS and UMP subjects was made to identify significant differences. The ratio in mean of the DTS, DMS and DFS was calculated against the UMP data and can be found in Table 5. A T-test was used to check if the means differ significantly. The ratios of Table 5 were plotted to identify differences and can be seen in Figure 36. Most of the differences in facial measurements were significant.

The descriptive statistics of all subsets and their comparison can be found in appendix D.

Nr.	Facial Measurement	M_{DTS}/M_{UMP}	M_{DMS}/M_{UMP}	M_{DFS}/M_{UMP}
1	Head breadth$_1$	1,02**	1,04**	1,00
2	Head length$_1$	1,03**	1,03**	1,02**
3	Head circumference$_1$	0,97**	0,99**	0,96**
4	Face length$_1$	0,97**	1,01**	0,94**
5	Lower face length$_2$	0,92**	0,96**	0,88**
6	Nose length$_2$	1,05**	1,09**	1,02
7	Nose protrusion$_2$	0,97**	1,01	0,93**
8	Face width$_1$	0,87**	0,88**	0,85**
9	Chin width$_2$	1,00	1,04**	0,95**
10	Nasal root breadth$_2$	1,24**	1,24**	1,23**
11	Nose width$_2$	1,01*	1,04**	0,99
12	Lip width$_2$	0,99**	1,02**	0,96**
13	Bitragion chin arc$_2$	0,97**	1,01	0,94**
14	Bitragion subnasale arc$_2$	0,97**	0,99**	0,95**

Table 5: *Ratio in means of selected facial measurements*

Figure 36: *Ratio in means of selected facial measurements*

The most significant differences between the DTS and UMP data was seen in the face width (Figure 37) and nasal root breadth (Figure 38). The DTS group has a narrower face and wider nasal root compared to their American counterpart.

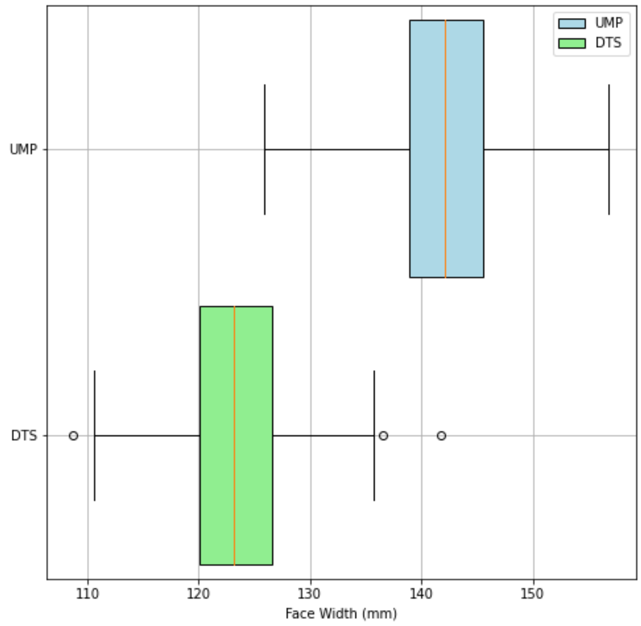


Figure 37: *Boxplot of face width of UMP and DTS data*

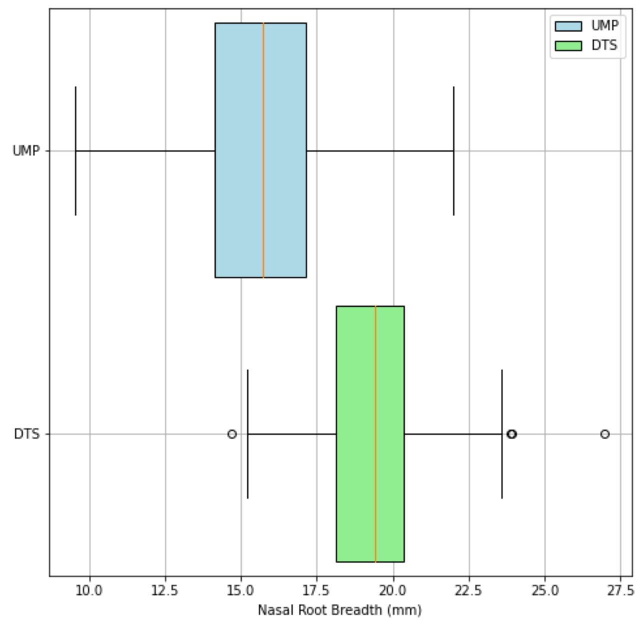


Figure 38: *Boxplot of nasal root breadth of UMP and DTS data*

The difference in nasal root breadth could be explained by the difference in measurement type used between the DTS and UMP data.

On average the DTS group has a larger head, but a smaller face. The nasal root breadth and nose length is larger. The DTS group has a less protruded (pointy) chin compared to their American counterpart, based on the bitragion chin and subnasale arc.

To evaluate the possibility of gender specific oxygen mask design, the DMS and DFS groups were compared. The full comparison can be found in appendix D. On average Dutch males have a bigger head an larger face compared to their female counterpart. Although females have a shorter nose length, the nose width and nasal root breadth is similar

Due to the current absence of female fighter pilots in the RNLAF and the small amount of active fighter pilots, it was decided not to further research gender specific oxygen masks for the redesign. To better accommodate female facial features for the future, the DTS group was chosen to further evaluate the current design.

4.3.4 Conclusion

Based on the assumption that the filtered data could represent the fighter pilot population of the RNLAF, significant facial measurement differences were seen compared to the American pilot data on which the oxygen mask is based.

Although these differences could be explained by the different measurement types used, it still suggests that USAF male pilots from 1967 have a different face compared to current RNLAF fighter pilots.

Dutch males and females significantly differ in facial measurements. However, it was decided not to further research the possibility of gender specific oxygen masks. The differences in facial measurements suggest that the current oxygen mask design does not fit the DTS group properly and the 3D shape should be looked into.

4.4 Physical fit evaluation

A good fitting product should not deform by a large amount to accommodate it's user. The shape of the product should have a shape which roughly represents the body dimensions of the user for the intended use. To get a better understanding of how the current mask deforms to the face, physical representations of users were made, onto which the oxygen mask was pressed, Figure 39. The silicone facepiece will deform to the face when pressure is applied.

Figure 39: *Oxygen mask laying on foam face*

4.4.1 Subject selection

Four extremes of the Lip width and sellion-supramenton from the Medium-Narrow sized subjects were chosen, Figure 40. The subject ID's can be seen in Table 6. These extremes were milled out of foam.

The average face of the Medium-Narrow sized subjects was created from the corresponding 3D scans. This average face was created in ParaView (Sandia National Laboratories et al., 2000) and 3D printed.

Subject ID from DTS data	
Extreme	ID
1	6630
2	5514
3	5955
4	6337

Table 6: *Subject ID's of chosen extremes*

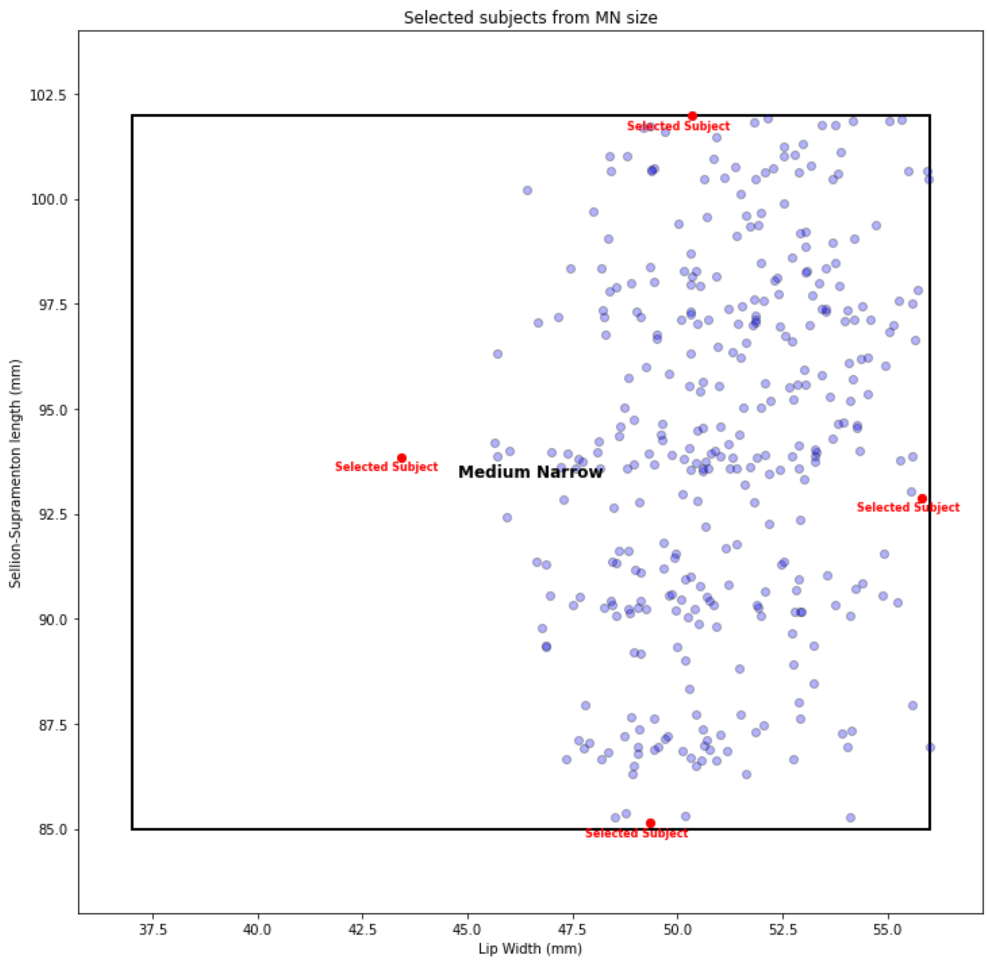


Figure 40: *Distribution of chosen subjects from MN group*

4.4.2 Chin gap

A gap at the chin was seen when the oxygen mask was pressed into the face Figure 41. Only by increasing the pressure of the oxygen mask on the face this gap could be closed by the facepiece deformation. The chin gap was also seen on the average face and was more present. This gap could be caused by the difference in chin protrusion seen in the facial measurements comparison.

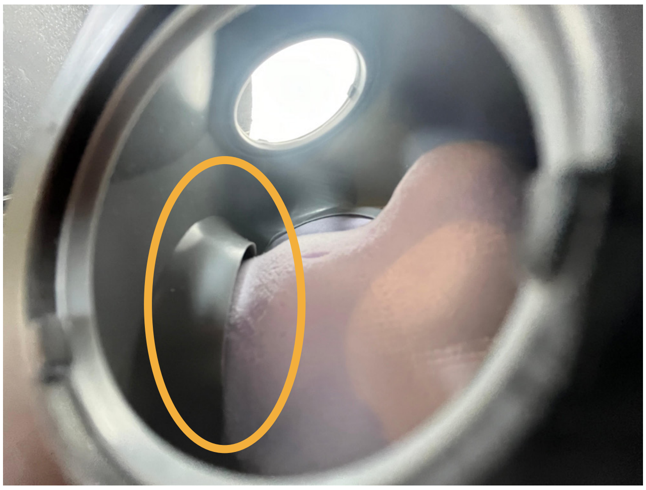


Figure 41: *Highlight of chin gap at the chin of subject 5955*

4.4.2 Nasal root gap

On some faces a gap on the nasal root occurred when the oxygen mask was pressed into the face, Figure 42. This gap could be closed by increasing the pressure of the oxygen mask on the face, increasing the facepiece deformation.

The nasal root gap was also seen on the average face, yet slightly less present. This gap could be caused by the difference in nasal root breadth seen in the facial measurements comparison.

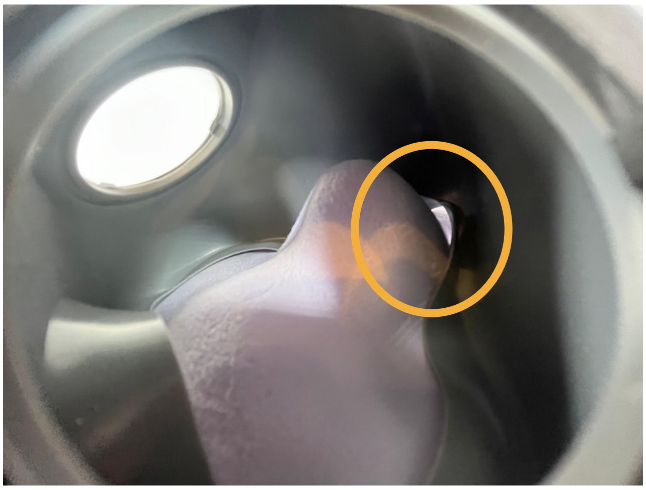


Figure 42: *Highlight of nasal root gap of subject 5514*

4.4.3 Rigid materials and skin deformation

The deformation seen could be more extreme compared to reality. As the faces onto which the oxygen mask was pressed were made from rigid material. Actual faces will deform together with the silicone facepiece, because of the soft tissue in the face. A better method to quantify the fit of the mask is needed, which takes the soft tissue of the users into account.

4.4.5 Conclusion

Simple physical fit evaluation indicates that the 3D shape of the Medium-Narrow oxygen mask does not correspond with subjects of the Medium-Narrow sized DTS subjects.
Gaps are seen at the chin and nasal root, only by increasing pressure these gaps could be closed. This increased pressure will probably increase the experienced discomfort when wearing the oxygen mask.

The 3D design of the mask and it's corresponding deformation to the face of the user will have an effect on the experienced discomfort. A more advanced form of analysis is needed to understand the fit of the mask and it's corresponding discomfort. The gaps at the chin and nasal root should be taken into account while redesigning.

4.5 Facial pressure sensitivity and soft tissue thickness

As discussed in chapter 3, some facial areas of pilots were less sensitive to discomfort.
To better understand how exerted pressure of the oxygen mask onto the face is experienced by pilots, pressure sensitivity of the face needed to be looked into. The deformation of the face by the oxygen mask has an effect on the fit of the mask, thus more knowledge of facial soft tissue thickness was needed.

4.5.1 Pressure discomfort threshold in adults

A study conducted by Smulders et al. (2023) looked at the perceived pressure discomfort threshold (PDT) in kPa of males and females. The researchers found indications that no gender deviation is needed in product design, when looking at the PDT (Smulders et al., 2023). Figure 43 shows the PDT of males and females combined.

The research shows that the PDT differs across the face. The PDT of the nasal root is higher than the cheekbone. The differences in PDT should be taken into account when redesigning.

4.5.2 Facial soft tissue thickness of Caucasians

A large scale study conducted by De Greef et al. (2006) looked at the soft tissue thickness (STT) of 967 Caucasian males and females, varying in age and BMI. The study measured the STT of 52 landmarks on the face in mm.

The landmarks, number, name and description can be found in appendix C.

To better understand the mean STT of the DTS, DMS & DFS, values of the 20-25 BMI range and age groups of 18-59 were averaged for these subjects and per gender.

The resulting values were used to create a heatmap of average facial STT for the DTS, DMS & DFS in rhino/grasshopper (McNeel & Associates, 2010). No big deviation in STT was seen in the selected male and female values, the average heatmap of STT the selected values is shown in Figure 44.
All values and heatmaps can be found in appendix C.

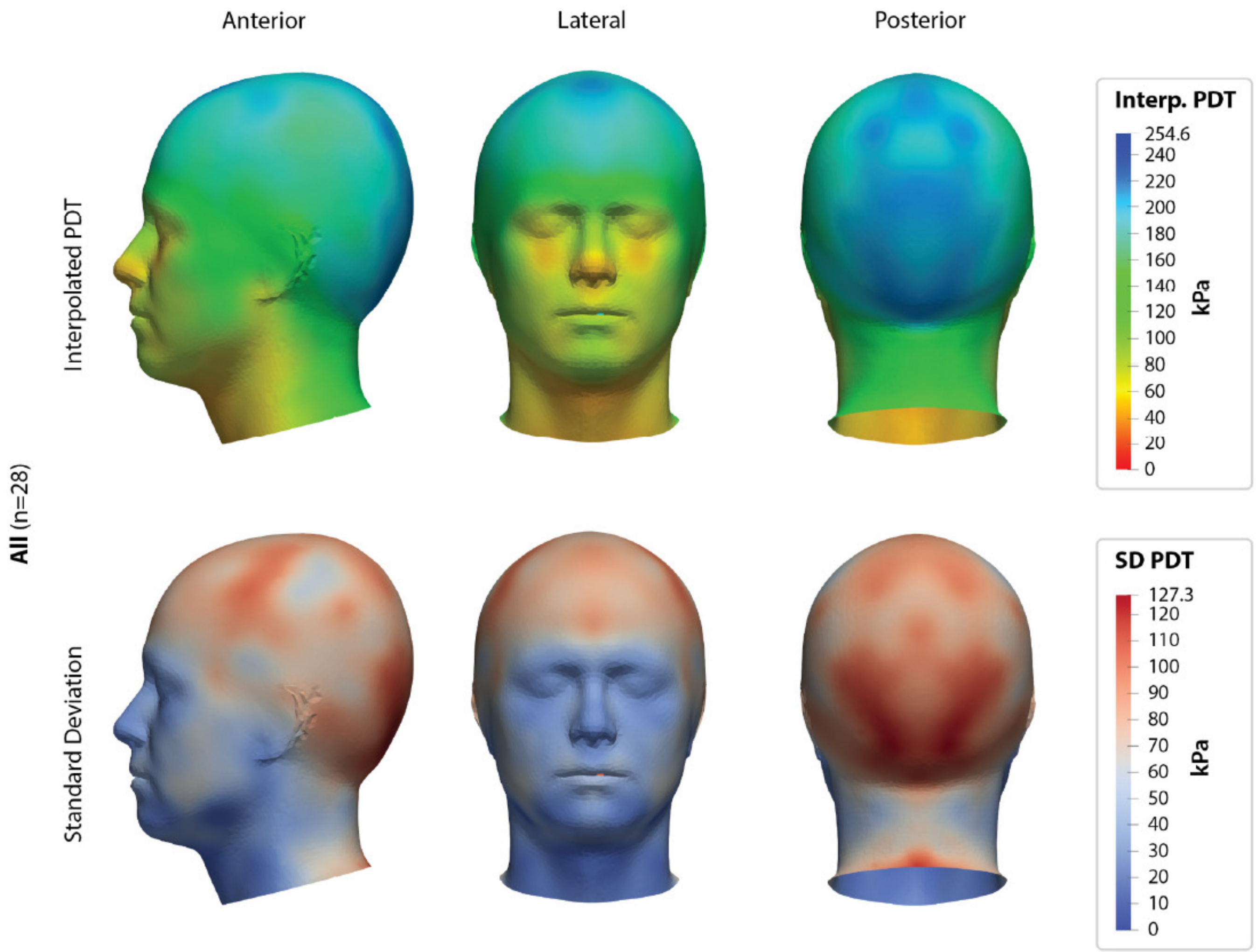


Figure 43: *Mean and SD interpolated PDT map in kPa of all participants (Smulders, et al., 2023)*

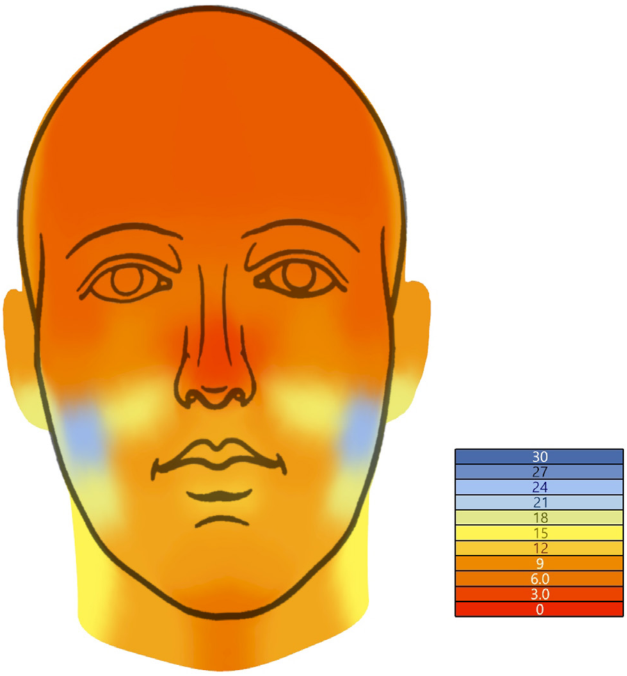


Figure 44: *Average soft tissue thickness in mm, based on values of De Greef et al. (2006)*

The heatmap indicate the average maximum possible intrusion distance of the mask into the face. However, an intrusion of the maximum distance will lead to a lot of pressure and discomfort. The soft tissue can only be compressed a certain amount, so a margin is needed when redesigning to prevent this increased pressure.
The nasal root area shows the least amount of STT.
The cheekbone areas, together with the cheeks show the highest amount of STT.

4.5.3 Conclusion

The PDT and STT provide good insights into the interaction of the mask shape, face of the user and how this can influence their experienced discomfort.
The nasal root area has a little amount of soft tissue, yet a fairly high PDT.
The cheekbone areas have a lot STT, yet are more sensitive when looking at PDT. This should be taken into account when redesigning the facepiece.

4.6 Virtual fit analysis

As the mask size and 1D facial measurements are not the only factor of determining the fit and perceived discomfort of the mask, a better understanding of the 3D shape of the facepiece was needed.

The shape of the mask, with regards to the face of the user has a big effect on the fitting, pressure needed to create a seal and (dis) comfort associated with the mask.

To create a better understanding of how the shape of the mask effects the fitting and (dis)comfort, an algorithm was made in Rhino/Grasshopper (McNeel & Associates, 2010) to analyse the mask fitting in 3D.

First a mask size was chosen and the part of the facepiece, which interfaces with the face of the user, was modelled in 3D. This created a 3D ribbon representing the mask.
Then a 3D head scan of a subject from the mask sizes was loaded into the algorithm.

The ribbon was then aligned with the face and the distances between the ribbon and the face was measured and plotted. These distances gave an insight into how the 3D shape of the interacts with the faces of the subjects and it's assumed pressure and deformation.

4.6.1 Mask size selection

With the original sizing system, described in Technical order MD 5901-00001 (Gentex & CMA, 2017), and the filter criteria from chapter 4.1, subjects were assigned into their corresponding mask sizes. The corresponding 3D scans were copied into these groups.

Table 7 shows the amount of 3D scans per mask size.
For further analysis the Medium-Narrow mask was used, as this mask size had the most subjects. This increased the information density, which resulted in better analysis outcomes.

size	subjects
XSN	22
SN	32
MN	252
MW	50
LW	43

Table 7: *Amount of 3D scans from DTS data per mask size*

4.6.2 Ribbon modelling

The ribbons of the mask sizes were modelled as a 3D surface, with no thickness.
The ribbon of the Medium-Narrow can be seen in Figure 45 and the corresponding 3D modelled ribbon can be seen in Figure 46. For all mask sizes a ribbon was created.

Figure 45: *Ribbon of MN oxygen mask*

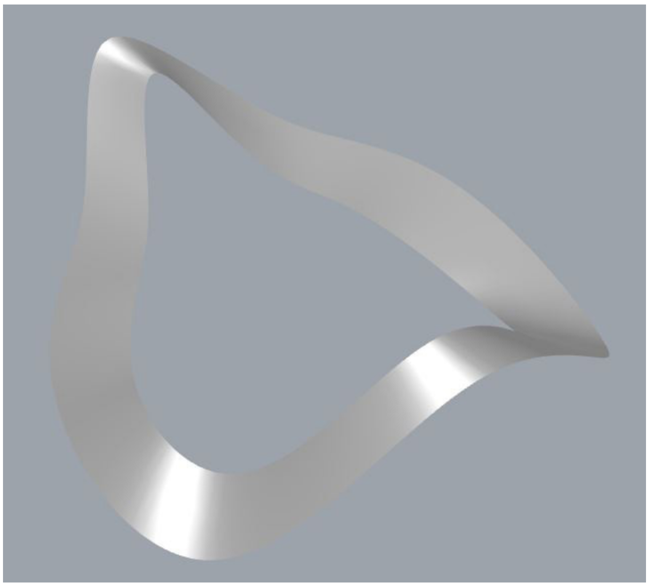


Figure 46: *3D ribbon of original MN oxygen mask*

4.6.3 3D algorithm

A 3D Virtual Fit Analysis (VFA) algorithm was created in Rhino/ Grasshopper (McNeel & Associates, 2010) to gain insight into how the 3D shape of the ribbon influences the fit of the oxygen mask on the face. The flowchart of this algorithm can be seen in Figure 47.

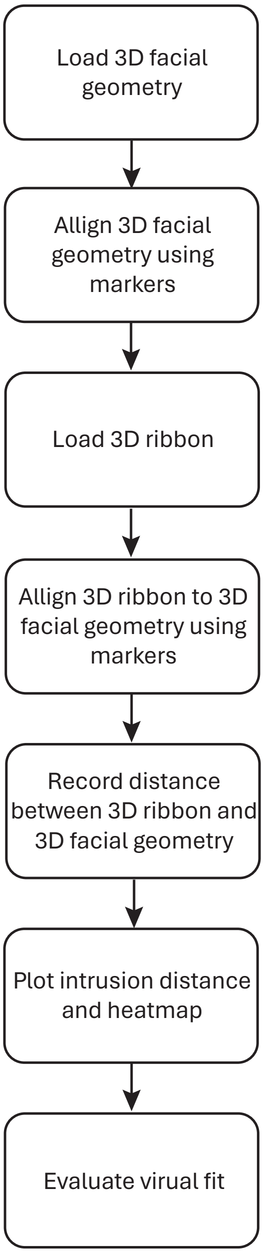


Figure 47: *Flowchart of 3D evaluation algorithm*

First the facial geometry of a subject was loaded into the algorithm. With facial landmarks the geometry was then alligned onto the axis, Figure 48.

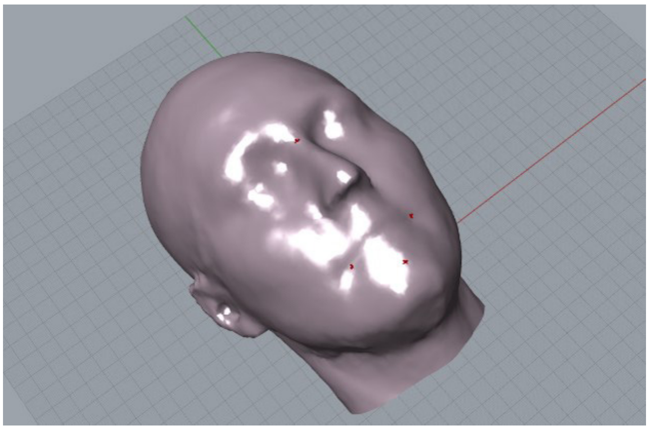


Figure 48: *Facial geometry alignment in grasshopper using facial landmarks*

The sellion-supramenton length was alligned with the y-axis of the 3D space, with the supramenton being on the origin.
Both cheillons (points of which the lip width is measured) were used to ensure the lip width was parallel to the x-axis, so the face was oriented to the z-axis of the 3D space.

This allignment step ensured that all 3D scans were oriented the same. The Z-plane of the 3D space can be seen as a sagittal plane of the face.

After the facial geometry was properly alligned the 3D ribbon could be placed onto the face.
The 3D ribbon was alligned on the face with the following landmarks: middle of the ribbon at the nasal area, bottom of the ribbon, left of the ribbon and right of the ribbon, Figure 49.

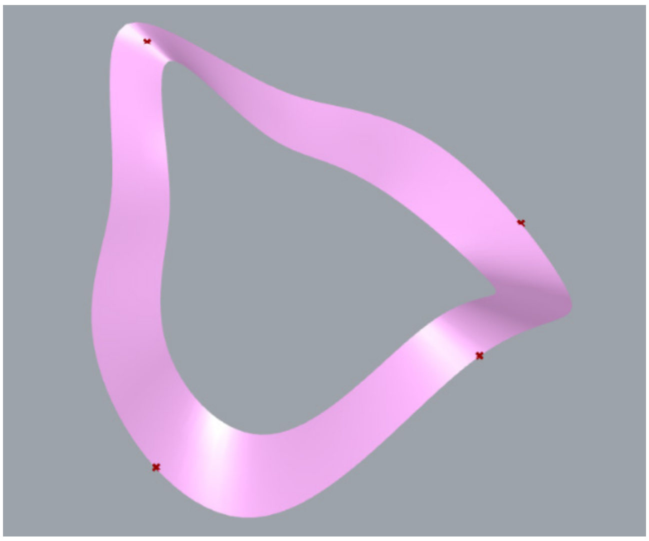


Figure 49: *Landmarks on the 3D ribbon*

The bottom of the ribbon was alligned with the supramenton of the facial geometry. The middle of the ribbon at the nasal area was alligned with the nasal root of the facial geometry.

The left and right landmarks of the ribbon were used to ensure the ribbon was alligned parallel with the cheilion landmarks. With these landmarks the ribbon could be consistently alligned with the facial geometries of the mask size group, Figure 50. The middle of the ribbon at the nasal area was chosen instead of the top of outer edge, as it was observed that the top of the outer edge does not touch the face of pilots when wearing the oxygen mask.

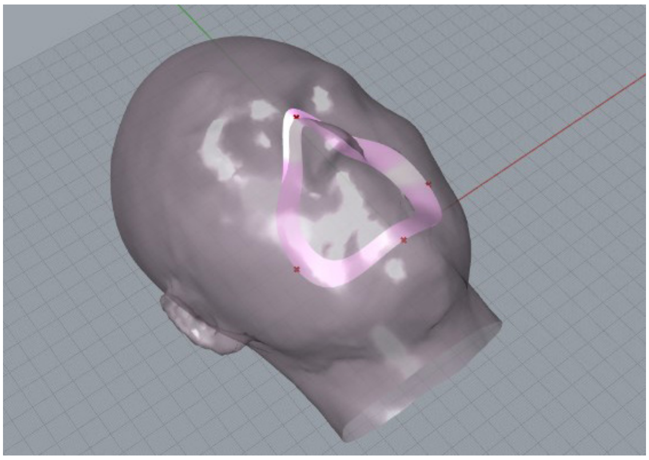


Figure 50: *3D ribbon aligned on the facial geometry*

The edges of the ribbon were populated with points on the outer and inner edge, with corresponding colours for further analysis. The colour assignment of the edges can be seen in Figure 51

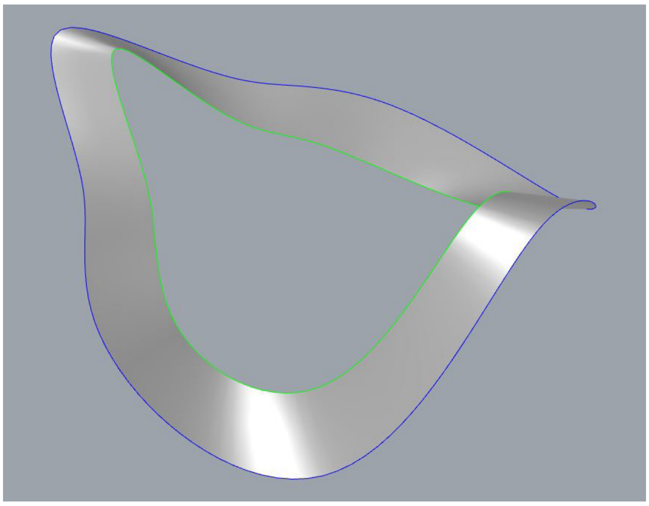


Figure 51: *Outer and inner edge of 3D ribbon with corresponding*

The points of the edges were projected onto the face in the Z-direction of the 3D space and the distance was measured per point, Figure 52.

This distance was dupped the intrusion distance, as it represents how far the 3D ribbon has intruded into the facial geometry.

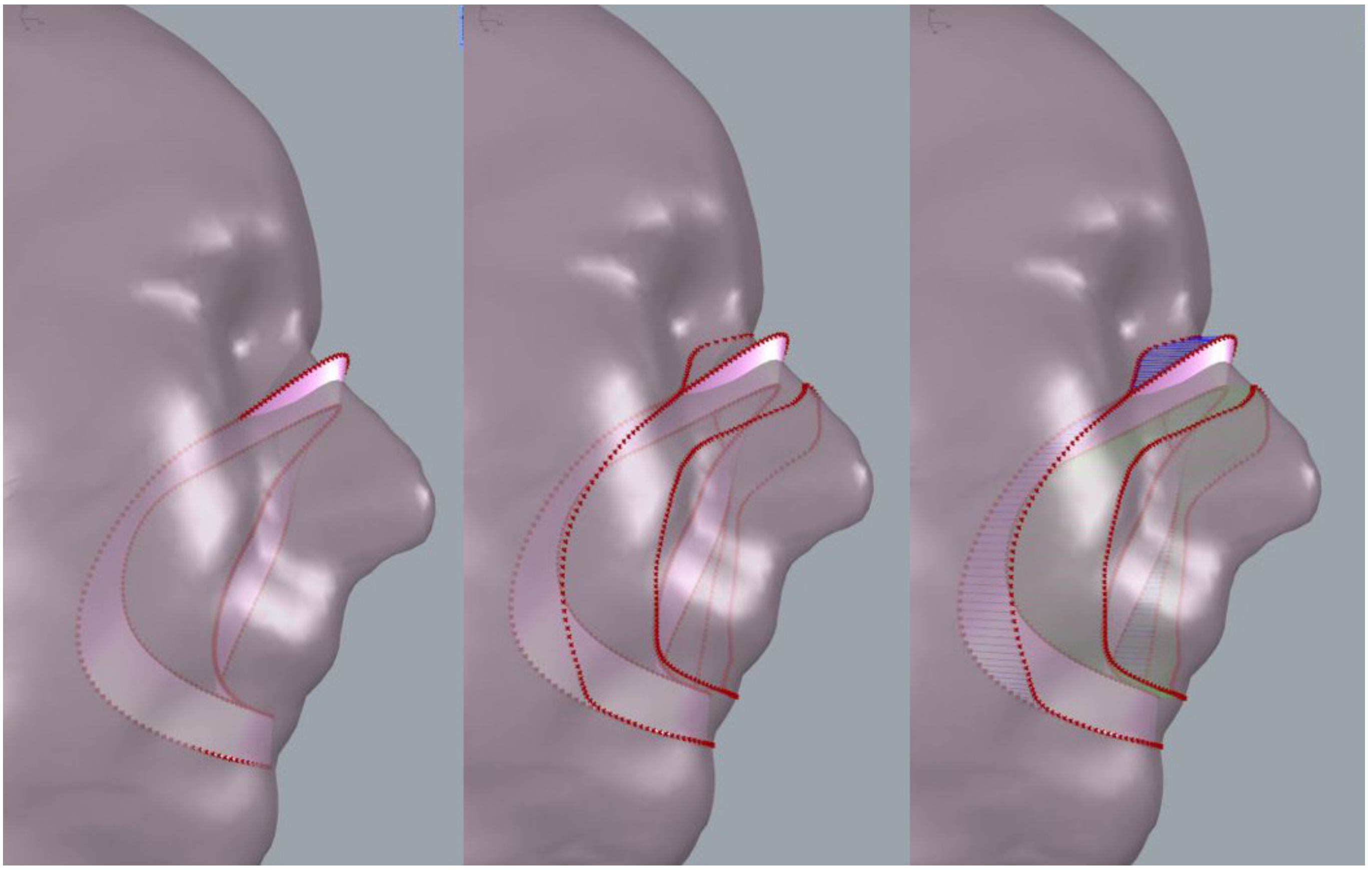


Figure 52: *Steps of measuring intrusion distance of 3D ribbon*

The hypothesis was that the higher this intrusion distance was at a specific location, the higher the applied pressure of the oxygen mask on the face would be.

Note that this analysis static and no deformation of the silicone facepiece or face was moddeld.

The measured distances were split through the Z plane into a left and right measurements. The left and right measurements were averaged per point to create a single representation of 100 measurement steps per edge from the top of the mask to the bottom and plotted in 2D.

This resulted in an intrusion plot per 3D ribbon where all subjects could be represented. A red line at a distance of 0 mm was added, as this represents the facial geometry boundary. The resulting plot of the Medium-Narrow mask can be seen in Figure 54.
A positive intrusion value can be seen as that part of the ribbon not touching the face.

Note that the ribbon has no linear shape, but is in a way unfolded to be plotted on a linear axis. To aid the understandability of the plot, the different facial regions are annotated in the plot.

The intrusion values of all subjects were averaged per point, to create a heatmap of the mask shape and can be seen in Figure 53.

The intrusion plot and corresponding heatmap show that the 3D algorithm is capable of visualizing the intrusion values of the 3D ribbon and the subjects of the mask size.

The PDT and STT differ across the face, absolute intrusion values do not give a full insight into the fit and experienced discomfort. These values needed to be incorporated in the analysis to better understand the 3D shape of the mask and the fit and experienced discomfort.

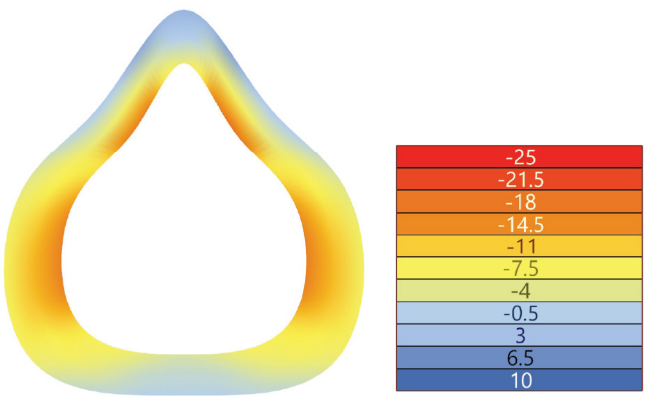


Figure 53: *Average intrusion distance in mm heatmap of MN 3D ribbon n=252*

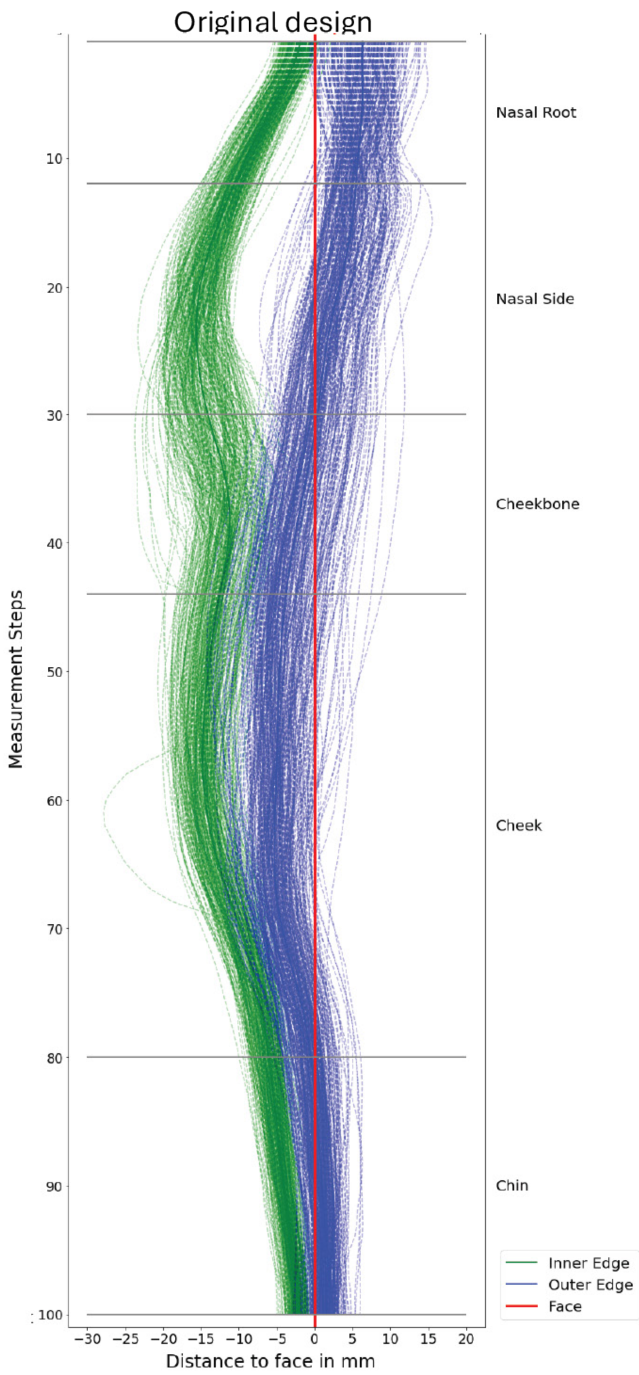


Figure 54: *Intrusion plot in mm of MN 3D ribbon n=252*

4.6.4 Maximum allowable intrusion values

The PDT and STT values of chapter 4.5 were analysed and together with expert fitters of the CMA and Collins Aerospace the maximum allowable intrusion values were defined per facial region.

As described in chapter 4.5.2 a percentage of the maximum STT was needed. This percentage was set at 80%. The upper bound of acceptable intrusion distances was also defined.
A heatmap of the maximum allowable intrusion values can be seen in Figure 55. The lower and upper bound can be seen in Figure 56.

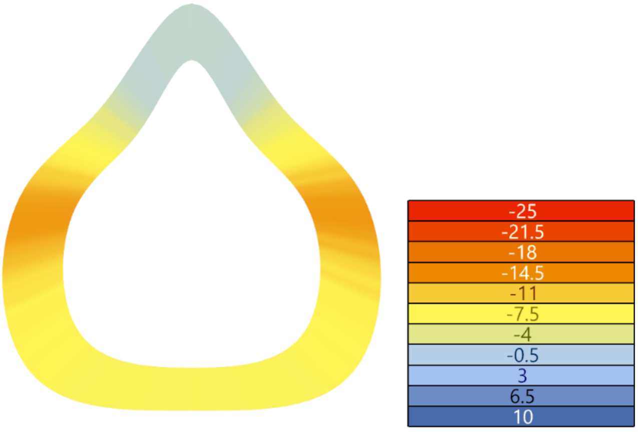


Figure 55: *Heatmap of maximum allowable intrusion values in mm*

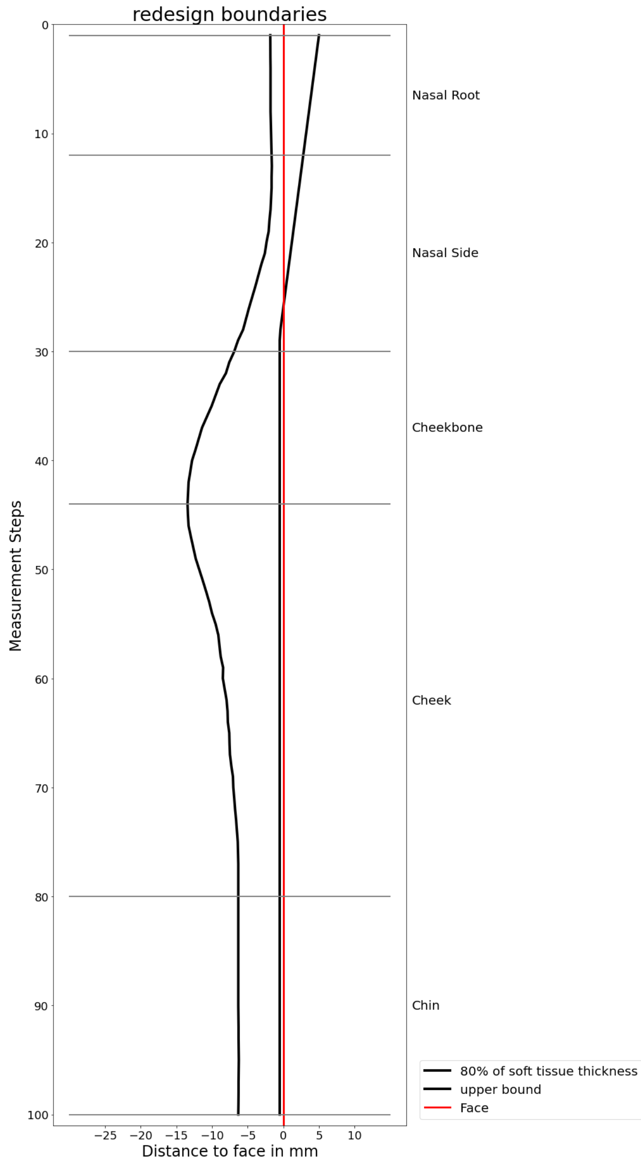


Figure 56: *Lower and upper bound of allowable intrusion values*

4.6.5 Evaluation of 3D ribbon on subject data

With the maximum allowable intrusion values, the measured intrusion values per 3D ribbon could be better evaluated. The intrusion distance plot and heatmap of the Medium-Narrow ribbon can be seen in Figure 57 & Figure 58. The percentage of average intrusion distance compared to the maximum allowable intrusion distance can be seen in Figure 59.

The plots show an excessive intrusion of the Medium-Narrow mask at the nasal area, suggesting that the facepiece shape could cause the discomfort at the nasal area seen in chapter 3.1. Figure 59 confirms the discomfort distribution seen in chapter 3.1, except for the chin area. Excessive intrusion was seen in all mask sizes. The nasal area scored the worst in all mask sizes. When redesigning the maximum allowable intrusion distance should not be exceeded as much as possible, attention should also be given to the nasal area

The intrusion distance plots and heatmaps of all mask size ribbons can be seen in appendix F.

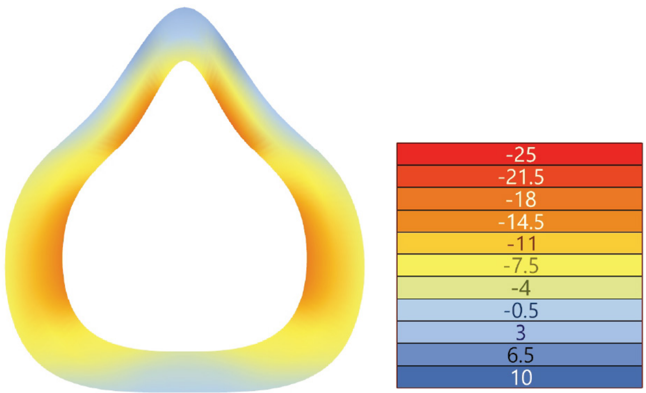


Figure 57: *Heatmap of average intrusion distance of MN ribbon n=252*

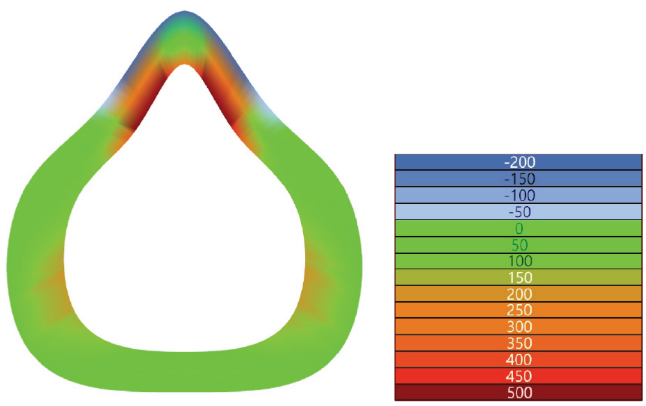


Figure 59: *Percentage of average intrusion distance compared to the maximum allowable intrusion distance of MN ribbon n=252*

The static alignment algorithm could explain the acceptable scores seen at the chin area, compared to the higher discomfort score seen in chapter 3.1.

The low middle of the outer edge of the is aligned with the supramenton. This will result in acceptable intrusion values, as little to no intrusion is seen with this alignment.
This also explains why middle of the ribbon at the nasal area is green in Figure 59, as this part of the ribbon is aligned with the nose of the subjects. Resulting in acceptable intrusion distances.

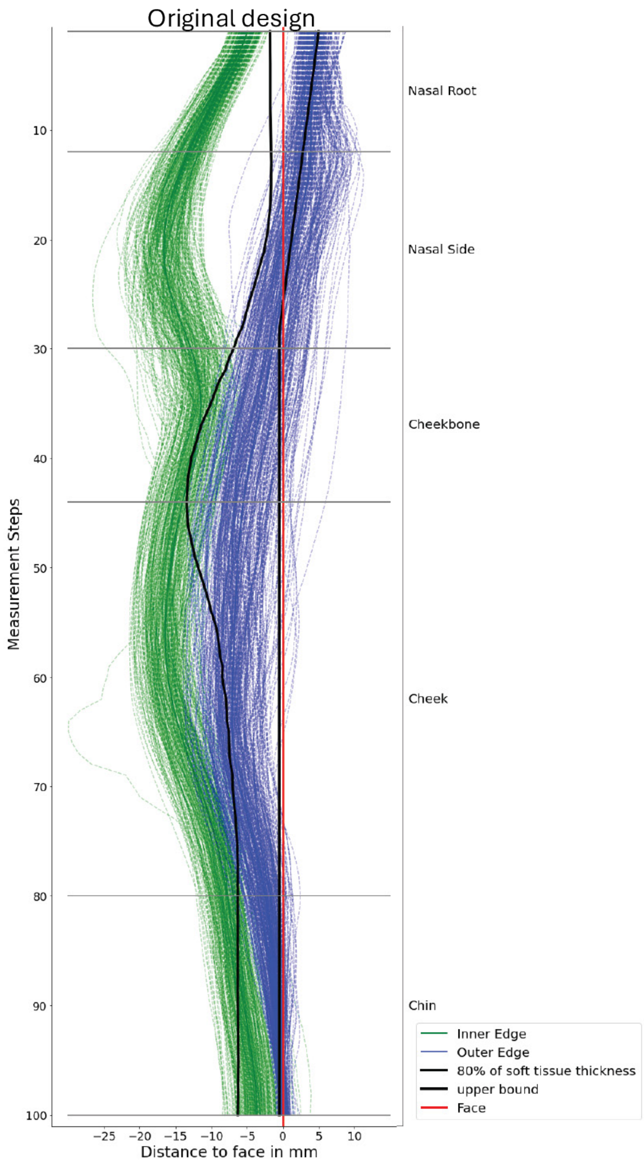


Figure 58: *Intrusion distance plot with bound of MN ribbon n=252*

4.6.6 Conclusion

The virtual fit analysis allows for a better understanding of the 3D ribbon of an oxygen mask influences the fit of the oxygen mask on subjects from the corresponding mask size.
If the PDT and STT are taken into account with the intrusion values a better understanding can be created of the mask shape and its associated discomfort.

4.7 Conclusion

By applying filter criteria, datasets could be created which better represent the fighter pilot population of the RNLAF, compared to the full CAESAR database. These datasets helped provide insights into the sizing system and differences in facial anthropometrics. The current sizing system cover the intended 94% the DTS population and could partially explain the discomfort experienced by fighter pilots.

The subjects from the DTS dataset have significantly different facial features compared to American fighter pilots from 1967 on which the oxygen mask design is based. Physical evaluation confirmed some of these differences, but proved limited in gaining a better understanding how the mask shape affects fit and discomfort.

The pressure discomfort threshold (PDT) and soft tissue thickness (STT) vary across the face, which is important to keep in mind during the redesign process. The virtual fit analysis (VFA) algorithm provides a visual understanding of how the mask shape interacts with facial features and the differences in PDT and STT, which could cause discomfort.

Excessive intrusion distance values were observed at the nasal area for all oxygen masks, which could be the main cause of the discomfort seen. Minimizing the intrusion distances during the redesign process could help reduce the discomfort experienced. The 3D shape of the facepiece should be altered to better fit the DTS subjects, which represent the fighter pilot community.

Combining statistical analysis, PDT, STT and the VFA algorithm provide a foundation for redesigning the oxygen mask to better meet the users' needs and be technically achievable. This creates a framework to create a more desirable and feasible design alternative for the current oxygen mask.

Chapter 5

Redesign framework

5 Redesign framework

The research indicates that redesigning the silicone facepiece of the MBU-20/P oxygen mask could help decrease the experienced discomfort of fighter pilots. Using the virtual fit analysis algorithm, with insights gathered about facial differences, PDT and STT, design alterations can be visually compared to the original design.
During the redesign process, multiple factors need to be taken into account. The final design must be able to pass flight safety regulations and existing procedures to ensure the design is implementable. Based on the research findings into the current mask design and pilot discomfort requirements and wishes for the new design could be formulated.

5.1 Research findings

The most important research findings were used to formulate requirements and wishes, which are listed below.

Manufacturer safety requirements
The current design of the oxygen masks has safety requirements to ensure safe operation of the product during flight. This resulted in requirement 1 and 2.

Sizing
Chapter 4.3 showed that the current sizing system accommodates 77% percent of the DTS population. This resulted in requirement 3.

Retrofittable
As the redesign will focus on the facepiece, the new design needs to be retrofittable with existing hardware to be implementable and maintainable. This resulted in requirement 4, 5, 6, 7 and 8.

Situational awareness
As the oxygen mask could be used during tense moments in flight, the mask cannot interfere with the situational awareness of fighter pilots. This resulted in requirement 9.

Discomfort
Discomfort of the mask is one of the main reasons for adverse mask usage, chapter 3, as the proper use of the oxygen mask is important for the safety of the fighter pilot wish 1 was formulated. The localized pressure point on the nasal root, chapter 3.1, was identified as a major contributor to the discomfort experienced. This resulted in wish 2, 3 and 4. Mask instability and movement, chapter 2.2 & chapter 3.2.1, contribute to the increased discomfort, resulting in wish 5. The VFA, chapter 4.6, showed high intrusion distance values with the current design, resulting in wish 6.

Costs
Viability needs to be kept in mind for a good design, chapter 1, resulting in wish 8.

5.2 Requirements

1. The design needs to pass the oxygen pressure leakage test
   - 1.1 With 9 inches of water pressure the oxygen flow to keep the mask pressurized cannot exceed 100 SLPM (Gentex & CMA, 2017).
   - 1.2 With 16 inches of water pressure the oxygen flow to keep the mask pressurized cannot exceed 100 SLPM (Gentex & CMA, 2017).
2. The mask cannot be blown of the face at an air blast of 600 knots (Gentex, 2023).
3. The new sizing system should accommodate 94% of the target population.
4. The facepiece is made from a skin-contact safe silicone with a shore hardness of 45A
5. The mask needs to fit in combination with the helmet system of F-16s and F-35s and cannot be larger than the original mask.
6. The mask should accommodate current valves, tubes and communication equipment.
7. The facepiece needs to fit in current hardshell
8. The facepiece needs to be cleanable
9. The mask cannot interfere with the situational awareness of
   - 9.1 Cannot obstruct the sight of the user
   - 9.2 Cannot limit head movement

5.3 Wishes

1. The new design should minimize discomfort perceived by the user.

2. The localized pressure point on the nasal root/nasal side should be eliminated or decreased as much as possible.

   2.1 The new design should prevent force localization on the nasal root under high-G loading.

3. The mask should have a more even pressure distribution.

4. The pressure of the mask on the face while wearing should be decreased by at least 30%

5. Mask tilt and movement should be minimized during high-G loading

6. The intrusion distance should not exceed the 80% of soft tissue thickness at a given area. This distance should be as low as possible.

7. The mask cannot have sharp edges in contact with the face

8. The production cost of the mask should be as low as possible

5.4 Conclusion

Keeping the requirements and wishes in mind during the redesign process will result in a design solution which is more suitable to address the needs of the users, compared to the original design. By focussing on reducing discomfort it is thought that the redesign will have an increased desirability.

Keeping production costs, technical requirements for safety and retrofittability in mind, will result in a design which is both technically and operationally viable. The primary focus of the redesign will be on the facepiece, where most improvements can be realized.

Chapter 6

Redesign and prototyping

6 Redesign and prototyping

The Rhino/Grasshopper (McNeel & Associates, 2010) VFA algorithm provided a method of evaluating designs of 3D ribbons. To redesign the facepiece a parametric model was created to alter the shape of the 3D ribbon. After which the full facepiece could be modelled if a suitable ribbon shape was found.
The redesign it was chosen to focus on the Medium-Narrow mask size, as most subjects from the DTS population are in this group, Table 7.

The redesign was split into two phases. The first phase focused on the rough size and shape of the facepiece. After evaluation, the second phase focused on fine tuning the design. The design

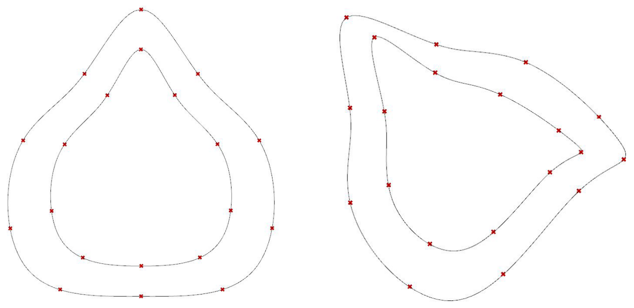


Figure 61: *3D and top view of MN ribbon modelling based on control points and splines*

6.1 Parametric model

Another algorithm was created to parametrically model 3D ribbons. The ribbon was created with control points and splines.

Each of the edges, outer and inner, were modelled with 10 control points through which the spline was created, Figure 61. Between the splines a surface was created.

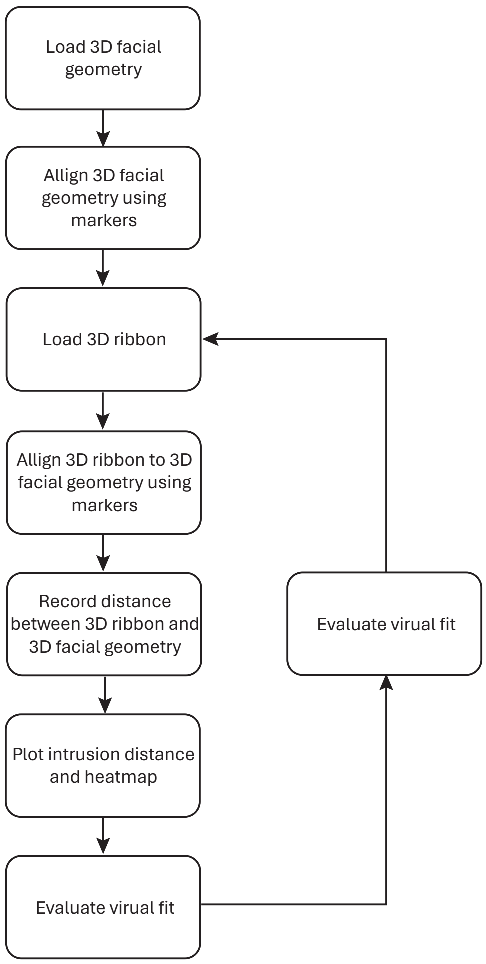


Figure 60: *Digital redesign workflow*

All control points could me moved in the XYZ directions, Figure 62. With the VFA algorithm each digital alteration could be evaluated for improvements, Figure 60. This enabled a quick and iterative digital design process.

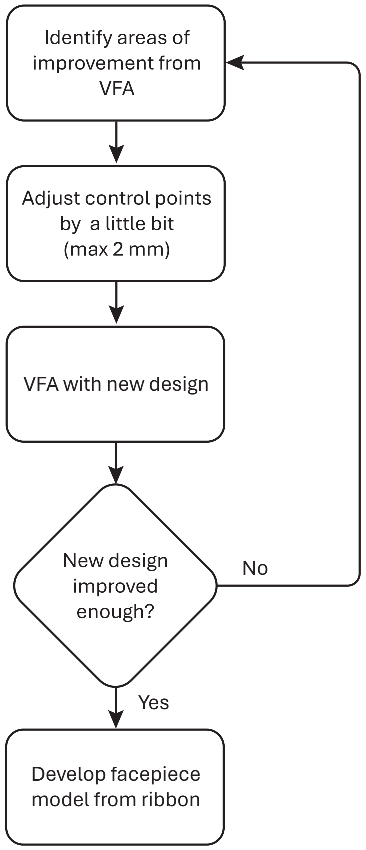


Figure 62: *Ribbon design alteration process*

6.2 First redesign

After 17 digital iterations a ribbon shape was created which showed good results in the VFA algorithm. Figure 63 shows the differences in shape of the original and the first redesigned ribbon. The nasal area is widened and the overall mask is less concave.

The intrusion plot and heatmap indicate a better fit of the ribbon design, Figure 64 & Figure 65.
The percentage fit plot shows a better fit compared to the original design, especially around the nasal area, Figure 66.

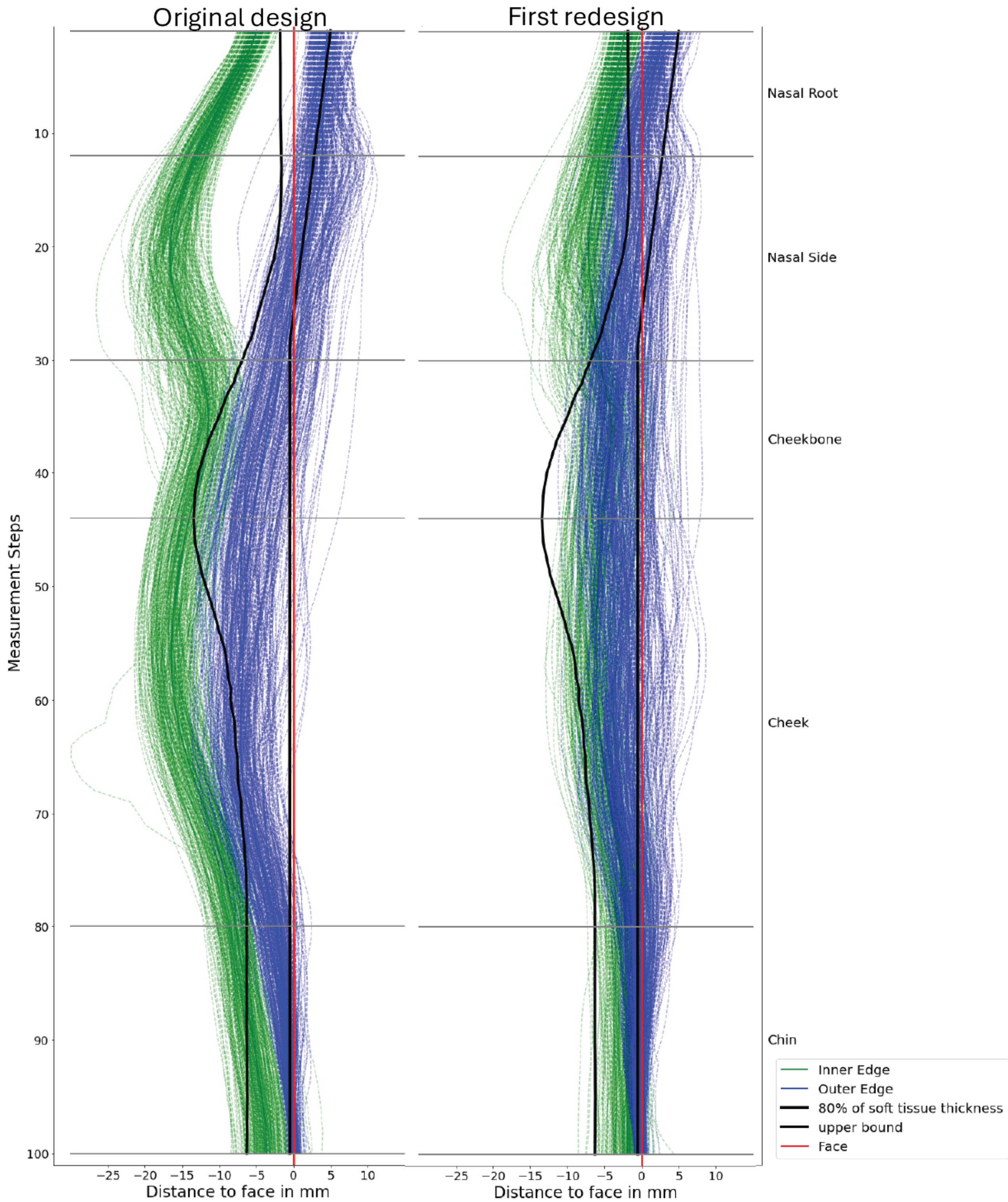


Figure 64: *Intrusion plots of original and first redesign n=252*

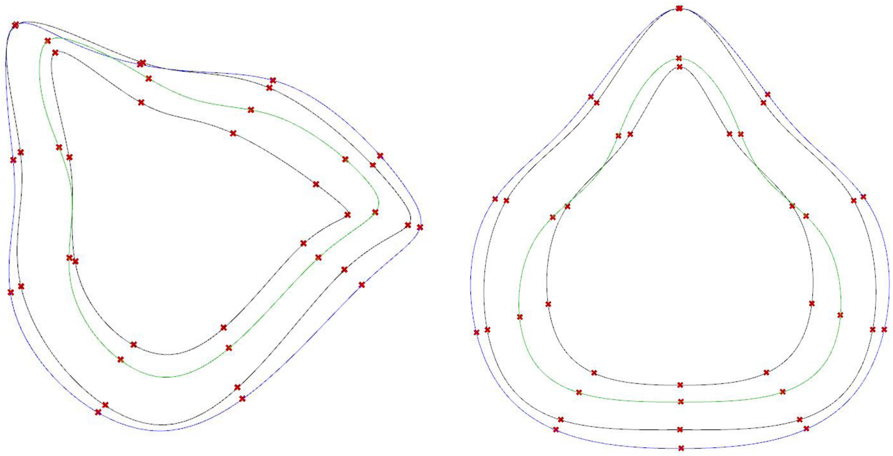


Figure 63: *3D and top view of ribbon splines of original (black) and first redesign*

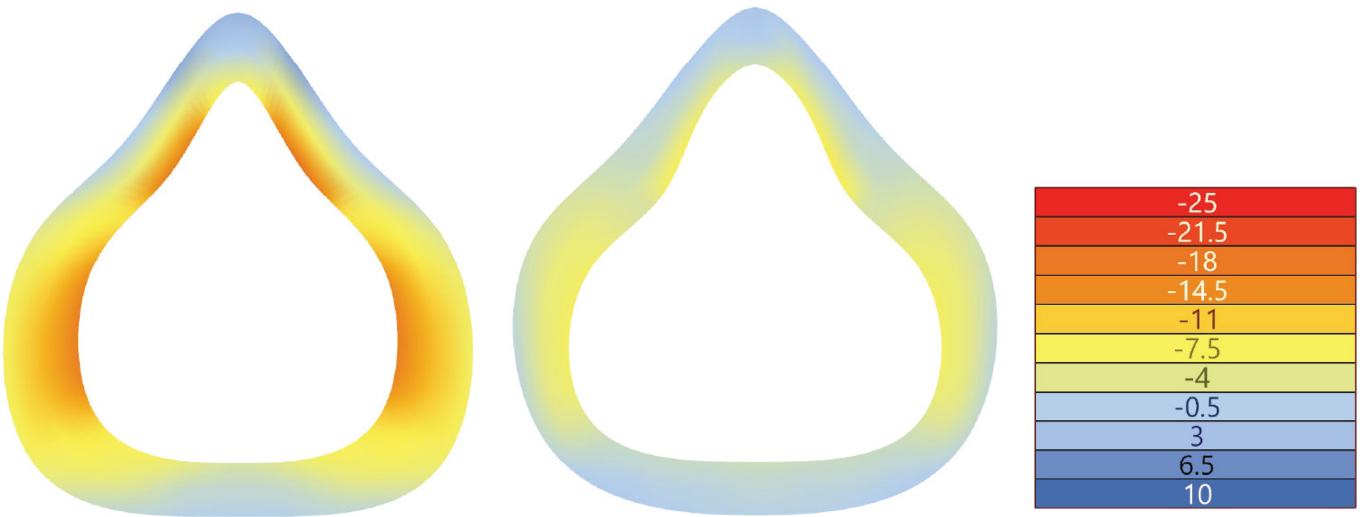


Figure 65: *Average intrustion distance (mm) heatmap of original and first redesigned ribbon n=252*

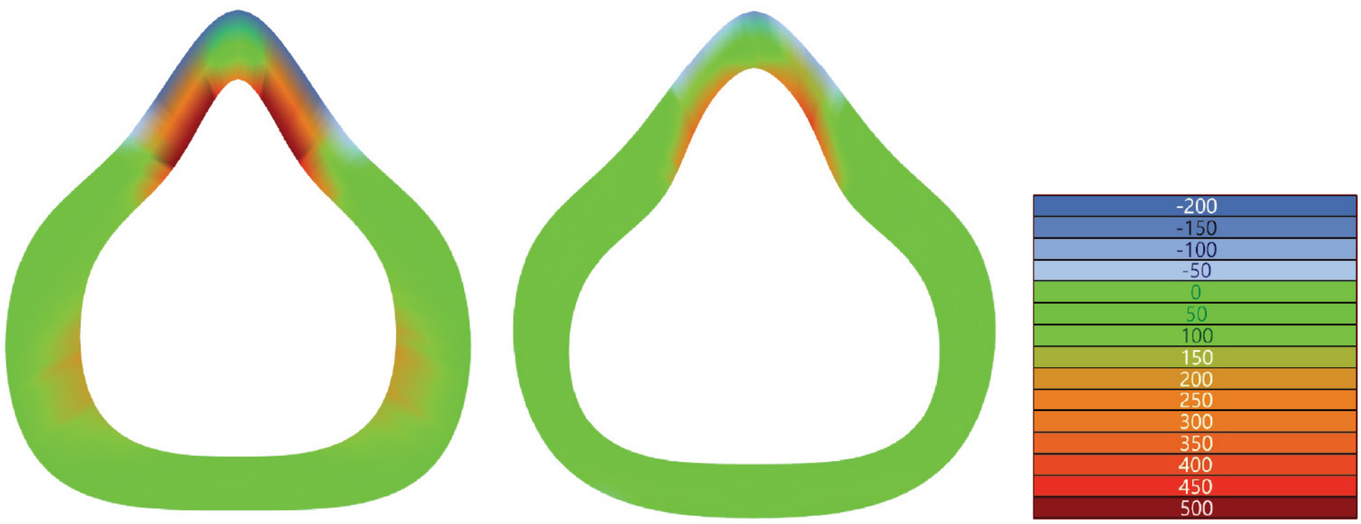


Figure 66: *Percentage of maximum allowable intrustion distance of original and first redesigned ribbon n=252*

6.3 First prototype

This first redesign of the ribbon was further developed into a facepiece design which would fit into the Medium-Narrow hardshell. A prototype was created of this model.
The fully modelled facepiece can be seen in Figure 67.

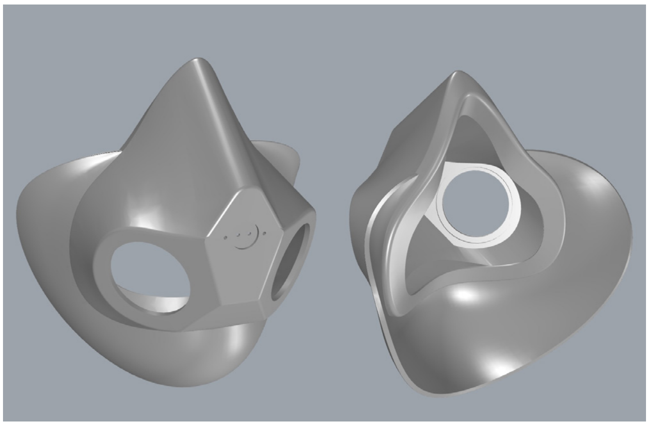


Figure 67: *3D model of the first MN redesigned facepiece*

The product needed to made from silicone with a shore hardness of 45A. It was decided to use chemically hardening liquid silicone for the prototyping. As it has similar properties to the compression moulded silicone facepieces used by Gentex.
3D printing was chosen as the manufacturing method for the moulds/tooling, because this was cheap, quick and readily available at IDE TU Delft. However, this eliminated the option to use compression moulding machines, as 3D printed parts cannot withstand high heat and pressure. The 3D printed mould can be seen in Figure 68.

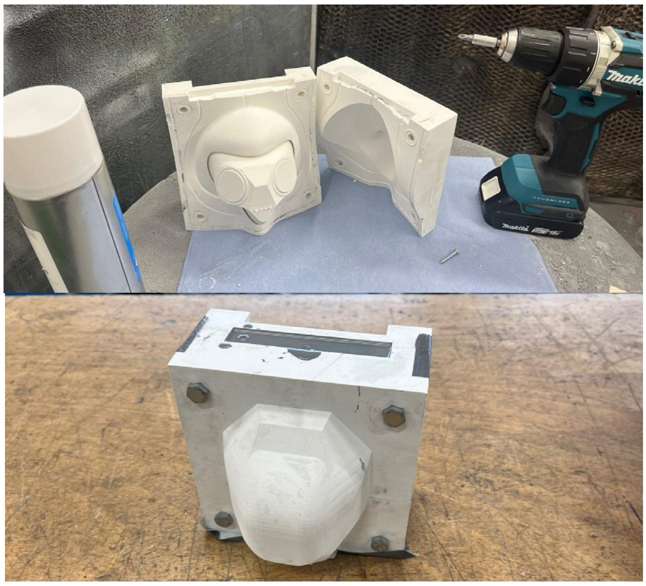


Figure 68: *Mould preperation and filling with silicone*

The resulting silicone prototype of the first redesigned facepiece can be seen in Figure 69.

Figure 69: *Silicone prototype of first redesigned facepiece*

6.4 First redesign evaluation

To get a better understanding of the first redesign, the prototype was physically evaluated by a professional fitter of the CMA/ Collins Aerospace, an aero physiologist and a F-35 pilot with a medium mask size. The design was discussed on improvements compared to the original design and possible improvements.
The F-35 pilot compared the original and redesigned facepiece by pressing them both onto his face. The pilot experienced less pressure and pinching of the mask around the nasal area. This indicates that the redesign would probably lead to less discomfort during flight. Some improvement points were also mentioned.
The experts noted that the ribbon in the prototype was too narrow and should be widened.

Due to the prototyping process the silicone thickness varied in some places of the mask, which could affect the material behaviour of the mask. The ribbon thickness was higher than the intended thickness.

The top of the prototype mask was also found to pointy by the experts. This increased the stiffness of the mask around the nasal root and could negatively affect the discomfort at the nasal root.
The prototype was assembled with the hardshell and valves, however the dimensions of the facepiece did not match the hardshell properly.

All experts saw the first redesign as an improvement over the original design. Taking the improvement points into account when further developing the redesign should result in a better designed facepiece.

6.5 Second redesign

The redesign was further developed, with the improvement points from the first evaluation and the requirements and wishes in mind. Overall the shape did not change significantly from the first redesign. After 24 digital iterations, a new ribbon shape was found with good results from the VFA algorithm, Figure 70.

The intrusion plot and heatmap indicate the second redesign would have a better fit compared to the original design, Figure 71 & Figure 72. The percentage of maximum allowable intrusion also indicate a better fit, Figure 73

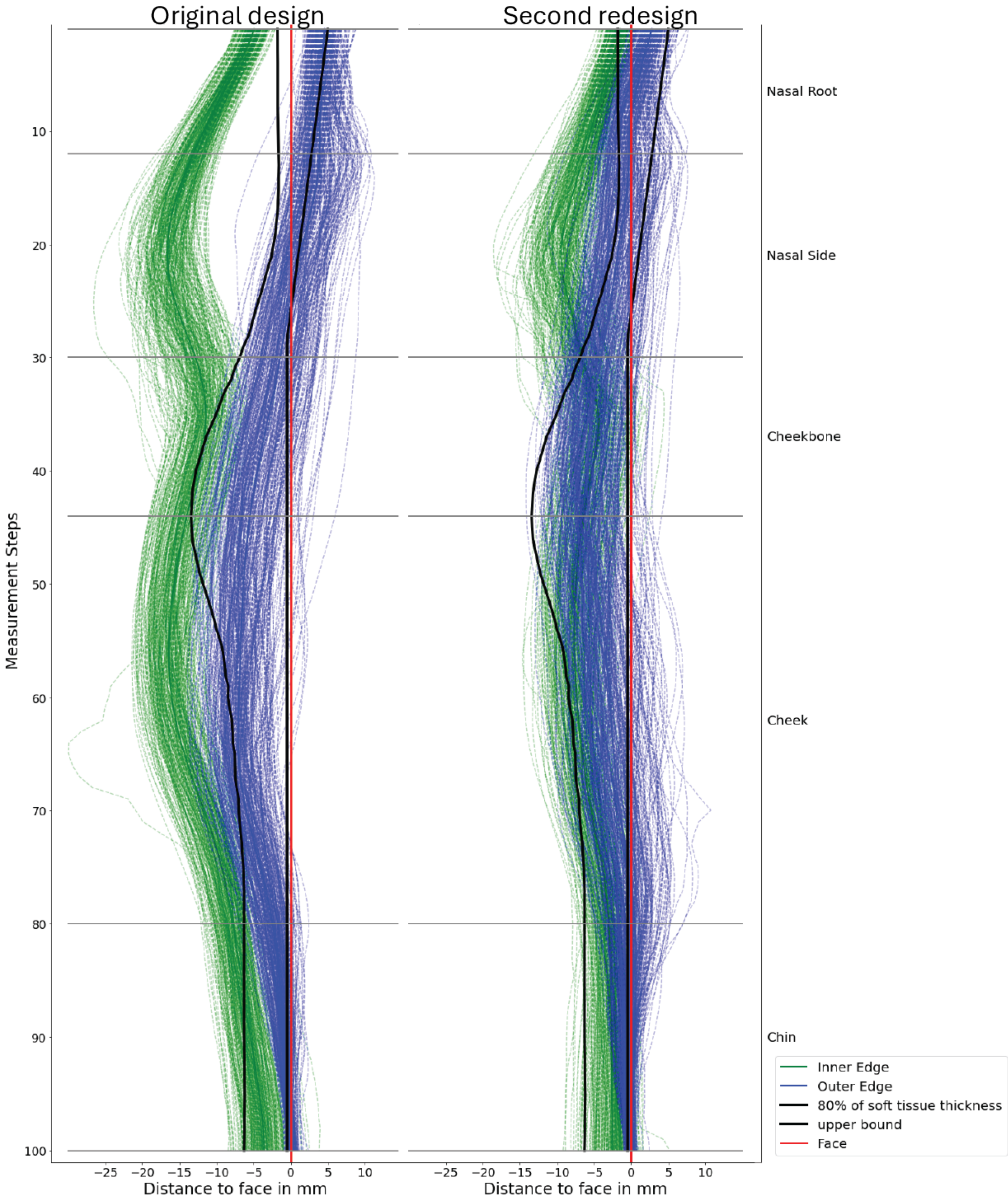


Figure 71: *Intrusion plots (mm) of original and second redesigned ribbon n=252*

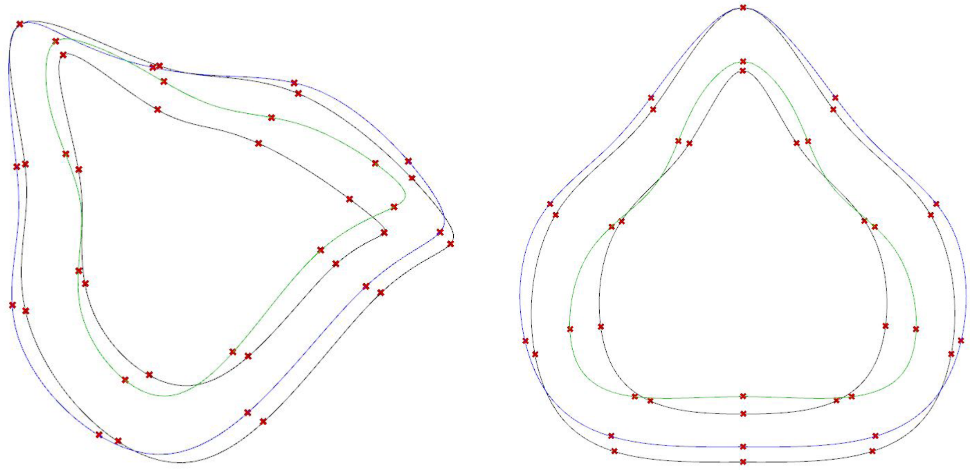


Figure 70: *3D and top view of ribbon splines of original (black) and second redesign overlayed*

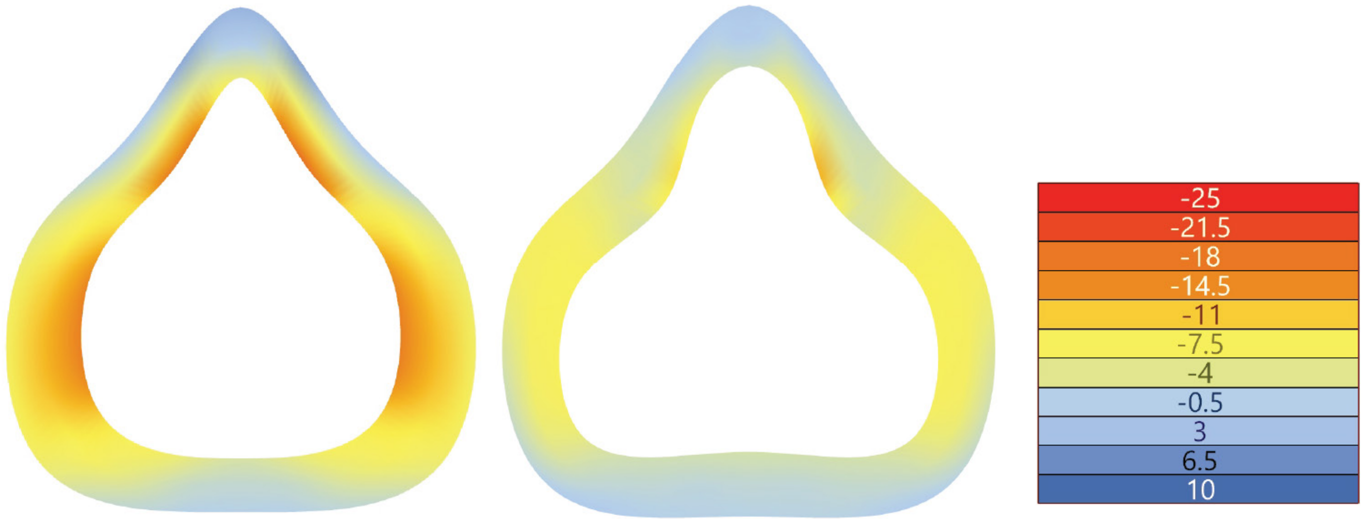


Figure 72: *Average intrusion distance (mm) of original and second redesigned ribbon n=252*

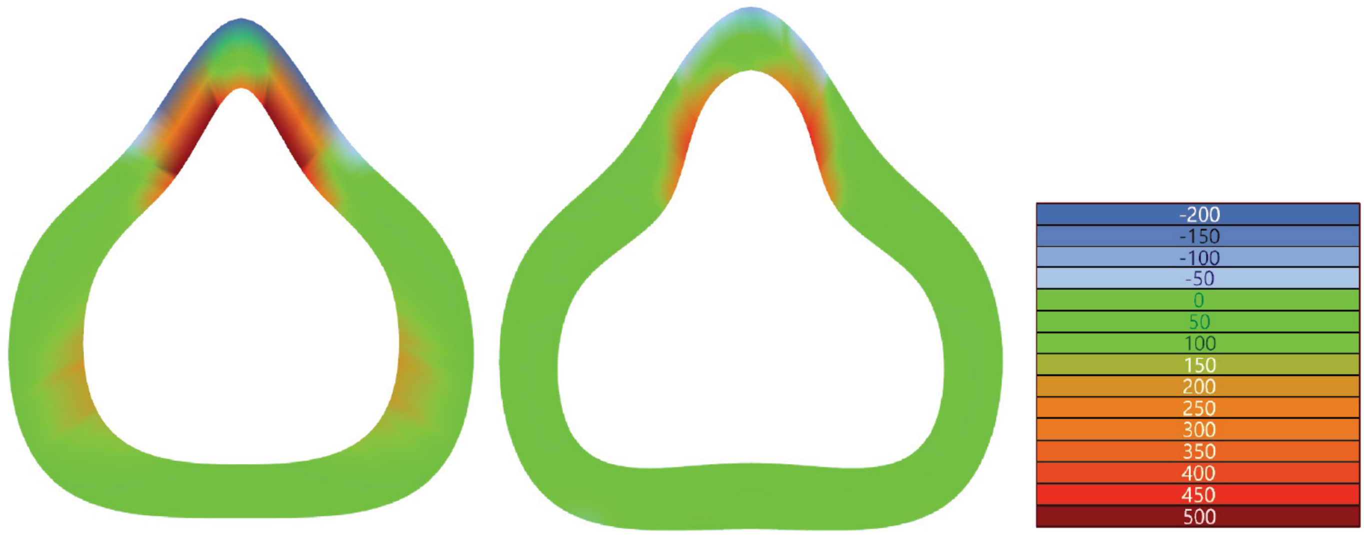


Figure 73: *Percentage of maximum allowable intrusion distance of original and second redesigned ribbon n=252*

6.6 Second prototype

The second redesigned ribbon was further developed into a facepiece design. The improvement points of the first evaluation were taken into account, resulting in the final design as shown in Figure 74. The second redesign has a wider and varied ribbon width, compared to the first redesign. The ribbon is wider at the cheekbone. A more rounded top of the facepiece was modelled to prevent stiffness of the facepiece at the nasal root.

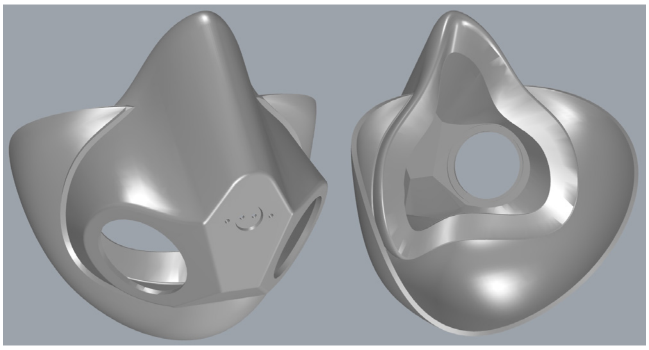


Figure 74: *3D model of second redesigned facepiece*

The same prototyping method of the first prototype was used. This resulted in the prototype of second redesign and can be seen in Figure 75.

Figure 75: *Silicone prototype of second redesign*

6.7 Redesign overview

With the VFA and ribbon design algorithms an iterative approach for designing the ribbon of the facepiece was shown. The intrusion plots, heatmaps and intrusion percentage heatmap of the three (original, first and second redesign) can be seen in Figure 76, Figure 77 and Figure 78.

The intrusion plots and heatmaps show a higher intrusion of the second redesign compared to the first redesign.
This is due to the increased width of the ribbon and the static intrusion analysis. The increased intrusion values were still within the acceptable range compared to the original design.
The nasal area exceeds the maximum allowable intrusion distance in both redesigns.

A lot of variation was seen in the shape of the nose of subjects. This made it difficult to design a shape which could accommodate all noses properly. The exceeded limits are only shown on the inside of the ribbon, which is the part of the ribbon which can deform most to the face of the user. It is suspected that this will not have a great impact on the fit of the redesigned mask.

The VFA does not give a complete picture of the oxygen mask fit, as deviations will be in the fit of each subjects and the VFA aligns the ribbon in a fixed manner. The fit and deformation of the facepiece could vary between subjects and this could influence the facepiece behaviour in real life use.

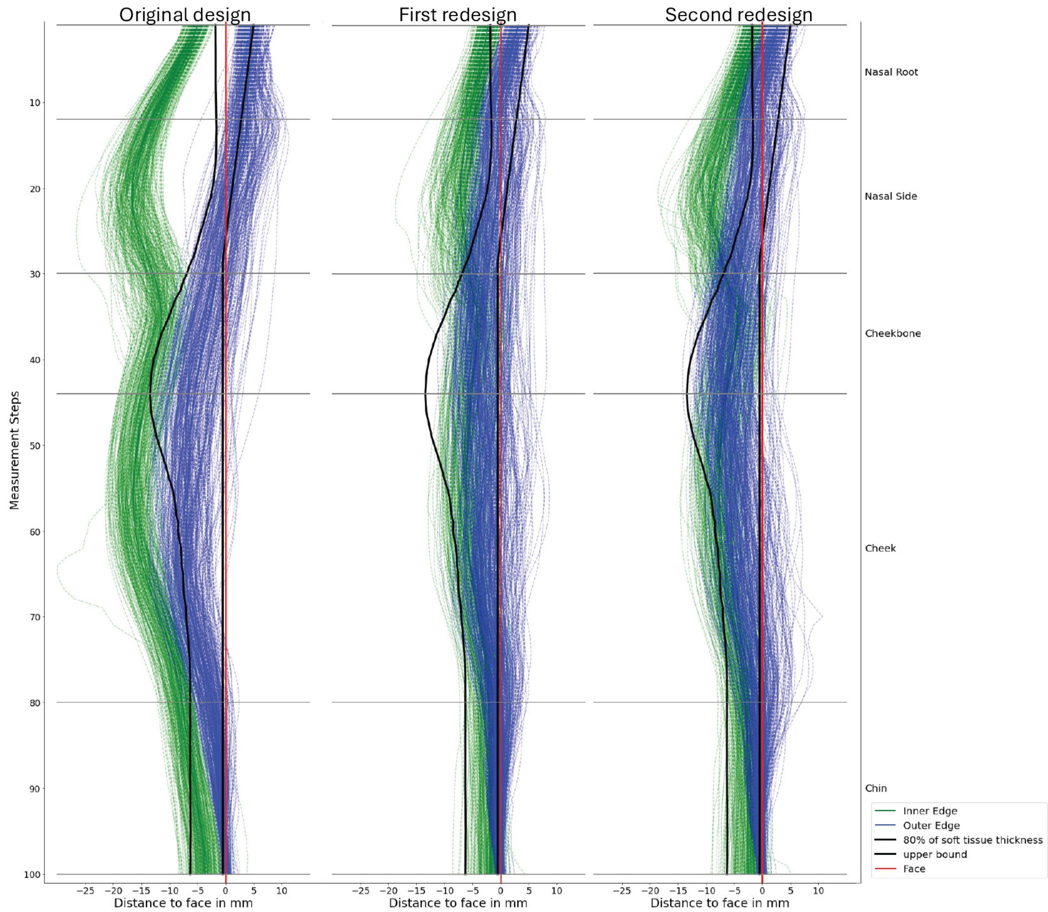


Figure 76: *Intrusion plots of original, first and second redesigned ribbon n=252*

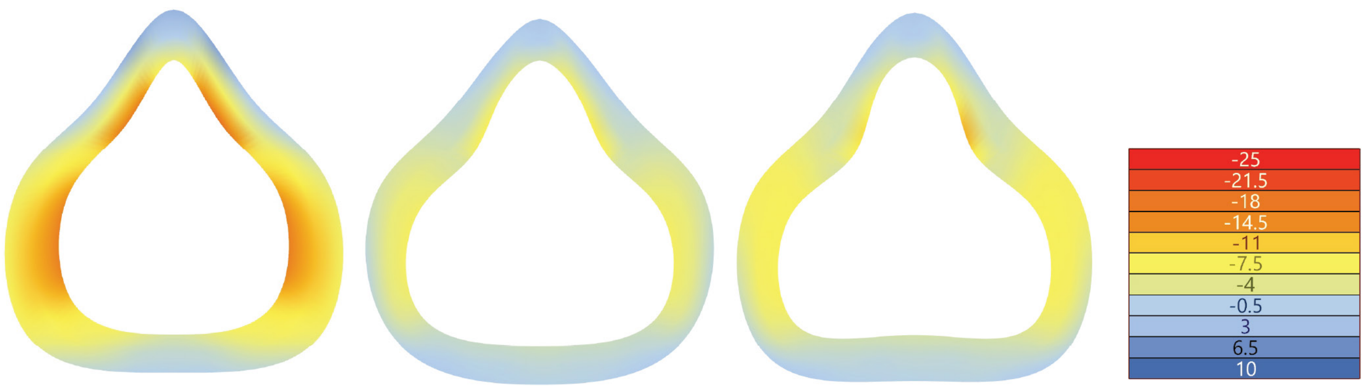


Figure 77: *Heatmaps of average intrusion distance of original, first and second redesigned ribbon n=252*

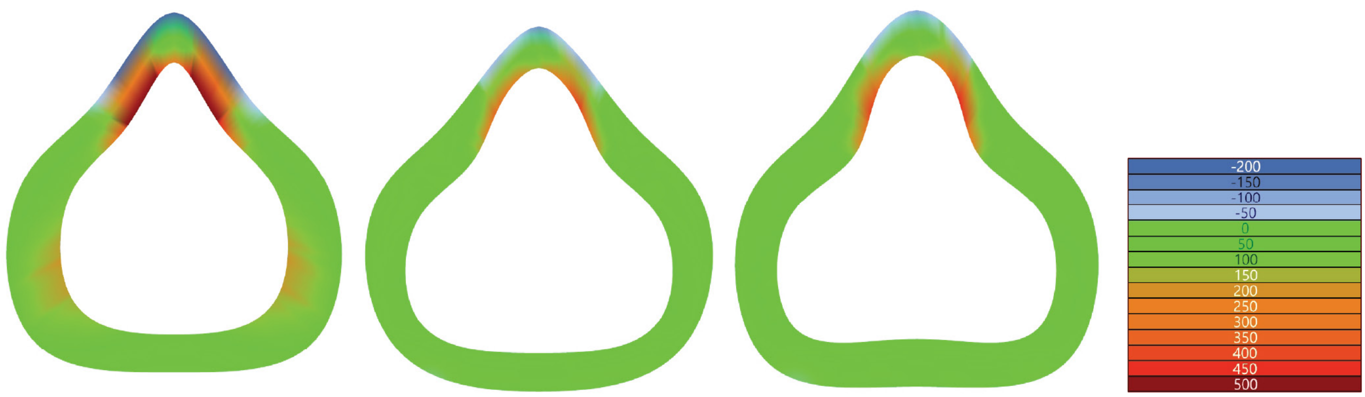


Figure 78: *Heatmap of percentage of maximum allowable intrusion of original, first and second redesigned ribbon n=252*

6.8 Conclusion

The combination of the VFA algorithm and parametric model for designing ribbons demonstrate the possibility to quickly and iteratively design alternative ribbon shapes of the facepiece. While the redesign process focussed on the Medium-Narrow facepiece, the process can be applied to all mask sizes to better accommodate the facial features of the target group.

Although the virtual fit of the redesign shows improvements over the original design, the static analysis of the VFA algorithm does not fully reflect the actual fit and discomfort during use in flight.
Throughout the redesign process, the requirements and wishes were kept in mind to address the design from a desirability, viability and feasibility perspective.

Chapter 7

Design evaluation

7 Design evaluation

When a redesign solution is proposed, it is important to evaluate the design to see if improvements have been made and to what extend the problem has been solved. During design evaluations new problems could arise, which could indicate another design iteration is needed to solve these problems. During a design evaluation the program of requirements and wishes is used to quantify if improvements have been made. The redesigned facepiece was evaluated using a physical evaluation and production cost estimations, to evaluate the design on desirability and viability.

7.1 Physical evaluation

To evaluate if the design changes to the facepiece have a positive effect on the fit and experienced discomfort of pilots, real life testing was necessary. Testing the prototype redesigned facepiece in real flight conditions is impossible since it has no flight approval. The human centrifuge is the closest to actual flight for the evaluation of the redesigned facepiece. To test if the redesigned facepiece has improved in comfort, fit and stability, an experiment was carried out in the human centrifuge of the CMA. This experiment consisted of standardized test protocol by the CMA to evaluate if a mask has improved in comfort, fit and stability. An additional pressure measurement preformed to see if the redesigned facepiece exerted a lower pressure on the face.

All requirements except for oxygen pressure leakage (1), air blast protection (2) and 94% population coverage (3), from chapter 5, were met for the prototype masks for the evaluation. Requirements 1, 2 & 3 were left out of scope due to time constraints and/or the absence of the proper test equipment.

Figure 79: *The human centrifuge of the CMA in action*

7.1.1 Test subjects

4 F-35 pilots of the RNLAF participated in the test to research if the redesign is an improvement over the original design. All participants were male, with an average age of 35 years ranging from 27 to 42 years old. The average flying experience was 10.5 years ranging from 4 to 21 years. 2 pilots had former flying experience with the F-16.

7.1.2 Test protocol

The CMA developed a mask testing protocol in earlier research, consisting of three parts:

A talk test, a head movements test and a dynamic test. A pressure measurement was added to the protocol to research pressure distribution of the mask on the face.
Before a mask could be tested, an expert fitter of the VUT (Vlieg Uitrusting Techniek) fitted the mask conform TO MD 5901-00001 (Gentex & CMA, 2017). This ensured consistency in the fitted masks and prevented oxygen leaks. The masks were tested for oxygen leaks with a different method than with a specialized leakage testing machine. The valves were pressed shut, to listen for oxygen leaks during exhaling.

The redesigned facepiece was evaluated in a balanced experiment, where each pilot wore the original mask and the redesigned mask. After each run, a questionnaire was used to evaluate the fit and discomfort of the mask. The full test protocol and questionnaires can be found in appendix H.

Talk test

During flying in formation, approach and landing communication with other pilots or air traffic controllers is essential. The interviews and questionnaires, chapter 3, found no additional discomfort of the current oxygen mask during communication, appendix A. The redesign should also cause no additional discomfort during communication.

Nederlof, (n.d.) developed 6 sentences, which mimic basic communication used during flight, to determine if the mask design has an effect on the experienced discomfort. These sentences can be found in appendix H.

A copy of the sentences was placed in the cockpit of the centrifuge, for the pilots to read out loud. The questionnaire contained questions about increased discomfort during communication.

Head movements

Situational awareness is an important aspect during flight, especially during Air Combat Manoeuvres (ACM) or dogfighting. Nederlof, (n.d.) identified the 6 most common head movements during flight. These head movements could have an effect on the mask fit and could increase the discomfort. Each movement began by looking straight ahead, and finished in the intended final position. These final positions can be found in appendix H.

Stickers were placed in the cockpit of the centrifuge, to ensure the final position of the movement would be the same for all subjects. The questionnaire contained questions about increased discomfort during these movements.

Dynamic test

G-forces have a negative effect on the experienced discomfort of the oxygen mask, as described in chapter 3.2.1. A G-profile was created in earlier research (Nederlof, 2018) which mimics the most common higher G-forces seen during flight. The peak G-force was limited to 4 G's, as it is quite uncommon to pull higher G-forces during flight and specialized medical personnel needs to attending the experiment. The G-profile used for dynamic testing can be seen in Figure 80.

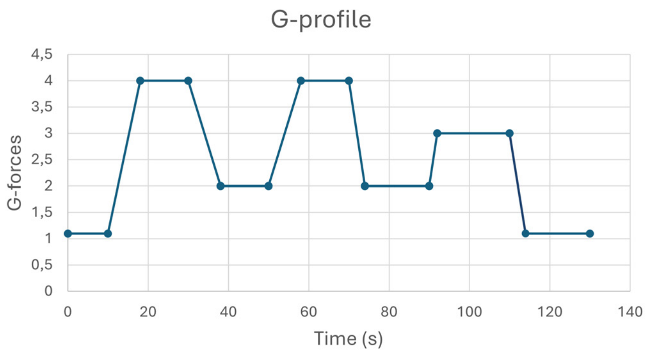


Figure 80: *G-profile used for dynamic testing*

Questionnaire

After each run a subject was asked to fill in a questionnaire about the fit and discomfort of the mask. After the second run a second questionnaire was filled in. This questionnaire contained the same questions as the first and also included questions directly comparing the first and second oxygen mask based on comfort. The questionnaires can be found in appendix H.

Pressure distribution

The oxygen mask is pressed with a certain amount of pressure on the face, chapter 3, to prevent leakage and ensure a good seal of the oxygen mask. A higher pressure will lead to a higher discomfort in the face, chapter 3.

A specialized film for recording pressure was used to evaluate the pressure distribution of the oxygen mask on the face of the pilot. The pressure film used was Prescale pressure film (Fujifilm, n.d.). A measuring range of 50-200 kPa was chosen, as this range corresponded most with the 40-180 kPa pressure discomfort threshold range of the face, chapter 4.5.

The film was roughly cut into a shape representing the oxygen mask ribbon. The film was then placed between the oxygen mask and the face of the pilot wearing the mask on the second detent, as described in TO MD 5901-00001 (Gentex & CMA, 2017).
This was important, as multiple pilots admitted in chapter 3.2.2, that they wear the mask looser than the protocol describes to relief pressure on the face and increase their comfort.
The film was placed in such a way that the ribbon of the mask was covered.

After 2 minutes the film was removed and scanned using a photocopier against a reflective white background for evaluation. The scans were then edited in photoshop (Adobe, 2024), removing the background and libs for handling and placement. Afterwards the scans were aligned in a grid of 300x300 pixels for further evaluation. Figure 81 shows a edited scan of pressure film of a pilot wearing the original design.

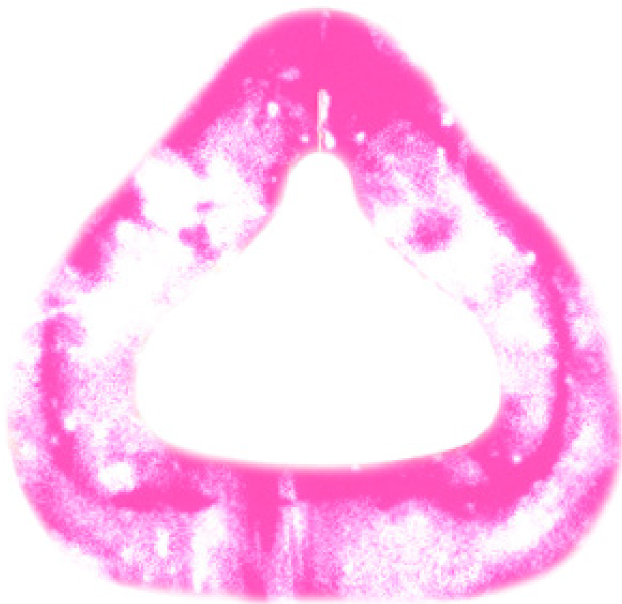


Figure 81: *Pressure film measurement of original design (pilot 1)*

The scan was evaluated using a python script which classified the pixels in one of five corresponding pressure ranges based on the intensity value (50-80, 80-110, 110- 140, 140-170 & 170-200 kPa). These ranges were based on the pressure film measuring resolution 50-200 kPa (Fujifilm, n.d.) and were chosen to evaluate low and high pressure distribution per facial area.

The 6 facial areas of interest from the questionnaires to highlight discomfort, Figure 82, were used to research how low and high pressure correspond to the discomfort of wearing the mask.
The pressure ranges were encircled for visualisation purposes and the percentual coverage of the ranges per facial area was calculated, Figure 83.

The average pixel intensity per facial area and the pressure film measuring range were used to calculate the average pressure per facial area. The total average pressure was also calculated.

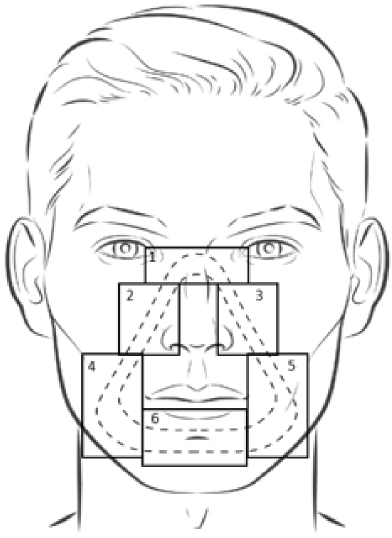


Figure 82: *Facial areas of interest*

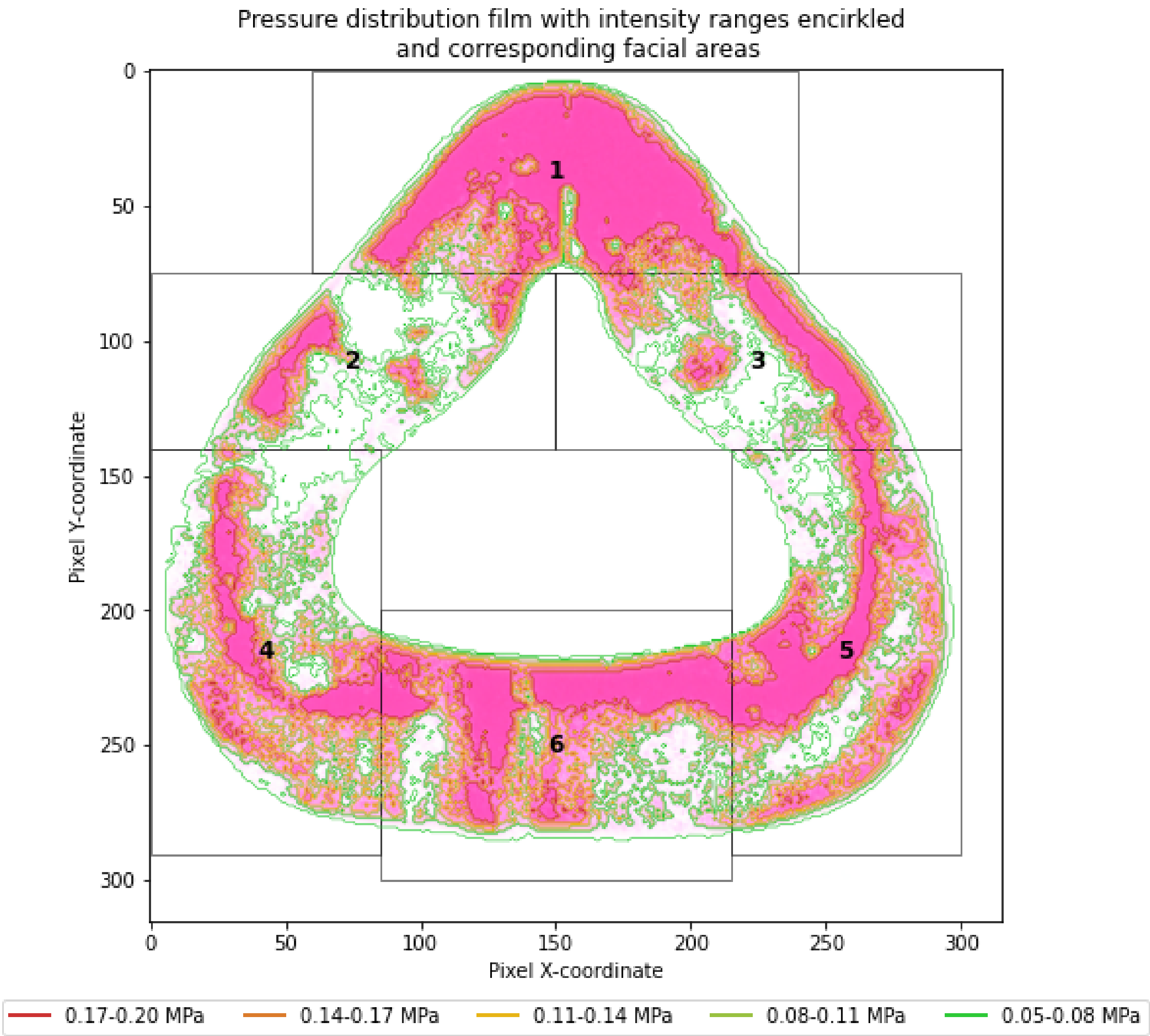


Figure 83: *Pressure distribution analysis with facial areas (pilot 1)*

7.1.2 Results

When asked about mask preference in the questionnaire, 3 pilots preferred the redesign over the original. 1 pilot had no clear preference, Figure 84.

The average overall pressure of the redesigned oxygen mask on the face decreased by 8,8%, with the highest decrease of 19,3% seen at the nasal root, Figure 85.

The overall pressure distribution of the redesign is more equal across the face when looking at means, compared to the original design.

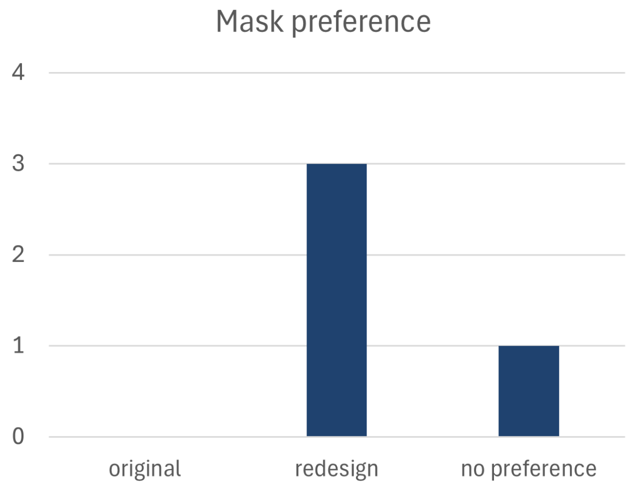


Figure 84: *Mask preference*

A Shapiro-wilk test was used to check for a normal distribution of average pressure per facial area. For all areas and the total area an normal distribution was found, except for area 1 of the original design.

An F-test and paired T-test were used to check for significant differences in variance and average pressure. A significant difference in average pressure ($p<0.05$) was found at area 1 (Nasal root), but no significant difference in variance.

A significant difference in variance ($p>0.05$) was found in area 4, but no significant difference in average pressure.

For all other areas no significant difference was found in variance and average pressure.

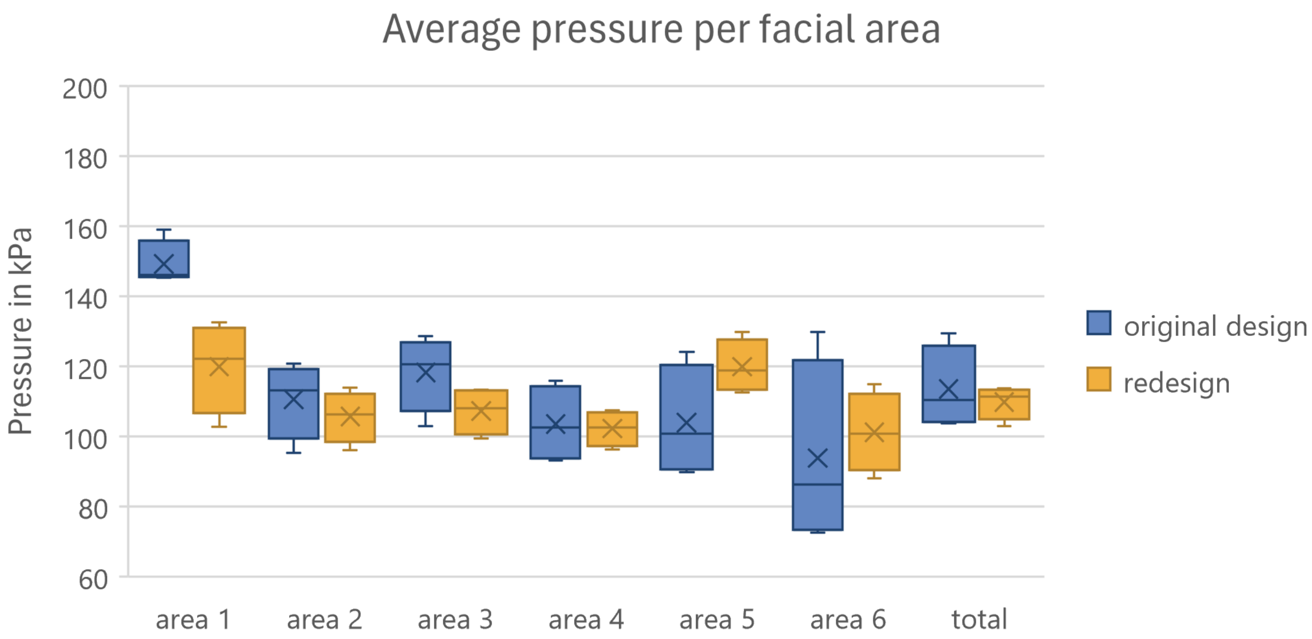


Figure 85: *Average pressure per facial area n=4*

The average percentual coverage of the pressure ranges was compared between the original design and redesign, by subtracting the values of the old design from the values of the current design. This resulted in Figure 86, where a negative value means a decrease of that pressure range in that facial area.

The amount of high pressure (170-200 kPa) has decreased in all facial areas, with the highest decrease seen at the nasal root, Figure 86.

This decrease in the nasal area could be visually confirmed, as for all pilots a decrease in colour intensity on the nasal root was observed with the redesign. Figure 87 shows an example.

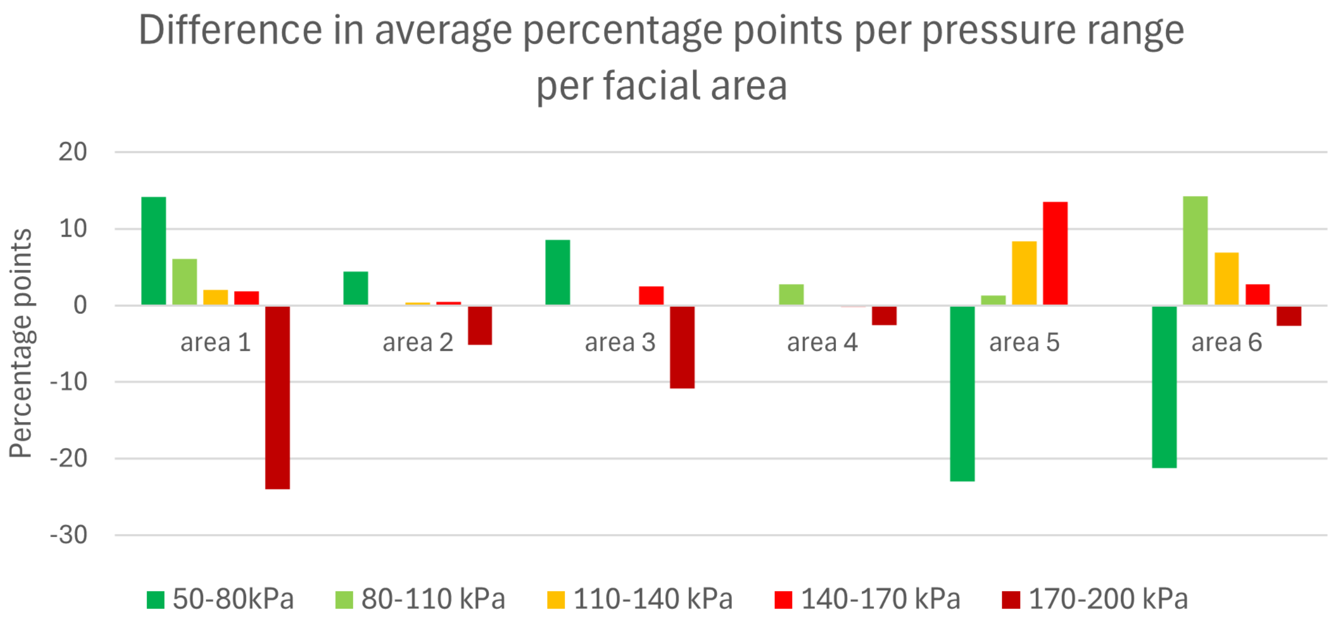


Figure 86: *Difference in average percentage points per area and pressure range*

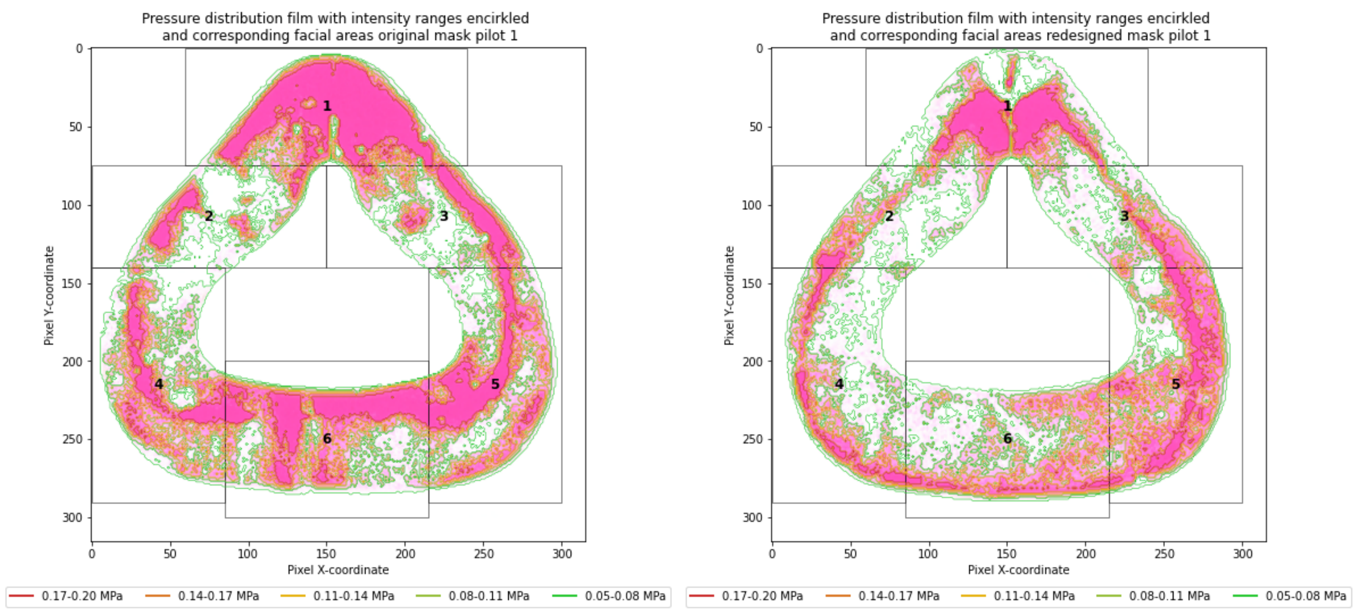


Figure 87: *Pressure film of original and redesign with pressure ranges encircled (pilot 1)*

The average discomfort scores of area 1 (nasal root) decreased from an average of 7,5 to 2,8 on a scale of 1 to 10, where a higher score means a higher discomfort in that region (Figure 88 & Figure 89).

However, the pressure increased in area 5 with the redesign and the average discomfort score of area 6 (chin) increased from an average of 2,8 to 4 on a scale of 1 to 10.

The individual scores can be found in appendix H.

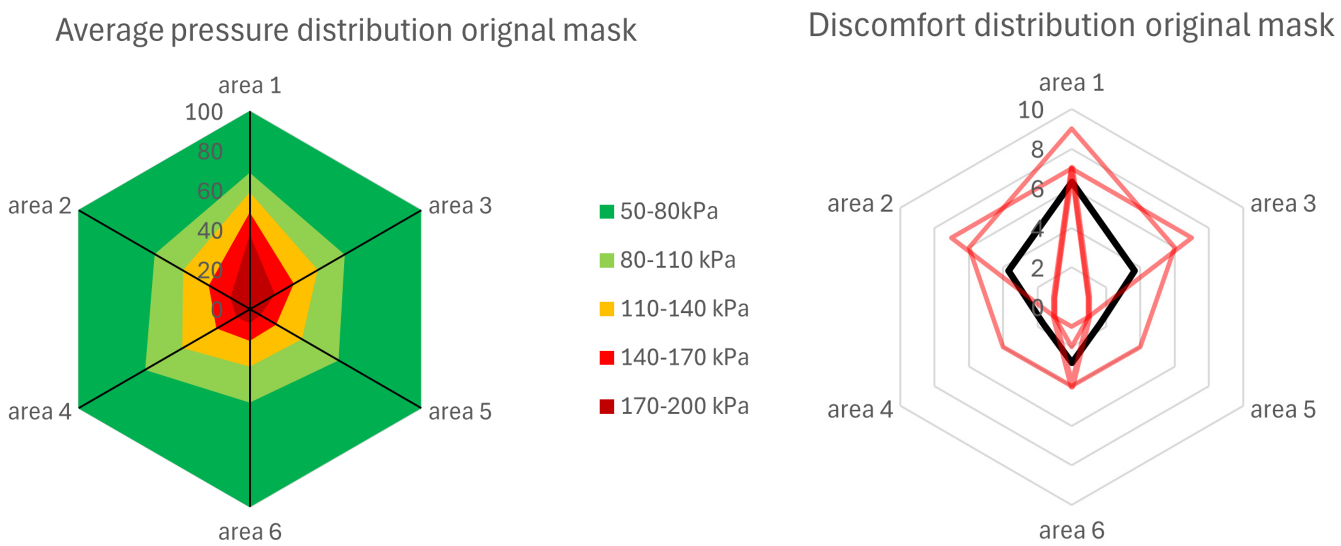


Figure 88: *Average pressure and discomfort distribution original mask n=4*

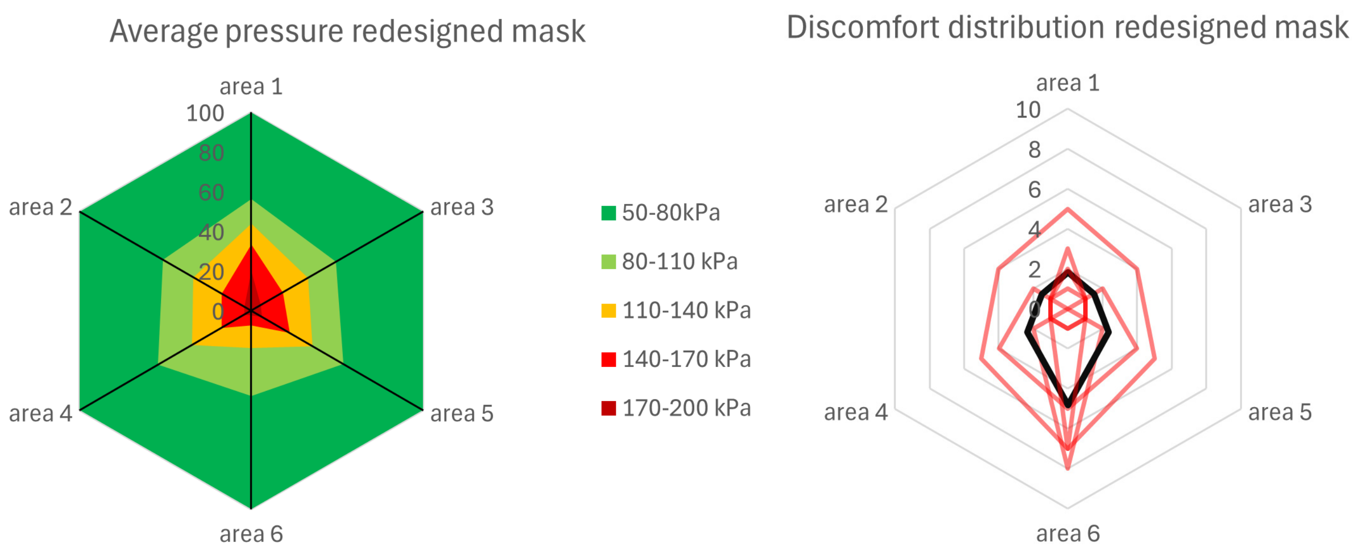


Figure 89: *Average pressure and discomfort distribution redesign n=4*

It was observed that the redesigned oxygen mask shifted less of the face of the pilots. 2 pilots needed to stabilize the original mask with their hands in the human centrifuge, Figure 90. This did not happen with the redesigned mask. This was also reflected in the questionnaire answers, Figure 91 & Figure 92.

When asked about mask stability, the average score for the original design was 6 and 7.75 for the redesign on a scale of 1-10, where 10 means very stable.

When asked about the mask shifting during a G-manoeuvre the average score for the original design was 6.75 and the redesign 1.75 on a scale of 1-10, where 10 means a lot of shifting.

Figure 90: *Pilot stabilizing original oxygen mask with hand in human centrifuge*

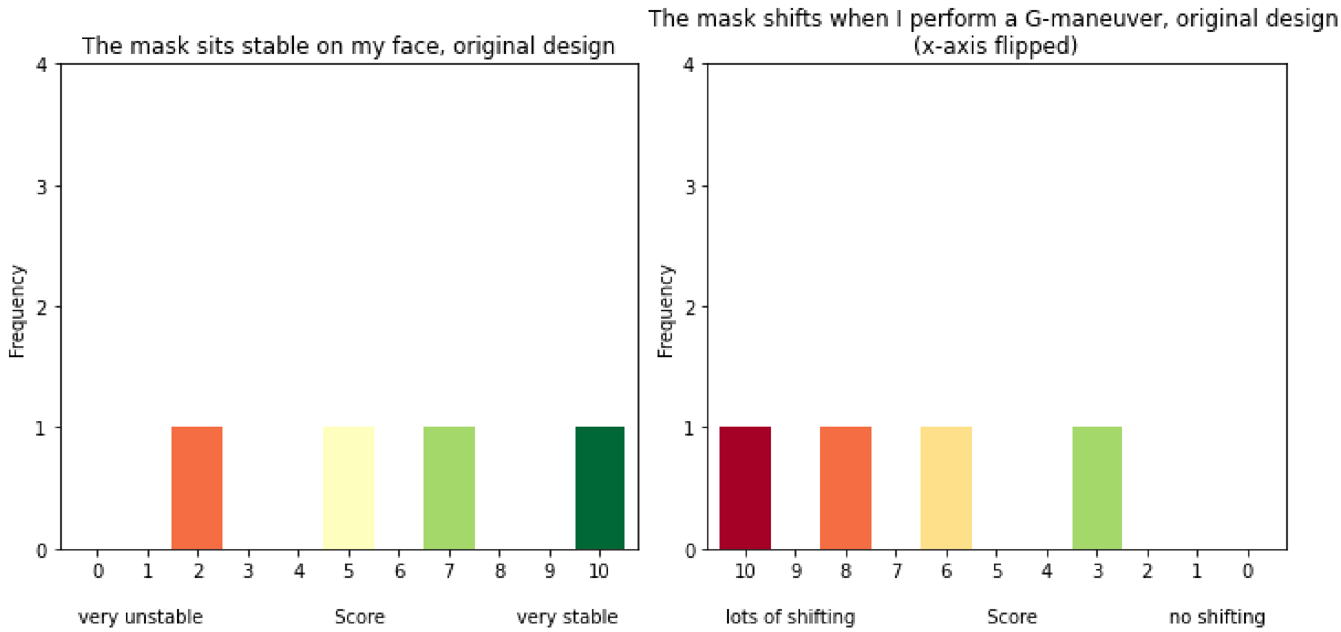


Figure 91: *Histogram of mask instability and shifting of original design*

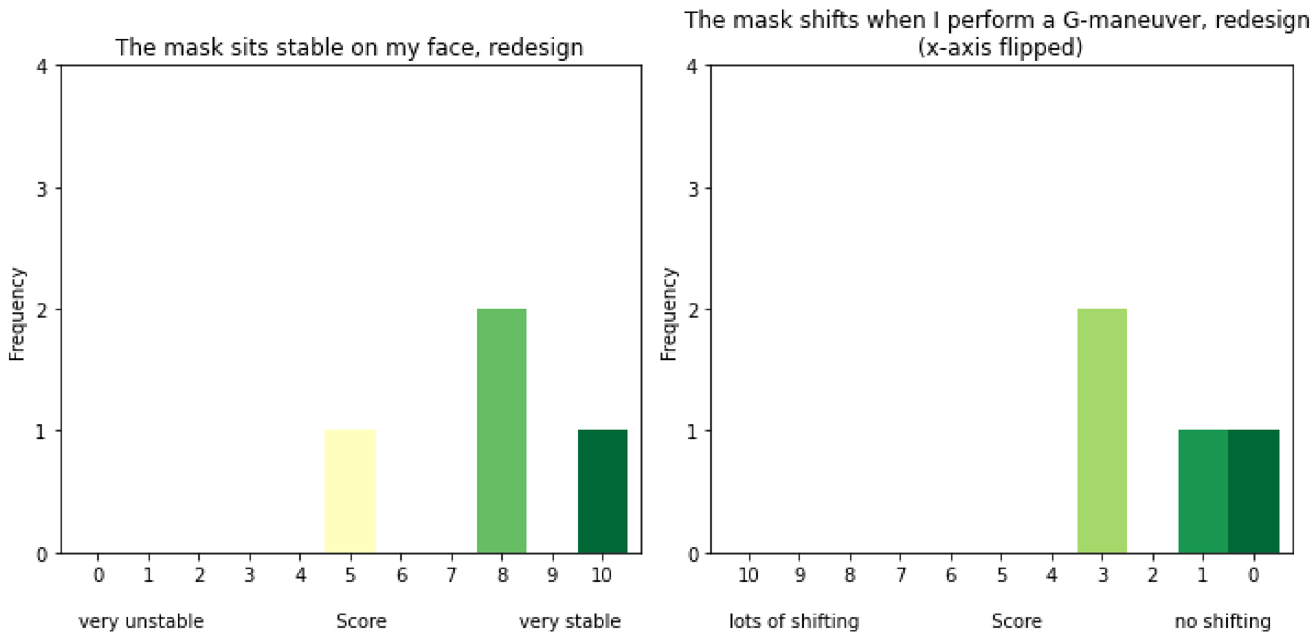


Figure 91: *Histogram of mask instability and shifting of redesign*

The redesigned mask was found to be slightly more comfortable and causing less pressure points in the face, Figure 93 & Figure 92. The average mask comfort of the original design was 6.5 and 8 for the redesign on a scale of 1-10, where a higher score means more comfortable.

The average score of the mask causing discomfort was 7.75 for the original design and 3.5 for the redesign on a scale of 1-10, where a higher score means the mask causes more discomfort.

1 pilot experienced a higher pressure and discomfort at the chin. This influenced the discomfort rating.

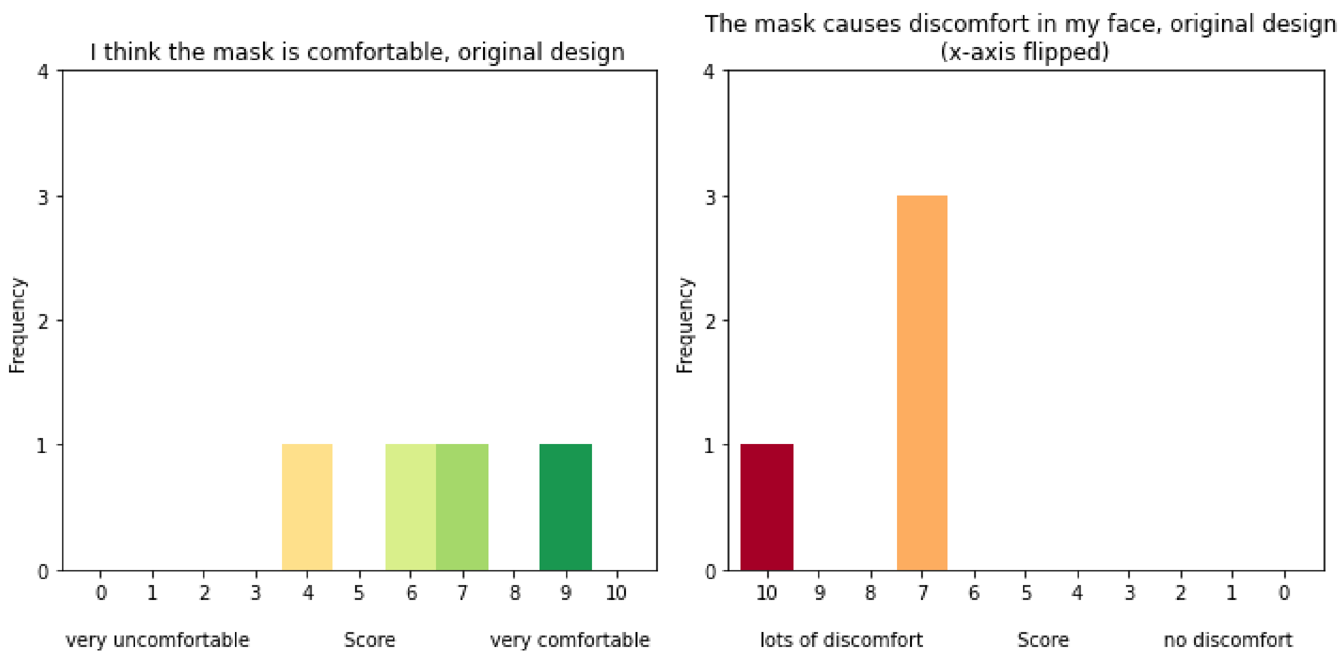


Figure 93: *Histogram of comfort and causing discomfort of original design*

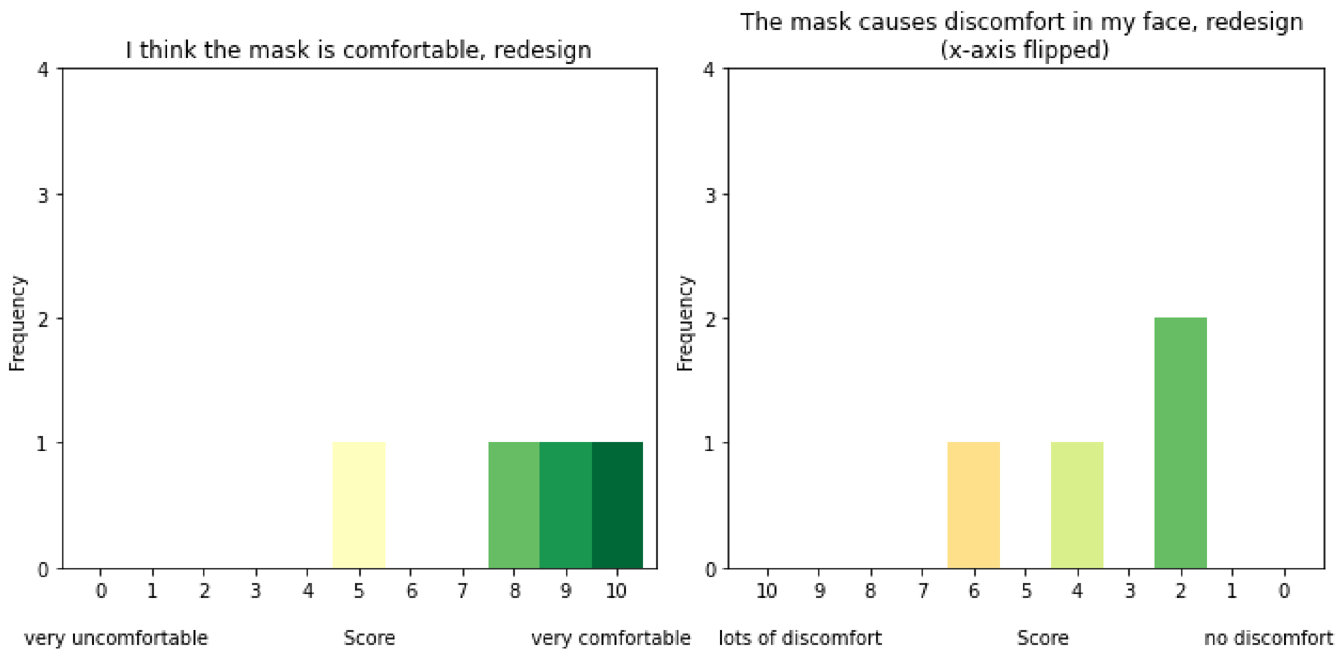


Figure 94: *Histogram of comfort and causing discomfort of redesign*

Comfort during communication saw no improvement with the redesign, Figure 95 & Figure 96. The pilot experiencing more discomfort at the chin also reported discomfort increasing during communication.

When asked about if communicating with the mask was comfortable, the average score for the original design was 6 and 7.5 for the redesign on a scale of 1-10, where 10 means very comfortable.

When asked about if talking increased the discomfort, the original design and redesign both had an average of 2.5.

High-G was still the main reported reason for increased discomfort in the questionnaire. The time wearing the mask was also noted as an important factor in the discomfort experienced by the pilots.

During the testing it was observed that the situational awareness of the fighter pilots was not decreased any more compared to the original design. All pilots had similar sight and no limitations in head movement were observed with the redesign, compared to the original design. 1 pilot reported a small increase in discomfort when looking over his shoulder.

No pilots reported experiencing sharp edges with the redesigned facepiece.

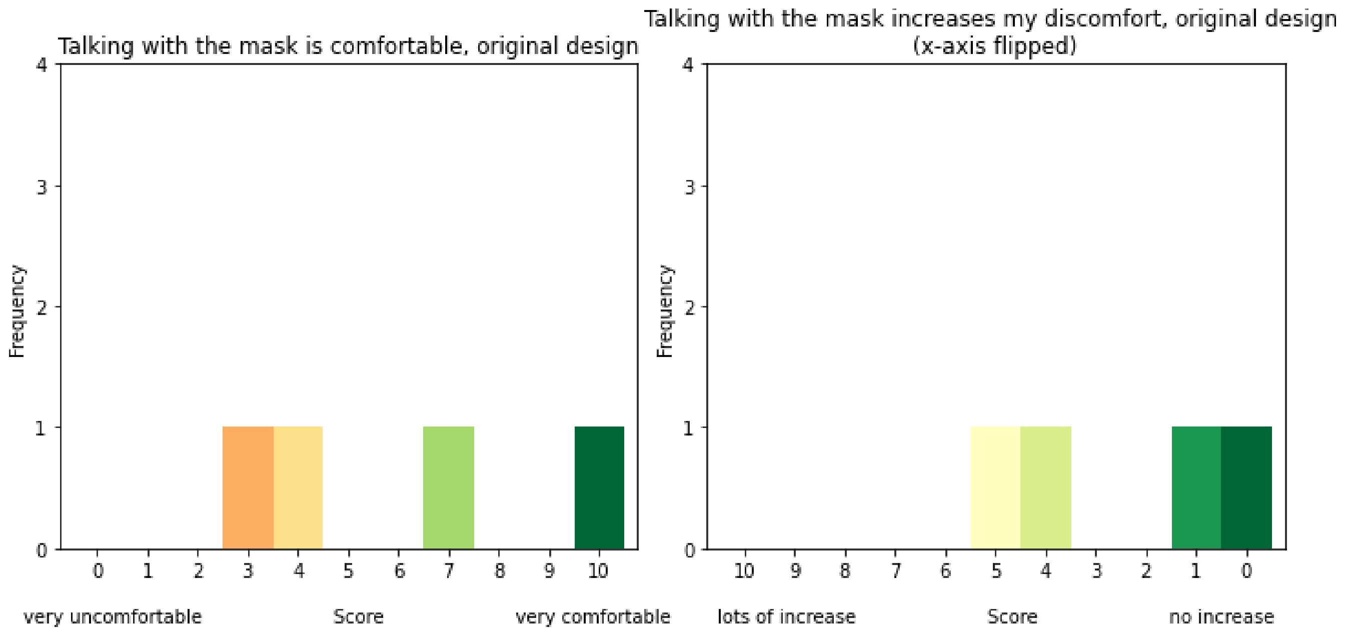


Figure 95: *Histogram of comfort and discomfort during talking of original design*

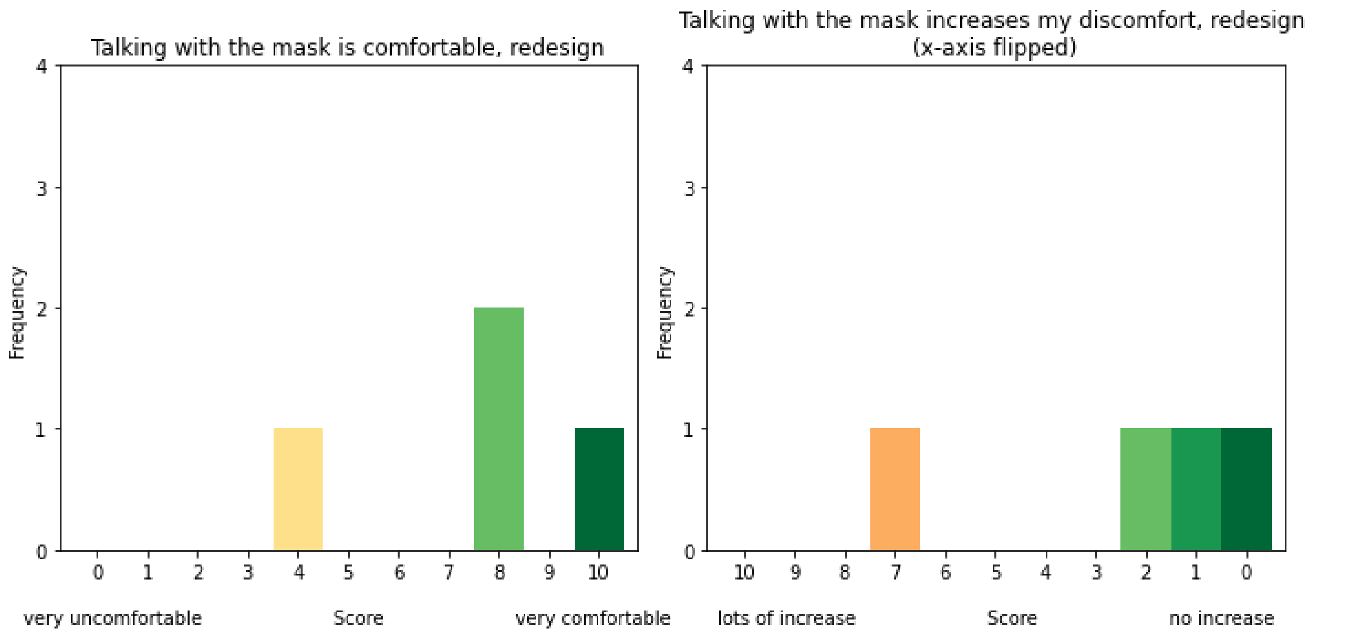


Figure 96: *Histogram of comfort and discomfort during talking of redesign*

7.1.3 Discussion

Because of the small test sample, it is too early to conclude significant improvements in pressure of the mask on the face of fighter pilots. The only significant improvement seen was at the nasal root (Figure 85), a key focus area during the design process. However, the results and especially the differences in high pressure (170-200 kPa) indicate that the redesign is an improvement in decreasing high pressure over the original, Figure 86. This decrease could be interpreted as an improved fit over the original design. Yet, more research and subjects are needed for confirming if significant improvements have been made.

The difference in pressure seen in area 4 and 5 of the redesign (Figure 85) could be explained by the fact that the oxygen supply hose is attached to the mask at area 5, increasing the pressure. This however does not explain the increase in pressure compared to the original design and more research is needed to explain this difference in pressure.

A similar discomfort distribution and score at area 1 of the original design (Figure 88) was seen in the questionnaire answers from chapter 3.1. This indicates that the pressure measurements and associated discomfort are valid for the evaluation of the redesign.

The increase in discomfort at the chin cannot be explained by the insignificant increase in average pressure seen at area 5 and 6 alone. It could be explained by the decrease in discomfort at the nasal area, elevating the perception of discomfort at the chin.
As the ribbon shape and size of the redesign differs from the original design, the contact area at the chin could be different, compared to the original design. This difference in location could have elevated the experienced discomfort, as the pilot's habituation to pressure could be different at that location. The pressure discomfort threshold of individual pilots could also affect this increase in discomfort seen. Further research is needed to explain this average increase in discomfort seen at the chin.

The similar comfort and discomfort scores seen during the talk test (Figure 95 & Figure 96), indicate that the redesign does not increase discomfort during communications, compared to the original design. Together with similar situational awareness of the original design and redesign, this indicates that the redesign is a feasible alternative for the original design considering operational requirements.

The questionnaire responses reporting high-G and time of wearing the mask as having the largest influence on experienced discomfort are in line with the answers given in chapter 3.
Future research is needed to evaluate how high-G and time of wearing influence the discomfort, to improve the design of the oxygen mask.

7.1.4 Limitations

This design evaluation was only limited to 4 F-35 pilots.
Even though the evaluation was a small sample, the results indicate a better performance with the redesign. Further research with more pilots is needed to confirm the indications from the results.

The time wearing the mask has an influence on the experienced discomfort of pilots. In this evaluation the pilots only wore the original and redesign for a maximum of 30 minutes due to time constraints. The dynamic test in the centrifuge was limited to 130 seconds, not fully representing the actual time pilots wear the oxygen mask during operations.

The alignment of the pressure film was not very consistent with all measurements, this could have influenced some of the pressure values measured. An improvement in pressure film alignment is needed in further testing, to ensure consistent measurements.
Requirement 1, 2 & 3, from chapter 5, were left out of scope during the design project and design evaluation. These requirements need to be met and evaluated in future research for the redesign to be implementable.

7.1.5 Physical evaluation conclusion

The new oxygen mask design shows improved results looking at the discomfort experienced by pilots around the nasal area.
The redesigned oxygen mask shows an increase in comfort, compared to the original design. Causing less pressure points, especially around the nasal area.

The redesign showed a decrease in average pressure and on the nasal root of pilots. The pressure distribution of the redesign is more equally spread across the face, compared to the redesign. However, pressure and discomfort on the chin have increased.
Mask instability and shifting during higher G-loads have decreased with the redesign.

The physical design evaluation indicates that the VFA algorithm has potential to assist in designing better performing and fitting oxygen masks. However, this needs to be tested further with a larger test sample and for all mask sizes.

7.2 Production and costs

In order for the design to be implementable, it should be manufacturable at a competitive price compared to the current facepiece. To evaluate if the redesign could compete with the current design, the manufacturing method of Gentex and the retailing price needed to be investigated. Comparing the prices of the original and redesigned facepieces will help estimate if the redesign is a viable alternative to the original design.

7.2.1 Production and materials

The current facepiece is made from a silicone rubber, which is compression moulded into the desired facepiece shape (Gentex, 2023). The facepiece is made from a silicone rubber with a shore 65A hardness (Gentex, n.d.). In the final weeks of 2023 Gentex confirmed that from then on the facepieces produced will be made from a silicone rubber with a shore 45A hardness, based on the recommendations from research conducted by de Vette (2013) at the Centre for Man in Aviation (CMA).

The moulding material (charge), which is generally preheated, is placed in an open heated bottom mould cavity. The mould is closed with a heated top mould and pressure is used to force the charge into contact with the entire mould cavity. Excess charge material is forced out of the cavity and between the moulds into overflow grooves. This excess material is called a flash. The heat and pressure is maintained until the moulding material is fully cured. The mould is opened and the moulded part can be removed. The flashes need to be cut-off in a post-process step to reach a finalized product. Compression moulding is a more cost effective production technique compared to injection moulding in low to medium volume productions (Formlabs, n.d.).
A simplified schematic of the compression moulding technique can be seen in Figure 97

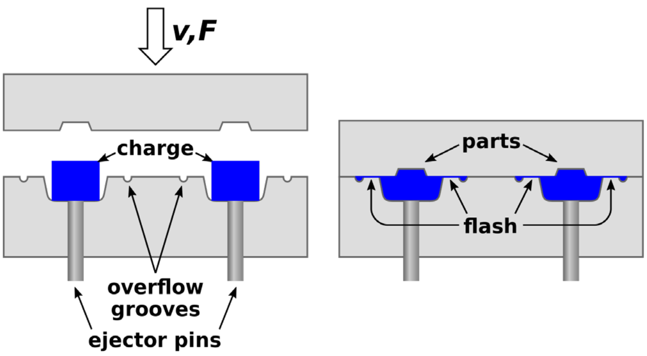


Figure 97: *Simplified diagram of the compression moulding process (Wikipedia, n.d.)*

7.2.2 Production and materials

One of the wishes from chapter 5 was to keep the costs of the redesigned facepiece as low as possible. The current price of a facepiece from Gentex was compared with an estimated production cost of the redesigned facepiece.

Current facepiece cost

The cost of the current facepiece is set at €79,30,- , with a full mask assembly costing between €1.000,- to €4.000,- depending on product line (CMA, personal communication). It is not known how this price is set, but R&D, marketing, certification costs and profit margins are probably included in this price.

Estimated cost redesign

A quotation of the redesign was submitted to a semi-large European manufacturer, to get a better understanding of the production costs associated with manufacturing the facepiece. The same manufacturing method and material as the current facepieces were chosen.

The manufacturing of the tooling necessary for the redesigned mask was the most expensive. The tooling was quoted at €4.846,-.
The production of 500 facepieces was quoted at €1.659,-.
Resulting in a price of €3,32,- per facepiece excluding tooling cost, or €13,01,- including tooling cost per facepiece. This price will only decrease if the volume of products produced is increased.

These prices do not include R&D, marketing, flight certification costs and profit margins. A rule of thumb is proposed in the Delft Design Guide (van Boeijen et al., 2020) where the consumer price is 3 to 4 times higher than the manufacturing costs. This resulted in a conservative price estimation of €52,04,- per facepiece. This price estimation still excludes the certification costs. Although the certification costs are not know, it is expected that these costs will not increase the price by such an amount that redesign price is not competitive with the original design.

7.2.3 Production and cost conclusion

Gentex uses compression moulding for the production of the facepieces, as it is a good manufacturing method for low to medium production runs.
The material used for the manufacturing of the facepieces is a silicone rubber with a silicone shore hardness of 45A.

Using the same material and manufacturing process, the quotation and rule of thumb estimation shows that the redesigned facepiece is not more expensive compared to the current facepiece, excluding the flight certification costs.

However, it is estimated with an higher price including these margins the price of the redesign would still be in the same range as the original facepiece. Indicating the viability of the redesign.

7.3 Requirements and wishes evaluation

It is important during a design process to evaluate to what extend the requirements and wishes were accomplished. An overview of the requirements and wishes from chapter 5 can be found in Table 8.

All requirements were met for the design evaluation, except for requirement 1, 2 & 3 which were left out of scope for this design evaluation.

Requirement 1 was not evaluated due to time constraints at the physical evaluation. A different method for oxygen leakage testing was used during the evaluation. This resulted in no leaks being present during the physical evaluation. It is likely that the redesign would pass this requirement when tested.

The air blast requirement was not tested for, due to the necessary test equipment not being present at the CMA. As the final product will be manufactured with the same material and manufacturing method, it is expected that this requirement will be met when tested

The new sizing system was left out of scope for this redesign project, to focus more on a retrofittable redesign for the facepiece. Further anthropometric research into the fighter pilot community of the RNLAF is needed before redesigning the product, including a new sizing system.

The results from chapter 7.1.2 indicate that most wishes were satisfied.

The redesign was found to be more comfortable than the original and causing less discomfort, satisfying wish 1.

The dynamic testing, questionnaire and pressure film measurements indicate that the pressure on the nasal root and sides has been decreased, satisfying wish 2. Looking at the pressure distribution on the face, the measurements indicate a more equal pressure distribution, satisfying wish 3.

A decrease in overall pressure of 8,8% was reached. This does not satisfy wish 4. However, a decrease of almost 19,3% was seen at the nasal root in the high pressure (170-200 kPa). Indicating the possibility of decreasing pressure by designing with the VFA and ribbon algorithms.

Mask instability and shifting have also been decreased, satisfying wish 5. This decrease in instability and shifting indicate that the redesign has a better fit compared to the original design for Dutch fighter pilots.

During the redesign process, Chapter 6, it proved difficult to design a facepiece which did not exceed 80% of the STT. The 80% threshold was exceeded at the nasal regions in the static evaluation of the VFA algorithm, not fully satisfying wish 6. However, the discomfort distribution of during the physical evaluation suggests this did not affect the experienced discomfort negatively. An improved VFA algorithm which accounts for differences in facial features and how this affects the alignment and fit of the mask could improve the design process of new oxygen masks.

The pilots reported no sharp edges of the redesign on their face, likely satisfying wish 7. G-forces exceeding the 4 G used for the physical evaluation could cause the mask to flip inside out, as described in Chapter 2.4. This could change the perception of sharp edges and needs to be tested for in future research to confirm satisfaction of wish 7.

The estimated price of the redesign, using the same material and production method as the original design, is in the same range of the original design. Although no indication for the flight certification costs is known, it is not expected that these costs will increase the price by such an extent that the price is not competitive with the original design. Indicating the viability of the redesign and satisfying wish.

Requirements		Wishes	
1	Pass oxygen leakage test	1	Minimize discomfort
2	Cannot be blown off at 600 knots	2	Decrease pressure point on nasal root
3	Sizing system accommodates 94%	3	Even pressure distribution
4	Made from skin safe silicone (Shore 45A)	4	Decrease pressure by 30%
5	Fit with F-16 and F-35 helmets	5	Minimize mask tilt and movement during high-G
6	Accommodate existing valves, tubes and microphone	6	Intrusion distance should not exceed 80% of STT
7	Fit current hardshell	7	No sharp edges in contact with the face
8	Be cleanable	8	Low production costs
9	Not interfere with situational awareness		

Table 8: *Overview of requirements and wishes from Chapter 5*

7.4 Conclusion

The redesigned oxygen mask was evaluated through physical evaluation, production cost estimation and reflecting on the requirements and wishes from Chapter 5. All evaluated requirements were met and most wishes were satisfied, suggesting the redesign could be a suitable alternative for the RNLAF.

The physical evaluation showed a significant decrease in pressure on the nasal root, an overall reduced pressure on the face and an improved pressure distribution and comfort of the redesign.

The redesign demonstrated increased stability and reduced mask shifting during high-G, indicating a better suitable fit of the redesign for the RNLAF. However, an increase in discomfort at the chin was observed, which could not be explained fully by the current physical evaluation. Further research is needed to identify to what extent the redesign has improved compared to the original design.

The improvements in comfort, fit, pressure distribution and stability suggests that the redesign is a more desirable alternative compared to the original design. This was also reflected in the mask preference of the pilots.

The production cost estimation suggest that the redesign could be competitively priced per unit. However, further research is needed to improve these estimations, including flight certification costs, to confirm the redesigns viability.

The evaluation of requirements and wishes, from Chapter 5, indicate that the redesigned facepiece is a feasible alternative for the RNLAF. Further design research with more participants is needed to evaluate the redesign and identify additional issues which need to be solved in future oxygen mask designs. This research will help to further validate the desirability, viability and feasibility of the redesigned oxygen mask.

Chapter 8

Conclusion and Discussion

8 Conclusion and Discussion

The purpose of this research was to decrease the discomfort and facial trauma seen with the use of fighter pilot oxygen masks for the RNLAF. To achieve this, the following research questions were answered:

- Are the reported issues in literature with oxygen mask usage still present with current fighter pilots?
- Are there differences in facial features between Dutch and American fighter pilots and does this influence the fit?
- Is it possible to design a better fitted mask with digital fabrication tools?

The research revealed that current F-35 pilots still experience the discomfort and, to an extent, facial traumas associated with oxygen mask usage seen in F-16 pilots. The most discomfort was still seen at the nasal root. High G-forces increase this discomfort, which leads to adverse behaviour with oxygen mask usage.

Significant differences in facial anthropometry between Dutch and American fighter pilots, on which the design was based, were seen. The current sizing system of the oxygen mask does not accommodate the RNLAF fighter pilot population properly. These differences were thought to be a main cause of the discomfort experienced by pilots. The VFA showed how the existing facepiece design does not accommodate the facial anthropometrics of the RNLAF properly. By incorporating the PDT and STT, the VFA provided better insights to evaluate the fit of facepiece designs.

The combination of the VFA algorithm and the parametric model for designing ribbons proved effective for quickly and iteratively redesigning the facepiece. These models enabled the creation of new designs better suited for the RNLAF fighter pilot population, based on the DTS dataset.

The redesigned oxygen mask was evaluated through physical evaluation, production cost estimation and reflecting on the requirements and wishes from Chapter 5. The physical evaluation showed a significant decrease in pressure on the nasal root, an overall reduced pressure on the face and an improved pressure distribution and comfort of the redesign.

The redesign demonstrated increased stability and reduced mask shifting during high-G, indicating a better suitable fit of the redesign for the RNLAF. However, an increase in discomfort at the chin was observed, which could not be explained fully by the used physical evaluation. Further research is needed to identify to what extent the redesign has improved compared to the original design.

The improvements in comfort, fit, pressure distribution and stability suggest the redesign is a more desirable alternative for the original design used by the RNLAF. This was also reflected in the pilots' mask preference.

The production cost estimation suggest that the redesign could be competitively priced per unit. However, further research is needed to improve these estimations, including flight certification costs, to confirm the redesigns viability.

In conclusion, this design project successfully demonstrated the potential of designing a better fitting and more comfortable oxygen mask for RNLAF pilots using anthropometric methods and digital fabrication tools. Further design research with more participants is needed to evaluate the redesign and identify additional issues which need to be solved in future oxygen mask designs. This research will help to further validate the desirability, viability and feasibility of the redesigned oxygen mask.

This design research focussed on a redesign of the facepiece of the MBU-20/P oxygen mask for the RNLAF. However, the redesign process for facepieces outlined can be applicable to demographics. The VFA algorithm and parametric model were developed as a toolbox to design better fitting facepieces. By changing the 3D facial geometries which are used as input, insights for redesigning will be created for that specific data.

The VFA could also be used on an individual level. Together with the advancements seen in 3D printing and other manufacturing techniques, this opens the door for personalized oxygen masks. Further development of the VFA algorithm would be necessary to streamline this process.

The research into facial discomfort and ergonomics of this project could also be applied to other products for the face. Although the VFA and parametric model can only be applied to oxygen masks in the current form, the process can be adapted to design better products for the face from an ergonomic and comfort perspective. A VFA method could help future designers design better products.

Chapter 9

Limitations

9 Limitations

Not a lot of literature was available about the ergonomics of fighter pilot oxygen masks. This could have resulted in an over generalized picture of how the MBU20/P causes discomfort. As no discomfort with the MBU20/P could be under reported.
The discomfort of the MBU-20/P could differ from demographic to demographic, this was not evaluated in this design research. Research from other field into ergonomics of products for the face could solidify the understanding of what causes discomfort.

The research has shown that facial features of the filtered CAESAR subjects differ from American pilots from 1967. The filtered subjects were assumed to represent the fighter pilot population of the RNLAF in this research. However, better filtering based on more fighter pilot data could result in a better subset. This study was limited to the CAESAR data, a more comprehensive study of anthropometrics of the RNLAF could help better identify facial features and differences.

The known problems of the oxygen mask in F-16 fighter pilots were also observed in F-35 pilots. However, the difference in flight time and equipment compared to the F-16 leads to a bit of an unfair comparison. As most of the discomfort and facial trauma is seen with long exposures and flight times. The current F-35 pilots do not experience this exposure length.
More comprehensive research about (ergonomic) problems associated with the oxygen mask, or combination with the helmets used, is needed to fully understand problems associated with this flight equipment.

The VFA algorithm analysis the mask fit based on fixed markers and static difference.
The intrusion distances give an indication of predicted pressure and deformation, but not the actual pressure. Small differences in fit between pilots were not modelled. Including pressure and deformation calculations could help increase the predicted fit and behaviour of the mask design. A VFA algorithm mimicking the differences in fit per pilot should help create a more accurate model. Including some form of FEA could increase the predictive value of the VFA algorithm, to more accurately represent the pressure induced of the oxygen mask on the pilots' faces.

The design evaluation was limited to 4 pilots and 1 mask size, limiting the generalizability of the findings for the RNLAF and other Air Forces. The dynamic tests in the centrifuge were limited to 130 seconds per pilot per mask. This time does not represent the actual time a pilot wears the mask during flight.
This is not enough data to draw firm conclusions about the fit of the new mask. Even though the data indicates that improvements have been made, more extensive research is needed to better evaluate the redesign.

Some requirements were out of scope for this study, these requirements do need to be tested for a proposed redesign to be implemented.

Chapter 10

Recommendations and Future work

10 Recommendations and Future work

This research mainly focussed on the shape of the facepiece of the MBU-20/P. Multiple areas of improvement were identified for future development and improvement of the oxygen masks used by fighter pilots. These concepts and product features are described below.

10.1 New sizing system

To better accommodate the DTS population, described in chapter 4.2 and requirement 3 of chapter 5, two new sizing systems were proposed.

Proposed sizing system 1, where the sizes are designed to cover an as equal as possible part of the population, Figure 98. This will ensure that all sizes need to be produced in almost equal amounts.

Proposed sizing system 2, where the boundaries between sizes are of a fixed size, Figure 99.his will make the design of the new masks less complex, as the designs can be scaled more easily to fit the desired size.

Both proposed sizing systems cover at least 97% of the population. Making it more suitable for the DTS population, compared to the original sizing system of Gentex. The proposed sizing systems, with regards to sellion-supramenton length and lip width, can be seen in Table 9 and Table 10.

Proposed sizing system 1 in mm						
	SN	SW	MN	MW	LN	LW
Sellion-supramenton length	78-92	78-92	92-99	92-99	99-116	99-116
Lip width	45-50.5	50.5-57	46-51.5	51.5-59	47-53	53-60

Table 9: *Proposed sizing system 1 boundaries*

Proposed sizing system 2 in mm						
	SS	SL	MS	ML	LS	LL
Sellion-supramenton length	75-92	92-109	80-97	97-114	85-102	102-119
Lip width	45-50	45-50	50-55	50-55	55-60	55-60

Table 10: *Proposed sizing system 2 boundaries*

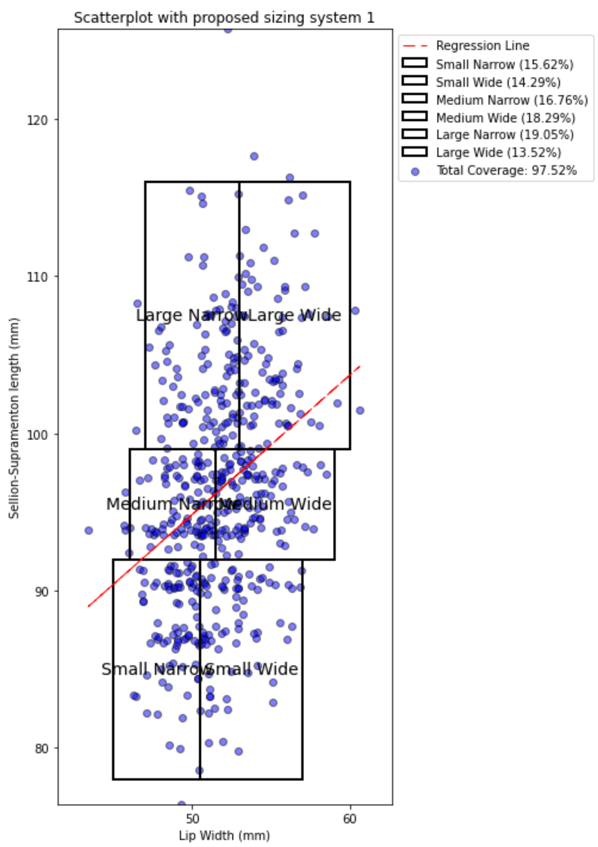


Figure 98: *Proposed sizing system 1*

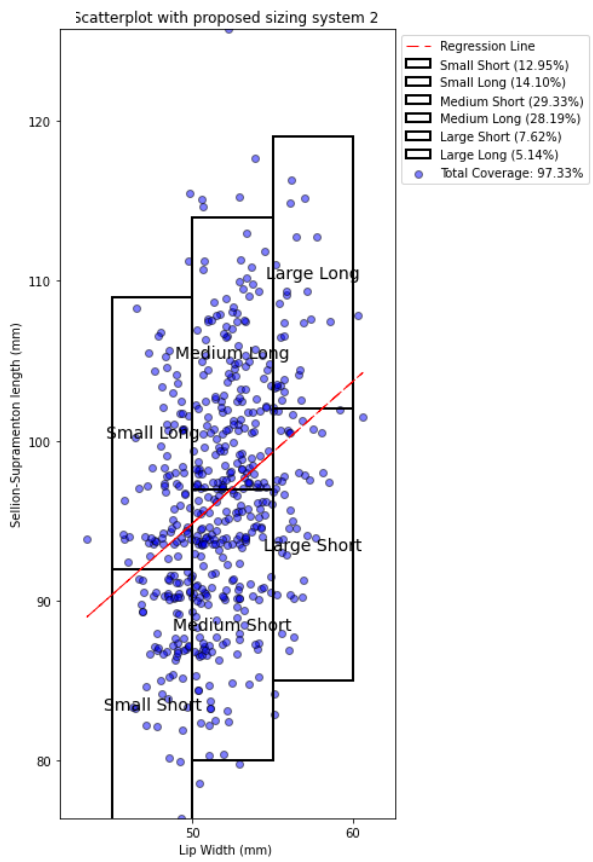


Figure 99: *Proposed sizing system 2*

10.2 Personalized oxygen masks

As all F-35 pilot receive an personalised helmet integrated with sensors based on a 3D scan of their head. In the future the possibility of personalised oxygen masks should be investigated further.

The scan of a pilot can be directly used in the design and evaluation algorithm described in chapter 4.6 and chapter 6.1, to design a personalized mask. Ensuring a perfect fitted oxygen mask for the pilot. With the development of 3D printing for tooling at fairly low costs, producing personalized facepieces should be possible for an acceptable price.
This price would probably be a factor of 10 higher compared to mass produced facepieces.
Factoring in that the current price of the personalized helmets for the F-35 is set at around €400.000,-, this higher price for a personalized facepiece should be acceptable.
Especially if the personalized facepiece shows better performance and decreases discomfort compared to their convection sized counterparts.

10.2.1 UPPS framework

The faculty of industrial design engineering (IDE) at the TU Delft developed a framework to personalize products. The framework was devised by the Ultra Personalized Product System (UPPS) team and can be seen in Figure 100.

The framework is intended to facilitate the development of products personalized on an individual level and could be a good guideline for the development of personalized facepieces.

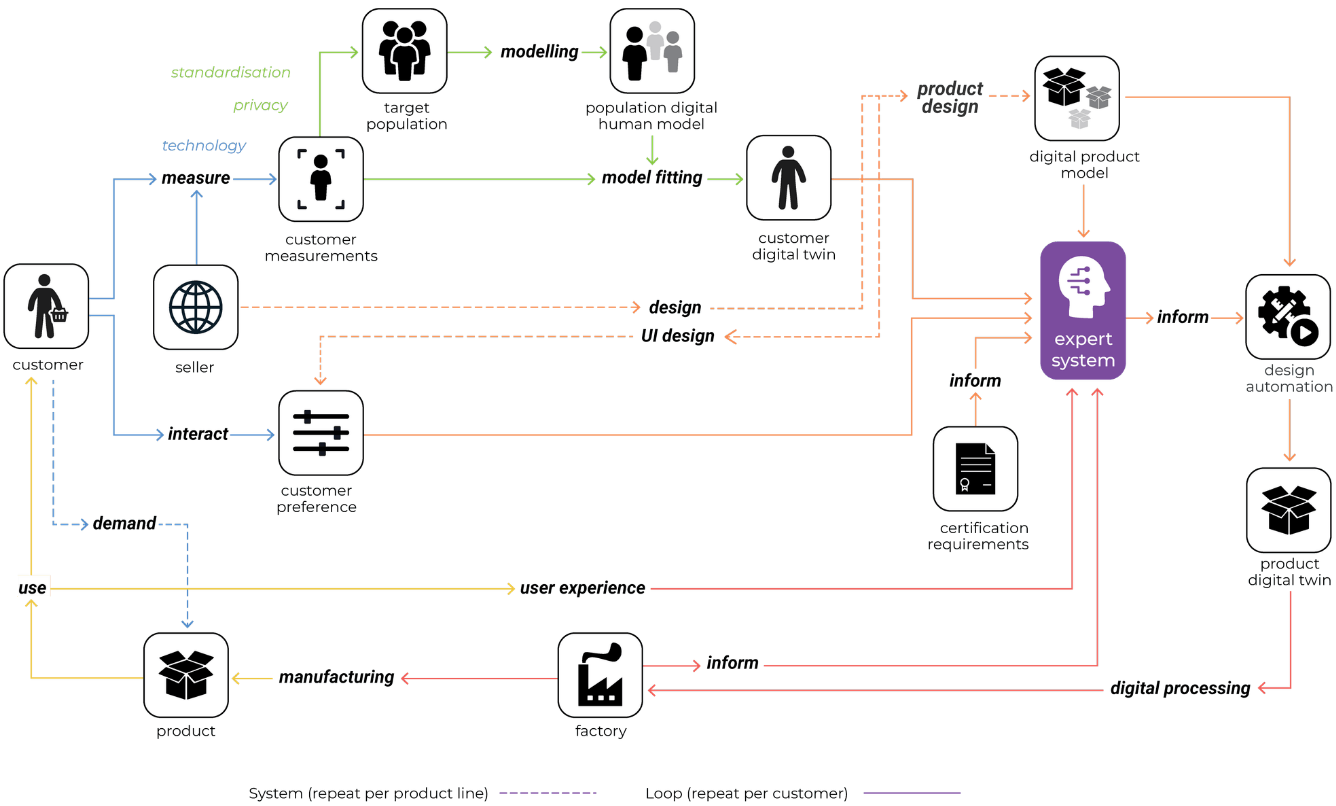


Figure 100: *UPPS framework (TU Delft, 2024)*

10.3 Asymmetric mask movement

The current oxygen mask has an asymmetric design. The oxygen supply hose is attached to the inlet valve on the left cheek of the pilot. The outlet valve is on the right cheek. This oxygen hose exerts a higher pulling force on the mask, especially under high G-loading, Figure 101. This causes a higher pulling force on the left cheek of the pilot. This asymmetric pulling force could result in a higher level of pressure injury sustained at the left cheek. Two concepts were developed to address this issue.

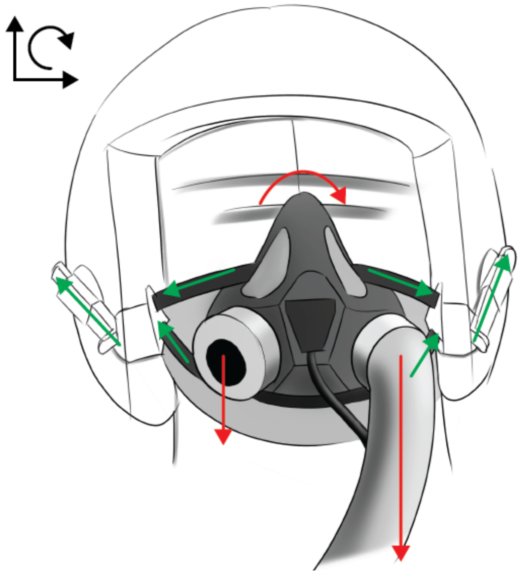


Figure 101: *Pulling forces on MBU020/P oxygen mask*

10.3.1 Asymmetric facepiece

The asymmetric facepiece has a wider ribbon located on the left cheek of the user. Reinforcement ribs can be added, Figure 102. More and thicker reinforcement ribs on the left side will ensure the asymmetric pulling force of the mask is transferred to a higher degree on the left cheek, compared to the right cheek. However, increasing the contact area of the ribbon on this cheek will help distribute the pressure better.

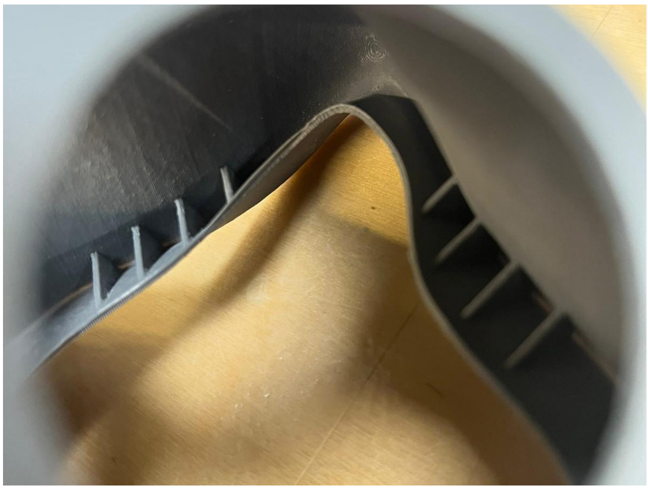


Figure 102: *Reinforcement ribs in a prototype facepiece*

10.3.1 Symmetric oxygen mask

Another way to address this asymmetric pulling force is to ensure the pulling force is in the centre of the face. This can be done by redesigning the in and outlet valves and attached oxygen supply hose to attach in the middle of the mask. Similar to the MBU-12/p mask, Figure 103.

This could cause the centre of gravity to shift away from the face, which could increase the rotational pulling force of the mask on the face. When relocating inlet valve and thus the oxygen supply hose, the rotational pulling force could be decreased.

Figure 103: *Symmetric oxygen mask (MBU-12/P)*

10.4 Ribbon design

As shown in chapter 7.1, the design of the ribbon has a great effect on the mask performance and perceived (dis)comfort. To further improve the facepiece performance, different design features could be considered. Two examples of these design features are described.

10.4.1 Curved ribbon

Currently the ribbon is designed as a straight sweep between two splines, creating the ribbon shape. Changing the shape of the sweep from straight to curved could help accommodate the variability in face shapes. As the current ribbon is designed from a distance calculation of the inner and outer edge. Sometimes it could be hard to come up with a shape which suits faces best in certain areas of the face. Changing the ribbon sweep to curved will result in an earlier contact point with the face, between the two splines, Figure 104.

This could deform the mask more to the shape of the user, compared to the fairly rigid outer edge of the ribbon.

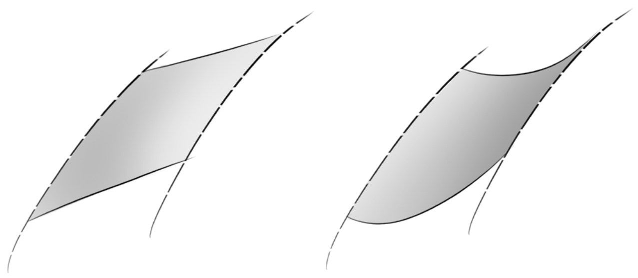


Figure 104: *Cross section drawing of ribbon shape*

10.4.2 Ribbon transition

Currently the ribbon transitions to the rest of the facepiece with an almost perpendicular edge, except for the nasal root and side region. This almost perpendicular edge could cause pressure buildup on this transition. To better facilitate deformation of the facepiece and decrease this pressure buildup, a more rounded edge could be considered, Figure 105.

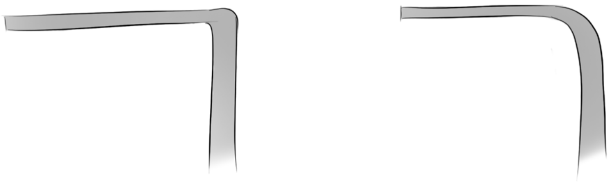


Figure 105: *Straight and rounded transition of ribbon to facepiece*

10.4.3 Reinforcement of nasal root

To eliminate the flipping inside out of the mask at the nasal root, as described in chapter 2.4, specially designed reinforcement ribs could be added to the nasal root area of the mask. These reinforcement ribs need to be designed in such a way that it will not increase the pressure on the nasal root, but prevent the ribbon from flipping inside out.

Chapter 11

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