Engineering and Design of

AeroGrip

an exoskeleton-lite solution towards ergonomic welding

-Master Thesis-

Author:	Floris Verdoes
Institute:	TU Delft
Program:	Integrated Product Design
Chair:	Dr. Ir. Tempelman, E.
Mentor:	Msc. Yuan, T
Skelex mentor:	Ir. G. Genani
Translas mentor:	Ir. F. Kreuk
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TU Delft

Abstract

This design project marks the collaborative efforts of Translas, a prominent welding company based in the Netherlands, and Skelex, a scale-up enterprise specializing in exoskeleton design. Translas developed the 8XE fume extractor torch. However, a common complaint of the new torch is its decreased usability and potential ergonomic risk. To address this problem, Skelex and Translas have united their expertise to develop an exoskeleton-lite solution, aimed at assisting welders in carrying the torch. The aim is to alleviate the physical strain of welding and enhance overall ergonomics. A literature review of welding, ergonomics, and exoskeletons reveal that musculoskeletal disorders form a significant societal problem with large financial losses, which provide opportunities for cutting-edge companies as Translas and Skelex, and form the groundwork for a problem definition, design goal, and drivers. Through a numerical model the specific ergonomic concerns of the 8XE torch are analysed, which is also used to assess the final design. It was found that generally static welding forces with the 8XE are within safe parameters as recommended by ergonomy experts. The bending stiffness of the 8XE cable contributes significantly to the wrist moment, being estimated to reach values of *0.5Nm* in conventional welding, compared to the *0.7Nm* contribution due to weight. Friction in the ball-and-socket joint, and inertia ore comparatively low, and do not significantly cause ergonomic concerns. An iterative prototyping phase diverges to explore various ways to offload the 8XE's weight on the wrist to stronger body parts, converging to two good concepts. A simple strap off loading the weight on the wrist to the lower arm for a limited amount of welding positions, and an exoskeleton worn on the waist and shoulders carrying the full weight of the torch using a tool balancer. After three user tests, two of which with welders in industry, both concepts were combined which led to the creation of AeroGrip. AeroGrip is an exoskeleton-lite product that eases welding by changing the weight distribution on the upper extremities, improving ergonomics and helping welders 'be their ultimate'; they can weld safely for longer, with more precision, whilst experiencing less strain. It is a system that attaches to the welding cable through a ladder strap and buckle. A hook attached to a kevlar cable can be pulled out and attached to the special AeroGrip Gloves, which feature a leather tab with grommet. The kevlar cable is attached to a powerspring via a spool in the casing, which ultimately results in a Tension of *~12N.* Two final user tests, and comparative numerical analysis show that AeroGrip eases welding, provides an ergonomic benefit, and is convenient to use. FEM analysis and friction analysis ensure feasibility, whilst an assembly plan and business case ensure viability.

Table of contents

Photo: PixaBay

X. Introduction

In today's industrial landscape, welding plays a vital role in building and maintaining our world's infrastructure. However, welding is also a hazardous job, and requires significant physical efforts from the worker. Hazards such as toxic fumes, fire or shock risks, and loud noises are paired with musculoskeletal risks in the lower or upper back, neck, upper arm, and wrist area. These problems in turn create market opportunities which can be stimulated or subdued by government policies and their advisory organizations, depending on the overall benefit of the provided solution weighted against the cost.

This design project marks the collaborative efforts of Translas, a prominent welding company based in the Netherlands, and Skelex, a scale-up enterprise specializing in exoskeleton design. Translas developed an exciting technology in the 8XE fume extractor torch that extracts the toxic fumes at the source, reducing health risks. However, a common complaint of the new torch is that it's more cumbersome to use, which decreases usability and might also pose an ergonomic risk.

To address this problem, Skelex and Translas have united their expertise to develop an exoskeleton-lite solution, aimed at assisting workers in handling the new Translas torch. The aim is to alleviate the physical strain of welding and enhance overall ergonomics.

This project explores various concepts and assesses their feasibility and viability, based on requirements coming from Translas' and Skelex' business case and the context of welding.

The design process will encompass an investigation into the ergonomic aspects of welding, as well as an exploration of the potential and limitations of exoskeletons, conducted through literature review and numerical analysis. This comprehensive groundwork will guide the subsequent design phase, characterized by a strong emphasis on early and iterative prototyping, followed by a complete engineering phase focused on delivering a successful Minimum Viable Product of an exoskeleton-lite solution that improves musculoskeletal health of welders, and eases the welding experience.

1.1 Primary Stakeholders

Translas - A prominent welding technology company that specializes in developing and manufacturing high-quality welding equipment. In addition to their MIG and TIG welding torches they also offer a wide array of welding accessories, such as gloves, helmets, or protective clothing. Their goal is to improve the acceptance of their Extractor series welding torches by increasing its usability

Photo: Translas

Skelex - An innovative and technology driven scale-up specializing in passive exoskeletons. With the growing success of the Skelex-360, a passive exoskeleton supporting overhead work whilst allowing for full freedom of movement, they are looking for new opportunities for products. Having identified the welding industry as a promising market due to the prevalence of physical and repetitive work, Skelex is looking to break into this market.

Photo: Skelex

Welders: Ultimately the most important stakeholder. Welders are skilled tradespeople who use heat to join metal parts together. They work in a variety of industries, including construction, manufacturing, and repair, and they are responsible for creating everything from bridges and buildings to cars and airplanes. In the scope of this project the focus is on MIG welders in industry, who form a major part of the customer base of Translas.

Photo: Pavel Chernonogov

Policy makers - Skelex and Translas both focus on technologies improving the health of various workers by reducing ergonomic and respiratory complaints respectively. As these technologies often have cost and usability complications they are reliant on policy makers like governments, and advisory organs like TNO or Volandis. They can force employers to uphold safety standards, so they are more likely to invest in fume extraction, or raise confidence in emerging solutions like exoskeletons to persuade health insurers to invest in these preventive measures.

Photo: The Coach Space

1.2 Welding in Context

Welding is defined as the process of joining two materials using high temperatures or pressure (Lasinstituut 2021). Since the Second World War there has been a rapid development in arc welding, which uses an electric arc to create heat. There are various types, such as Metal Inert Gas (MIG), Metal Active Gas (MAG), Tungsten inert gas (TIG), Flux core, and stick welding, but they all have in common that they use a power source which creates an electric arc between electrode and workpiece. Variations in welding types occur in differences between electrode (consumable or non-consumable), whether material is added and in which way, and how the weld zone is protected against atmospheric contamination. This project limits itself to MIG/MAG welding, as these are both done with the Translas fume extractor torches. Here a spool continuously feeds added material to the workpiece through the welding torch. It's connected to a power source, generally DC, and when the material nearly touches the workpiece an electric arc will create vast amounts of heat and melt both the added material and workpiece. At the same time, a gas is extruded on the workpiece to protect it against atmospheric contamination - it prevents instantaneous rusting. If this gas is fully inert, such as commonly used Argon, it's called MIG welding. If it's (partially) active, such as the common mixture of Argon/CO_2/O_2, it's called MAG welding. The workpiece is connected to the negative of the circuit, creating a full loop (Gales et al., 2008). Figure 1 shows a simplified schematic of the process.

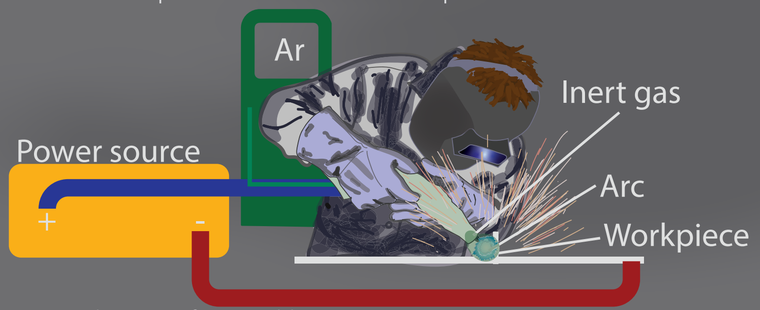


Figure 1: Schematic of MIG welding.

Translas' primary product is MIG and TIG welding equipment. In addition they also are involved in robotics, as well as safety equipment such as gloves, respiratory systems, and welding masks (Translas, 2023). This safety equipment is much needed, as welding is a hazardous job, and welders face numerous health risks - both short and long term (Gales et al., 2008).

Especially for this last hazard Translas has developed their Fume extractor torch. It features an extractor nozzle around the cup of the torch, through which toxic fumes are suctioned off. It necessitates an additional cable over the regular welding cable bundle, adding weight and stiffness.

Torches are available in a wide array of different amperages. Higher amperages are used in heavy-duty welding applications, such as construction, or shipbuilding - markets where Translas is active. This project focuses on the water cooled welding torches of high amperages (500A), as these are the heaviest torches of Translas. The usability complaints are most prominent in this sector. Figure 2 shows the green 8XE-500 MIG Fume extractor torch (8XE) and the regular 8XM-510 MIG torch (8XM). Translas' wish is to develop a product that makes the 8XE torch as easy to use as the 8XM torch.

Figure 2: regular and extractor welding torch

Welds are categorised by orientation (e.g. horizontal, vertical, round) and type (e.g. fillet, groove) according to ISO standard 6947:2019 (2019) and AWS A3.0M/A3.0 (2020). As these directly relate to the posture of the welder a selection of positions are introduced below covering important welding postures.

Table 1: Weld standards.

Description	Example	ISO	AWS
Flat	Rotating pipe	PA	1G
Horizontal	Rotating pipe	PC	2G
Vertical		PG / PF	3G up/ down
Overhead		PE	4G
Rotating		PJ / PH	5G down/ up
Inclined & rotating		PJ/PH -L045	6G down/ up

1.3 Musculoskeletal Disorders

Welding is a physically demanding task compared to other professions. In The Netherlands the experienced physical strain of workers in construction or metalworkers, often welders, is significantly higher than the national average (NEA, 2019). It is one of 20 occupations where more than half the population (54%) reported being 'worn out after work' (Kadefors, 2005)

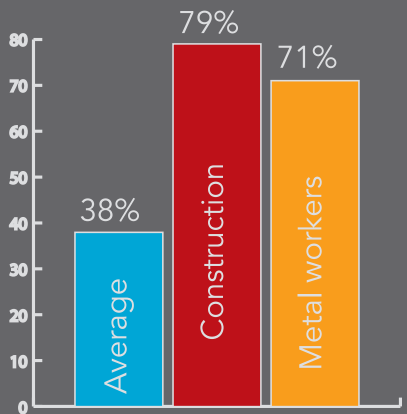


Figure 3: Experienced physical effort.

Various studies have investigated the prevalence of musculoskeletal complaints. The results of an Iranian, a Portuguese, and an Indonesian study are shown in Table 2 (Ebrahimi et al., 2011) (Susihono et al., 2020) (Lourenço & Luís, 2021) . Studies are generally aligned in magnitude and order of prevalence, although the study by Susihono et al. (2020) revealed significantly higher wrists/hands and shoulder complaints, and significantly lower elbow and lower back complaints.

Table 2: Prevalence MD's according to different studies

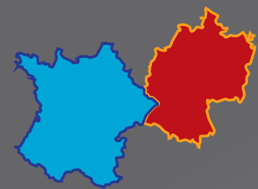
Source	**(Ebrahimi et al., 2011) (n=75)**	**(Susihono et al., 2020) (n=33)***	**(Lourenço & Luís, 2021) (n=40)**
Region	Welders	Welders	Welders
Neck	82.0%	88%	65%
Elbows	72.2%	26%	-
Lower back	72.2%	44%	50%
Knees	59.0%	70%	-
Shoulders	41.0%	82%	-
Thighs	36.4%	36%	-
Wrists / hands	27.3%	52%	23%
Upper back	27.3%	24%	35%
Legs / feet	22.7%	24%	-

*This study distinguished the right side body parts from the left side. The higher number was chosen

Suffering from a musculoskeletal disorder lowers Quality of Life directly, not only through bodily pain (Lourenço & Luís, 2021), and these numbers illustrate the importance of ergonomic solutions for welders. It is worthy to note that the studies shown in table 2 are all based on questionnaires and are based on self assessed complaints instead of diagnosed disorders. To what degree these numbers are representative of musculoskeletal disorders in general is unclear.

To translate these individual damages to quantifiable metrics useful to organisations and companies one can look at estimated costs of damages.

MD's are responsible for a loss of 0.5-2% of the GNP in The Netherlands and Nordic countries (Swift et al., 2001)



Germany and France, major markets for both Skelex and Translas, can as such be estimated to lose 27-120 billion euros yearly due to MD's (WPR, 2023).

In more intuitive language, in a study with 222 welders and metal workers, 51% of welders attributed at least one period of sickness to MD's within a two-year period, which accounts for 44% of all work days lost (3655/8306 days) (Burdorf et al., 1998). Assuming they earn €20,- per hour on avarage, this is a loss of €600 000,- among all welders in the two year period, or ~€1300,- per worker per year. This motivates (insurance) companies to invest in their workers' health.

Still, the current price of exoskeletons is quoted to be one reason for slow adoption (TNO, 2020). As such, exoskeletons are dependent on companies and insurers to invest. Companies, like Skelex, are as such stimulated to design products that can proof their effectiveness. This is generally hard to do, as products have to be tested over long periods of time to describe their effect accurately (TNO, 2020).
The numbers in table 2 can be used to show specific design directions for Skelex and Translas. Prior analysis done by Skelex on the extractor torch concluded that the joint moments on the wrist might be too high, when using the 8XE torch (Skelex 2020), and as such strategically positioned the project to focus on the moment on the wrist.

1.4 Ergonomics

The focus on this project is on the upper extremities; arms, forearms, wrists, and hands of the human body. This system is responsible for carrying and moving the welding torch. Movement of the upper extremities can be described through the following terms:

Table 3: Glossary of ergonomic terms (Humanics Ergonomics, n.d.).

Shoulder abduction	Placing the upper arm to the side and away from the body
Shoulder adduction	Placing the upper arm to the side towards the body
Shoulder flexion	Placing the upper arm forward
Shoulder extension	Placing the upper arm backwards
Elbow flexion	Closing the forearm and upper arm angle
Elbow extension	Opening the angle between the forearm and upper arm
Ulnar deviation	Hand shifts towards the little finger side of the wrist.
Radial deviation	Hand shifts towards the thumb side of the wrist.
Wrist flexion	Bending the wrist towards the palms
Wrist extension	Bending the wrist towards the back of the hand
Pronation	The clockwise rotation of the palm
Supination	The counter-clockwise rotation of the palm.

The development of musculoskeletal disorders are dependent on: 1) posture, 2) relevant forces, and 3) repetitiveness. However, the direct relation between these three factors is currently unknown (Falkenburg & Schultz, 1993). Other ergonomists state that duration might be more crucial, as it's a better predictor for ergonomic discomfort than repetition rate (Potvin, 2011). Research on dangerous postures and their harm is common, and is done for various types of jobs, such as research by Nguyen et al. (2001) on surgeons, research by Juul-Kristensen et al. (2004) on computer users, but also research done by Dev et al. (2018) on welders. This is also helped by the development of assessment tools for ergonomics, such as the 'Rapid Upper Limb Assessment' tool (McAtamney & Corlett, 1993).
Additionally, there is various research on maximum possible forces of the shoulder and elbow, such as research by O'Sullivan et al. (2022) or by Kattel et al. (1996). A clear recommendation is given by the The National Institute for Occupational Safety and Health (NIOSH) for maximum allowable forces during lifting (Waters et al., 1993), but no such recommendation is given by any similar organization for welding specifically, or for any other hand tools.

Potvin (2011) proposes an equation for the upper extremities, based on various research on measured Maximum Allowable Efforts (MAE), to predict MAE's based on a worker's Maximum Voluntary Effort (MVE), and duty cycle as follows:

$$MAE = 1 - [DC - 3.47*10^{-5}]^{0.24} \quad (1)$$

Where MAE is the Maximum Allowable Effort as a percentage of the Maximum Voluntary Effort, and DC is the length of a duty cycle as a percentage of the full cycle, or working day, accurate until DC > 0.9 . A good estimate for a worker's MVE of the shoulder can be taken at 57.1Nm for shoulder abduction/adduction, and 75.2Nm for shoulder flexion/extension. This is based on research by Otis et al. (1990), measuring torque in young adult males for various angles. Combining these values an estimated MAE for welders can be plotted against the expected duty cycle, as shown in figure 4.

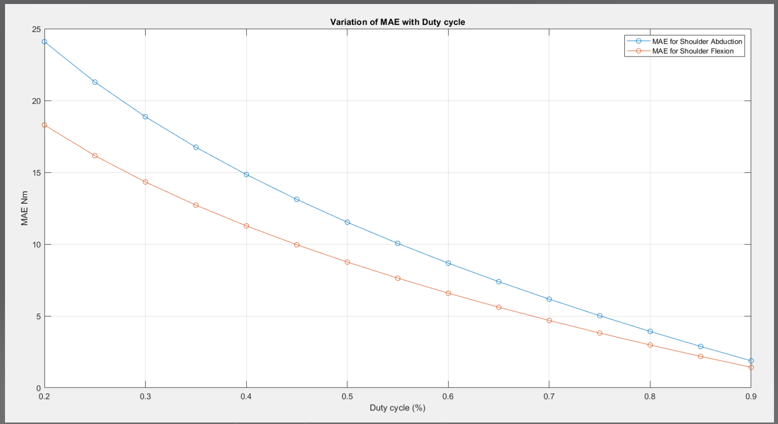


Figure 4: MAE [Nm] vs duty cycle [%]. Appendix X.

For the wrist specifically there can be relied on direct measurements. A research by Ciriello et al. (2012) on repetitive hand movements in industrial workers.

Table 4: MVE's for different movements. N=16, 95% confidence interval.

Wrist movement	Maximum Allowable Effort [Nm]
Ulnar/radial deviation	3.88 ± 1.34
Flexion/extension	2.26 ± 0.709
Pronation supination	1.56 ± 0.556

These are based on a ulnar deviation action with power grip, an extension action with a pinch grip, and a screw driving action with a yoke handle. Values were taken with a 95% confidence interval. For flexion/extension a value was available for both movements, and the lowest was chosen.

1.5 Exoskeleton Criteria

A successful exoskeleton is both accepted by policy makers and by the target demographic. These stakeholders rate the exoskeleton on more than efficacy.

At its core, passive exoskeletons are tools to reduce physical strain on the body by transferring forces in critical points to other parts of the body. In various review studies (Toxiri et al, 2019), (McFarland et al, 2019), (De Vries et al, 2019) efficiency of an exoskeleton is rated on direct (physical strain), short term (fatigue & discomfort), and long term effects (health). These effects and their measurable parameters are summarised in Table 5.

Table 5: Parameters for exoskeletons

Physical strain	Fatigue & discomfort	Health
• Experienced strain • Muscle activity (EMG) • Heart frequency • Oxygen uptake • Joint moments • Internal forces	• Locally experienced discomfort (LEC) • Endurance time work task • Changes in muscle activity (EMG)	• Prevalence and incidence of health complaints

According to De Vries (2019) it has been shown for upper extremities passive exoskeletons (like the skelex-360) to reduce physical strain, and fatigue or discomfort, which in turn might reduce long term injury.

Still, advisory organisations like TNO are hesitant in recommending the use and development of exoskeletons due to long term risks summarised in table 6 (TNO, 2020). These risks were stressed in an interview with a ergonomic expert (Caspers, 2023). Any proposed design for an exoskeleton should be mindful of these risks, as it could influence the long term acceptance of exoskeletons.

Table 6: Long term risks of using exoskeletons (TNO, 2020)

1	Exoskeletons might influence the natural movement of the body, and interfere with a complex system.
2	Exoskeletons might influence the natural movements of the body: some muscles work less, some work more.
3	Getting used to the exoskeleton might negatively influence worker behaviour.
4	Exoskeletons use straps and other features causing local stresses. There might be longterm effect not yet understood.
5	Undesired side-effect : weakening of the muscles.

The acceptation of exoskeletons depends on the experience of the users. They generally prioritise immediate and short term effects, and generally weigh the reduction of required effort against a wide array of usability complaints. Acceptance is also dependent on imago. See table 7.

Table 7: Factors determining the acceptance or 'intention to use'of exoskeletons

Positive	Negative
• Reduced effort • Less discomfort • Less fatigue (Bosch et al, 2016), (Spada et al, 2018), (de Vries et al, 2020a)	• Restraining freedom of movement • Difficulty donning / doffing • Damage to work due to protruding parts • Pressure • Heat (de Vries et al, 2020b), (Spada et al, 2018), (Hensel and Keil, 2019)
• Image: responsible (TNO et al, 2020)	• Image: weak (TNO et al, 2020)

Figure 5: the Skelex-360 exoskeleton also featured in TNO's reseatch (TNO, 2020). *Photo: Skelex*

1.6 Commercial Landscape

The Skelex-360 is an exoskeleton supporting the upper extremities by applying an external force on the upper arms. Currently, buying one Skelex-360 will cost upwards of around €2700,- (Skelex, 2023). Skelex faces broad competition, such as EksoBionics, Hilti, or SuitX to name a few. Where in 2018 a SuitX u exoskeleton would cost €3650,- (Shankland, 2018), and an EksoBionics exoskeleton €5500- (Crowe, 2018), currently an Ottobock (Who now own SuitX) exoskeleton costs around €1800,- (Ottobock, 2023), and the Hilti-01 exoskeleton retails at around €1300,- (Hilti, 2023). The visible trend is that passive exoskeletons will continue to decrease in price, making it an easier investment for companies, even with the reserved recommendations due to the inability of proving long term health effects (TNO, 2020). Currently, the Skelex-360 features many custom parts, and Skelex' focus is to simplify or standardising these parts.

At the same time, Skelex aims to expand their product line to be able to provide a full support system through exoskeleton technologies. A recent market-ready addition to Skelex' product line in a small neck support harness priced at €150,- , which supplements the Skelex-360 as it supports looking upwards as the worker does overhead work. A next project is the acquisition of a back support to aid lifting, which is to be optimised in usability, and production costs in the short term.

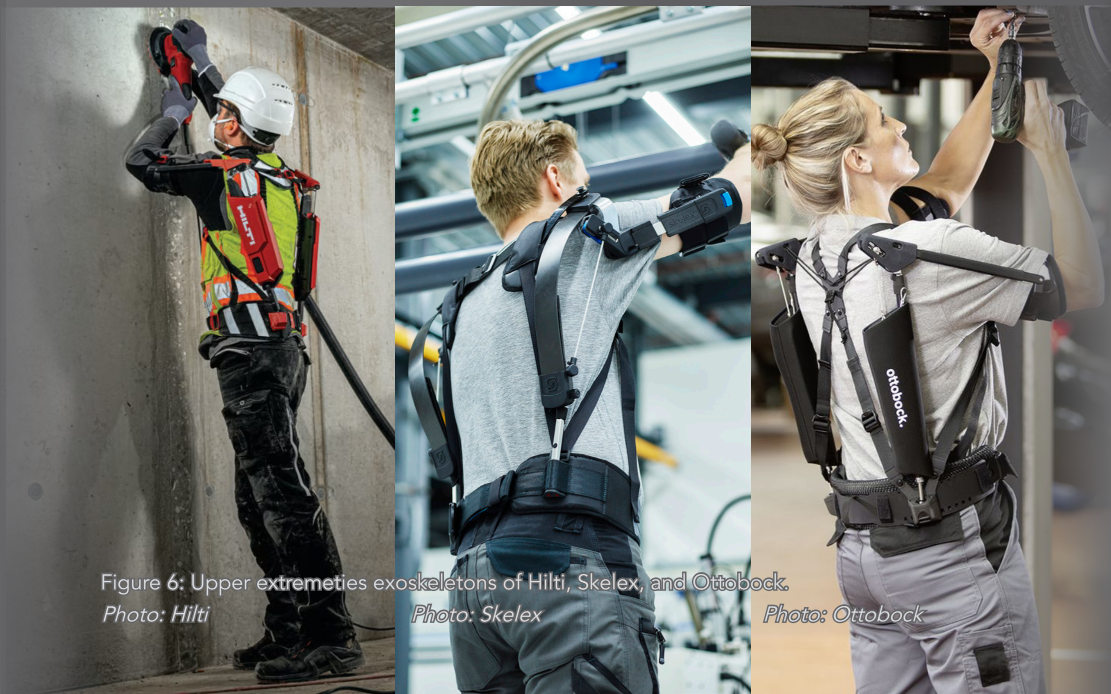


Figure 6: Upper extremeties exoskeletons of Hilti, Skelex, and Ottobock.
Photo: Hilti *Photo: Skelex* *Photo: Ottobock*

As it stands, for Translas the Skelex-360 solution is too expensive. Their regular 8XM torch retails for €198,- , and their 8XE Extractor torch at €667,- (Translas, 2023). As such, a viable solution for Translas cannot be priced more than a few hundred euro's, depending on the welding equipment it is integrated with. In 2022 Translas sold around 4000 regular MIG torches, and around 1400 Fume Extractor torches. There is a higher profit margin on Fume Extractor torches, as Translas has a technological advantage over competitors, making it a more attractive product to push.

Figure 7: Translas MIG and TIG Fume Extractor torch. *Photo: Translas*

For companies in general the acceptable cost for a solution relates to the ergonomic health benefit it gives. The desired solution for Translas and Skelex should alleviate complaints in the upper extremities. In Burdorf's research (1998), 40/222 welders and metalworkers had an absence due to complaints in the upper extremities. On average each worker missed 22.7 working days, amounting to 7264 hours of work lost in total over a period of two years. This means that over the whole group 16.4 hours were lost per worker per year due to complaints in the upper-extremities. Assuming a €20,- wage (Laskowska, 2023), a good solution can cost up to €330,- per year.

2. Defining

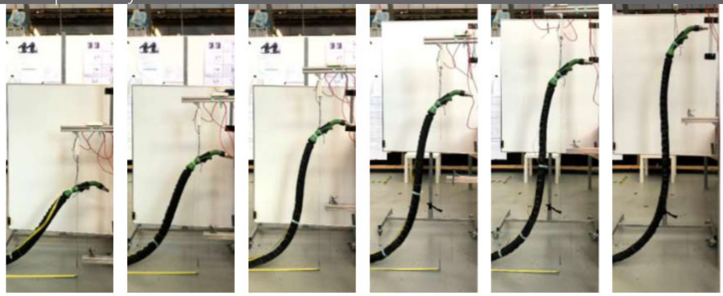
Photo: Aman Jakhar

2.1 Prior Analysis

The motivation behind this collaborative project is the unsatisfying user experience in using the 8XE as opposed to the 8XM, which results in many welders being hesitant to adopt the new torch. The source of these usability complaints were summarised by Skelex to be the high weight of the 8XE torch and the resulting high moment on the wrist necessary to rotate the torch handle (Skelex, 2020).

This analysis was done by lifting the torch up at the handle where the hand grips the torch with a Force meter, and rotating the handle horizontal by pulling it down a hand length away using a second Force meter. The results of the study are shown in Table 8.

Table 8: Skelex forces and torque analysis.



Height	60cm	80cm	100cm	120cm	140cm	160cm
Weight	1.35 kg	1.40 kg	1.71 kg	2.21 kg	2.47 kg	2.80 kg
Upward force	13.5 N	14.0 N	17.1 N	22.1 N	24.7 N	28.0 N
Torque for horizontal handle	0.99 Nm	**1.58 Nm**	**1.90 Nm**	**2.35 Nm**	**2.90 Nm**	**3.1 Nm**
Upward force for horizontal handle	25.9 N	33.7 N	40.8 N	51.5 N	61 N	66.4 N
Different vertical force for horizontal handle	+ 108%	+ 71%	+72%	+75%	+68%	+72%
Length of hose lifted	0.97 m	1.02 m	1.22 m	1.61 m	1.67 m	1.90 m
Horizontal hose lifted	0.75 m	0.62 m	0.55 m	0.8 m	0.75 m	0.68 m

This is an excellent study to gain initial insight into the usability problem and the magnitudes of the relevant variables. However, the study simplifies the bio-mechanics, as the point of rotation is an arbitrary point on the handle. When rotating the handle in the real world, it would pivot around the wrist, and the shoulder and elbow will work together to keep the height constant. The study measures the total torque required for rotation, but the specific contributions of geometry, mass, bending stiffness, and friction remain unclear. Further investigation is needed to understand their individual impacts on the measured torque.

2.2 Design Goal

As stated in chapter X, this project has two primary stakeholders in Translas and Skelex. It is important that both their goals are met. Translas ultimately wants to improve the strategic position of the 8XE as it has a significantly higher profit margin due to the market advantage through technological differentiation. Skelex ultimately wants an exoskeleton-like product to produce and sell. This results in the following flaws:

1. Any solution that eases welding with the extractor torch, could theoretically ease welding with a regular torch. As such, an additional product does not necessarily improve strategic position of the 8XE in the longer term.
2. Any product, no matter how well designed, will to some degree inconvenience the user. It has to be donned, or fastened, or make contact with the body and potentially apply a force. As such, it is improbable to improve the strategic position of the extractor torch compared to the regular torch by adding another product to the user experience.
3. Translas' goal is very specific to the 8XE. This limits the potential profitability of a potential new product for Skelex as it's limited to 8XE users, instead of welders in general.

Despite these potential flaws both parties are still positive towards the collaboration. To minimise the consequences of these flaws the project has the following additional aims:

1. Analyse the 8XE to find redesign options to improve the strategic position of a potential 9XE.
2. A design focus on maximum comfort and convenience, as opposed to maximum effect.
3. Consideration for future adaptations to the design, such that it can be widely used in welding context.

Welders will benefit from a solution that can potentially improve their musculoskeletal health of welders. Policy makers influence the commercial success of exoskeleton-like products depending on their health benefit, and the degree to which this can be proven.

The design goal of this project is as such defined as:

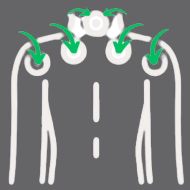
"Design an exoskeleton-like product that eases welding with the 8XE torch that welders actually would use, that can improve welding ergonomics"

2.3 Drivers

Chapter 1.5 defined exoskeleton criteria. These will function as design drivers for a successful exoskeleton-like product.

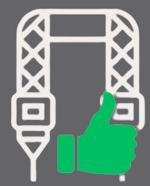
Complete Freedom of movement

Simplicity



Minimal contact points

Minimal Protruding parts



Easy donning / Doffing

Next to these general drivers the following three requirements are defined. These determine the success of the designed solution.

Seamless equipment integration

Eases welding experience

Ergonomic responsibility

In addition to these specific requirements, there are also the general requirements; any designed product must show to be desirable, feasible, and viable.

Photo: Greg Rosenke

3. Develop-

Photo: Greg Rosenke

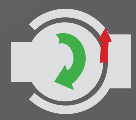
3.1 Problem Analysis

Three user tests were done. As part of these interviews welders were asked to compare the usability of the extractor torch with a regular torch. The findings are summarized below.

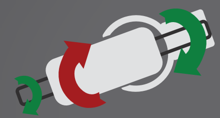
The welding cable is considerably larger. As a result it gets in the way more, and is more cumbersome to use.

The welding cable is considerably stiffer. This makes it more cumbersome to move, position, and rotate. It also gets in the way more.

The weight difference is negligible. When four workers were asked which torch is heavier, half thought the 8XM is heavier than the 8XE.



The ball-and-socket joint has a tight fit to ensure a completely sealed enclosure. As a result there is significant friction. Additionally, the material roughens up quickly in context, increasing friction rapidly.



The regular welding cable bundle, attached to the torch, can rotate 180° around the ball-and-socket joint. As an unwanted side-effect, the cable bundled regularly feels twisted, forcing the welder to position the welding cable more than normal before welding.

It suffices to say significant usability concerns arise from the design decision to put a larger, secondary cable over the normal cable bundle. Cable stiffness measurements (Appendix A) suggest a 30% increase in stiffness, and user tests show stiffness concerns. To alleviate stiffness complaints a ball-and-socket joint is engineered with it's own usability concerns related to the dis-coupled movement of the torch, regular cable bundle, and extractor cable, in addition to friction.
It can be considered to not have 'internal' fume extraction, bundling all cables together in one large cable bundle, but design around an external, additional cable to the cable bundle. This means the Fume Extractor cable can be smaller. This can immediately result in a 20% decrease is stiffness (Appendix X). This eliminates the possibility of having the cable rotate separately from the torch, potentially increasing the immediate rotation stiffness. Due to the high friction of the ball-and-socket joint, and the frustrations surrounding the dis-coupled rotations of cable and torch, it might still be a worthy for R&D investments for Translas. Of course, exploring such a direction properly is a project in and of itself, and is not within the scope of this project

3.2 Numerical Analysis

Welding is a task that requires dexterity and strength. Depending on the specific task a welder might be required to make turns or rotations whilst moving at a constant pace, occasionally with additional small movements to maintain a proper weld pool. To move the torch in this way requires the shoulder, elbow, and wrist to make considerable effort. This chapter breaks down the different loads originating from moving the torch, and their effects on the body, and describes the creation of a model that can analyse these forces. The third sub-chapter summarises the results, and discusses the consequences.

3.2.1 Physics Framework

1|| Bio-mechanics
Although at least 38 muscles are involved in controlling the upper extremities (Forro, 2022), it can be greatly simplified with a system consisting of three joints (shoulder, elbow, and wrist) and three beams. Movement of the torch can be fully described through the lengths of the beams (limbs), two rotations in the shoulder joint, one rotation in the elbow joint, and three rotations of the wrist joint. If we define reference frames in every joint, and a starting position of the beams, we can define the position of the beams and joints for every angle.
2|| Weight
The extractor torch with *1m* of cable weighs *1.68kg* (Translas, 2023). When holding the torch, gravity will pull the system down, resulting in a moment on the joint. An opposite but equal resultant moment of the joint will keep the torch in place. The general relation is given by:

$$\mathbf{M} = \mathbf{r} \times \mathbf{F} \qquad (1)$$

Where ***M*** is the resultant moment, ***r*** the position vector from the joint to the Centre of Mass (CoM), and ***F*** the force vector originating from the CoM. The CoM is crucial for defining both ***r*** and ***F***. Since the cable is flexible it is also dependent on the position and orientation of the cable and torch.
A good summary of both the bio-mechanics and the static load derived from the weight of the torch is given by figure 9.
3|| Bending moment cable
The welding cable has a significant stiffness, which introduces a tension in the cable, and a moment on the wrist. The cable can be simplified to a simple beam, so that its behaviour can be given by:

$$M = \frac{EI\, d\theta}{L} \qquad (2)$$

Where *EI* is the bending stiffness of the welding cable. For simple systems this can be derived from the Young's modulus *E*, and the second moment of inertia *I*, derived from the geometry of the cable. Since the welding cable contains multiple geometries and materials it is more practical and accurate to handle these variables as one, and derive this from experimental data, see appendix A. The *dθ* is the deflection angle, and *L* the length of the bend.


Figure 8: Static load by bending moment

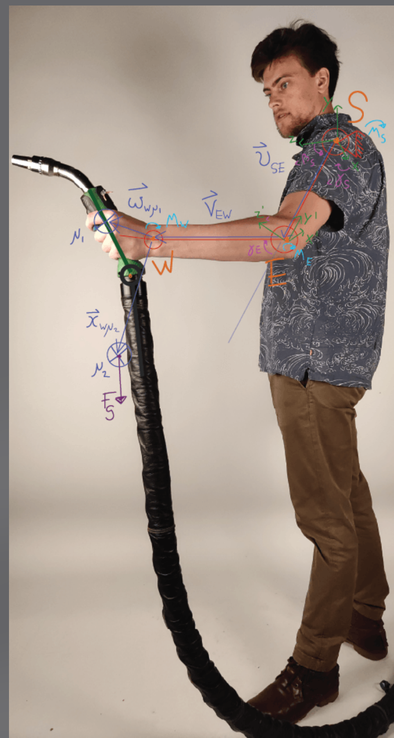


Figure 9: Static load by gravity on upper extremities

Table 9: Legend figure 9

S	Shoulder joint
E	Elbow joint
W	Wrist joint
μ_1	Centre of Mass - torch
μ_2	Centre of Mass - torch+cable
u_{SE}	Position vector from shoulder to elbow
v_{EW}	Position vector from elbow to wrist
$\omega_{W\mu_1}$	Position vector from wrist to centre of mass - torch
$\chi_{W\mu_2}$	Position vector from wrist to centre of mass - torch+cable
γ_S	'Roll' from shoulder joint (rotation around x)
γ_E	'Roll' from elbow joint (rotation around x')
β_S	'Yaw' from shoulder joint (Rotation around z)
F_g	Weight of the torch and cable
$\boldsymbol{M_W}$	Resulting static torque on the wrist
$\boldsymbol{M_E}$	Resulting static torque on the elbow
$\boldsymbol{M_S}$	Resulting static torque on the shoulder

4|| Inertia
In controlling the weld pool the welder occasionally has to introduce small and repetitive movements to the torch. These small rotations can be done without bending the welding cable due to the ball-and-socket joint. This allows for *180°* rotation around the axis in the direction of the cable, and *±15°* rotation around the other two axes. The relation between the moment on the wrist joint and the movement of the torch can be given by:

$$\mathbf{M} = \mathbf{I} \times \boldsymbol{\alpha} \tag{3}$$

Where ***I*** is the moment of inertia of the torch (and not the welding cable), and ***α*** is the angular acceleration of the torch. It is assumed this value is negligently small due to the low speeds of welding and the position of the CoM of the torch close to the wrist.

5|| Friction
In practice the ball-and-socket joint is far from a perfect joint. The PA-6 roughens up fast in welding environments, increasing the friction in the joint. There is also the requirement of an airtight joint, which also limits the movability of the joint. The friction forces exert a moment on the ball-and-socket joint, which results in a higher moment on the wrist. This relation is given by:

$$M = \mu m_c g r \tag{4}$$

Where μ is the friction coefficient of PA-6 on PA-6. m_c is the mass of the cable that hangs from the joint, g is the gravitational acceleration constant, and r is the radius of the joint.

It can be assumed that friction forces are small compared to the static forces of the bending moment and weights, due to the low speeds. Still, this relation is included as it relates to the usability complaints surrounding the ball-and-socket joint of the 8XE.

3.2.2 Modelling - static forces

To analyze the forces as mentioned in chapter 3.2.1 a combination of SolidWorks and MATLAB computation was used.

1|| Biomechanical model
A simplified model of the upper extremities was made in SolidWorks, consisting of an upper and lower left arm as beams, which connect a shoulder, elbow, and wrist joint. These joints have their own reference frames, as shown in table 10.

Table 10: Reference frames S,E, and W orientations

	X	Y	Z
S	'Left'	'Opposite gravity'	'Forward'
E	Perpendicular to frame rotated by γ_S and β_S	Direction of S	Orthogonal to X_E and Y_E
W	Parallel to X_E	Orthogonal to X_w and Z_w	Opposite direction of E

The system can be moved through 3 rotations. 1) A 'yaw' around the z_S-axis (Shoulder ab-/adduction), 2) a 'roll' rotation around the x_S-axis (Shoulder flexion/extension), and 3) a 'roll' rotation around the x_E-axis (elbow flexion/extension). In this system the wrist is assumed to be in a neutral position, and cannot rotate. The lengths of the limbs are taken from a Dined database (Dined, 2004). See table 11.
Dutch males aged 20-60 were chosen as they resemble the target demographic well. It was chosen to pick Dutch adults, as this dataset was complete, and especially relevant for Translas' direct context. The average (p=50) was chosen to have a general model.

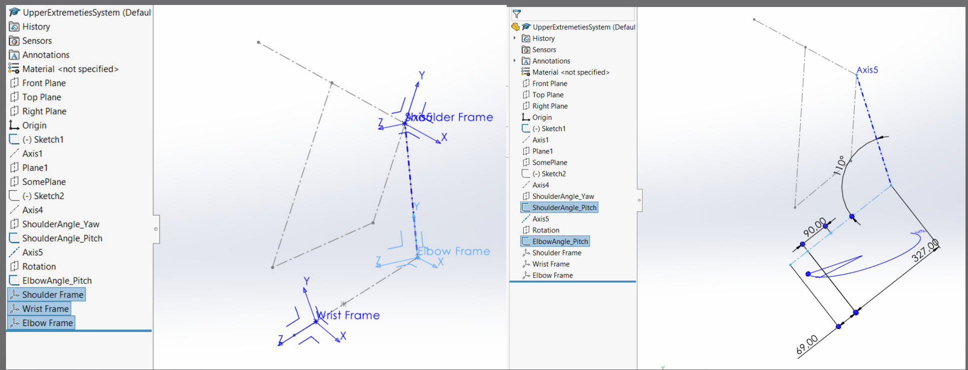


Figure 10: Screenshots of the SolidWorks model.

Table 11: Dataset Dined

Dataset	Year	Gender	Age	Nationality	P-value
Dined2004	2004	Male	20-60	Dutch	50

The used values are found in table 12.

Table 12: Avarage limb lengths

Dataset	Upper arm	Lower arm	Wrist-to-palm
Length [mm]	367	327	64

2|| Weight analysis

A CAD model of the complete assembly of the 8XE torch was made available by Translas. Each part was given the corresponding material so that a mass analysis could be done. It was as such estimated that the torch weighs 0.736*kg*. A hollow tube with an outer diameter of *50mm* (matching the 8XE cable) and a material density was arbitrarily given. The wall thickness was then varied until the torch and 1m of welding cable together had a mass of *1.68kg*, the complete weight of the torch and *1m* cable (Translas, 2023). This cable can then be redrawn in any position, so the CoM can be found for any orientation.

Table 13: weights torch, cable

Torch	0.736kg
Cable	~0.944kg/m

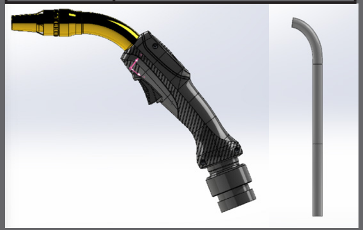


Figure 11: Model torch, 1m cable

3|| Static Loads - weight

During user testing welders in relevant context were photographed. Based on these photographs, pictures were taken from multiple angles of two welding postures.
A neutral pose was chosen, with elbow roll at 100°, and the welder working in a comfortable, upright position and working at waist height.
An extreme pose was chosen, with an extended arm with an elbow angle of 150°, and the welder working in an physically straining posture, working at shoulder height. These postures show the range of expected strain on the welder in most standing postures, excluding overhead work.

Table 14: Used data

	Shoulder roll [°]	Shoulder yaw [°]	Elbow roll [°]	Working height [m]	Weight [kg]
Basic posture	10	20	100	0.90	1.58
Extreme posture	70	50	150	1.5	2.08

These values can be inserted in the bio-mechanical model, after which the torch can be inserted and placed 'in the palm' at a distance of *64mm* from the wrist. It is assumed that the hand is in a neutral position, with the torch pointed forward. From the pictures it was derived how high the torch is lifted, and a cable was modelled fitting the situation. To make analysis practical the cable is split in two parts after the first bend. The end of the cable is attached to the torch, the two parts of the cable are attached at the centre of the face, but can freely rotate, and the straight part is aligned with the direction of gravity. This insignificantly affects the mass distribution of the system, and eases analysis. SolidWorks can find the CoM of the torch+cable, and find the position vectors from the joints to the CoM. The magnitude of the moments on the elbow and shoulder are analysed. The separate moments on all three axes of the wrist are analysed. These align with abduction/adduction, pronation/supination, flexion/extension of the wrist, as described in chapter 1.4 . In order for the model to make an accurate distinction, the position vector needs to be taken from the reference frame of the wrist.

Figure 12: Welding posture to model.

These position vectors from joint to CoM are placed in MATLAB, as well as a force vector for the gravity. For the shoulder and elbow joint, joint moments are calculated in the neutral plane, as no distinction in rotational direction has to be made. For the wrist moment the vector for the gravitational force has to be described from the frame of the wrist. This is done by drawing a vertical line from the neutral frame from the origin of the wrist frame in SolidWorks of length 1 to find the unit vector, u_{g_Wrist} . The corrected force vector is found by:

$$F_{g\_Wrist} = u_{g\_Wrist} \|F_{g\_Wrist}\| \quad (5)$$

These values are then computed in MATLAB following the formulas as described in chapter 3.2.1.

3.2.3 Results

Table 15: Joint moments - modelling results.

	Shoulder moment - Total [Nm]	Wrist moment - Abduction [Nm]	Wrist moment - Pronation [Nm]	Wrist moment - Flexion [Nm]	Wrist moment - total [Nm]
Basic posture	**2.3**	**0.70**	**0.24**	**-0.31**	**0.80**
Extreme posture	**12.8**	**0.56**	**-0.52**	**-0.07**	**0.77**

These values are then computed in MATLAB following the formulas as described in chapter 3.1.1. The results are shown in table 15.

Static loads: bending

The magnitude of the bending moment is estimated using the Bending stiffness measurements done in Appendix A. Although the error in the found bending stiffness *EI* of the welding cable is high, the found value of $EI = 0.6Nm^2$ will be used in estimations. The aim is to understand the magnitude of the bending stiffness' influence over the usability complains, more-so than accurately defining Translas product's specifications.

Analysing the welding cable in a neutral position, and bending it until the torch is completely horizontal shows how the welding cable bends if the welding cable can move freely. Defining the start of the bend as the part where the welding cable is straight ($d\theta/dL=0$), one can estimate *L*, the length of the bend, and measure θ.

Table 16: Joint moment: bending mo-

L [m]	$d\theta$ *[°]*	***M [Nm]***
0.5	23	**0.5**

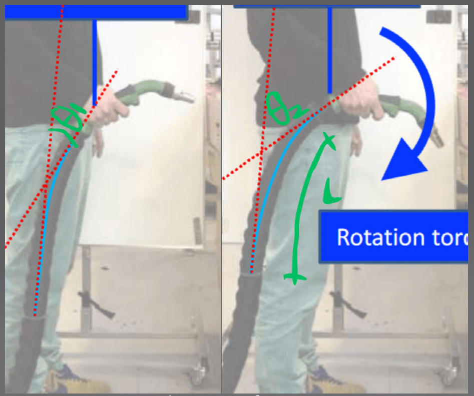


Figure 13: Typical range of rotation.

Dynamic Loads: friction

The ball-and-socket joint carries the weight of the cable, which varies between *~1-1.5kg*. Since the joint is generally rough according to the user interviews, a friction coefficient can be estimated to be in a range of $\mu=0.3\text{-}0.5$ (Zeus, 2005). The radius of the ball-and-socket joint is the inside radius of the 'socket', and can be measured from the CAD model, *r=22mm*. This results in an estimated friction force of **M=*0.06-0.16Nm***. Friction should not pose a significant usability concern, as long the only forces on the joint are from the cable's weight.

3.3 Concept generation

Generally speaking, passive exoskeletons are devices that reduce joint moments by redirecting forces and reducing the moment arm. The Skelex-360 for example adds an additional force close to the elbow upwards, and redirecting this force to the hips or lower back. This results in lower required effort by the shoulder, and elbow muscles. The increased force on the hips is safe, as the moment arm, the distance from the force to the CoM of the body, is comparatively small.

Likewise, the forces resulting from the weight of the torch carried in the hand can be redirected to other parts of the body. Concepts can be categorised by the limb or system the force is redirected to. In the current situation the weight is carried by the hand. Options for redirection are shown in figure 14, where colder colours represent a shorter distance to the body's CoM, and result in safer ergonomics (Caspers, 2023). A secondary distinction can be made in the actuation of the exoskeleton. It can either work directly on the body, like how the skelex-360 provides an external force on the upper arms, or work on the welding torch, like the FORTIS exoskeleton shown in figure X. Generally speaking, exoskeletons working on the body are more versatile, although according the ergonomists there might be unwanted longterm side-effects as a result of influencing the natural functioning of the body (Caspers, 2023) (TNO, 2020).

As the iterative prototyping process is not linear, the structure is done chronologically per concept direction.

Figure 14: Redirecting load from warm to cold colours is optimal

Photo: WIRED (2014)

Photo: Skelex

3.3.1 Towards WeldWing

Following the logic of redirecting the weight to the CoM of the body as much as possible, a prototype was created consisting of a metal frame worn on the hips with a Skelex-360 belt. The hook was wide so the welding cable could slide through. There is a bar above the hook, for experimentation with a locking mechanism. Using this the weight could also be suspended for overhead welding positions. The prototype shows clear promises insofar it takes away the weight on the arm, and moves it to the hip. It became clear however that a system like this needs a sophisticated reel system, so that the welding cable always has exactly the right length. Too little length and the welder cannot work unhindered, too much length, and the cable will twist. This twisting motion is a problem as the cable effectively makes high deviations in angle $d\theta$ in a smaller cable length L. This rapidly increases the tension in the cable, resulting in a high moment on the wrist, following equation 2.

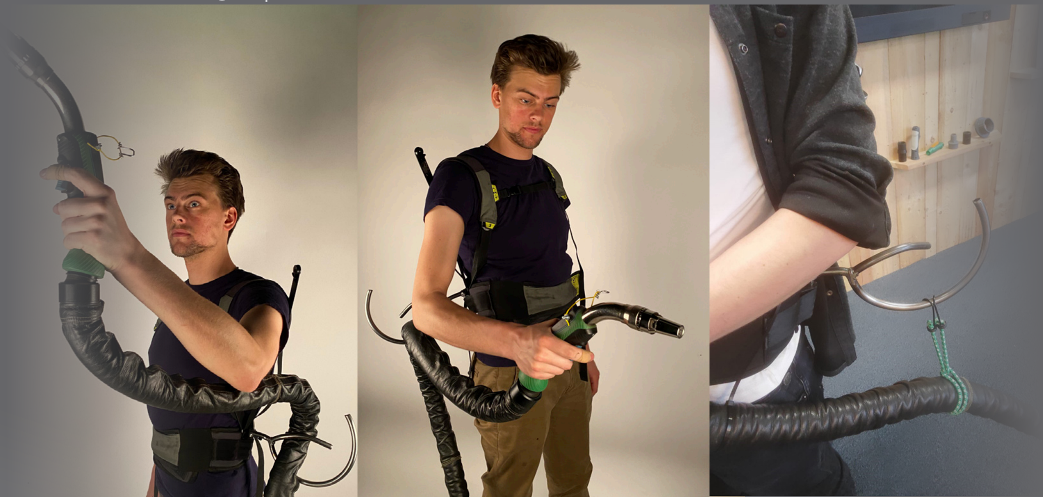


Figure 15: 'locked' position, 'free' position, 'suspended' position.

A simple suspension system was tested using an elastic cable. It was found it increased the movability of the welding cable since the system introduced less tension. It was most comfortable and intuitive when the cable could hang straight down, which makes sense as a cable provides a tension force only in the direction of the cable, and the only force that needs an opposite force is the gravitational force, which points straight down.

Another problem with this solution is the fact that more cable is needed when doing horizontal welds, and the 'pivot point' is on the side of the body instead of

Earlier concepts by Skelex (2020) ended in three variations of redirecting the weight from the hand to elbow or lower arm. The first concept attaches the cable the full lower arm, decreasing the joint moments. The second concept attaches a line from a helical brace to welding cable, with the idea that the helix torsions outwards as the weight hangs from it. The last concept uses the existing Skelex exoskeleton to lift the welding cable up.

Figure 16: Prior Skelex concepts (2020).

These concepts have in common that it decreases the effective length of the welding cable, increasing the experienced cable tension when moving the wrist. The first Skelex concept restricts the welder's freedom of movement if using existing welding technique - changing of which exceeds the scope of this project.
The second concept is promising due to it's simplicity of the suspension system. It inspired the direction of the WrapStrap prototypes, chapter 3.2.4, and the helix helped ideation of the FlexGuard prototypes, chapter 3.2.2.
The third Skelex concept requires the existing exoskeleton, which would result in a solution too expensive for Translas.

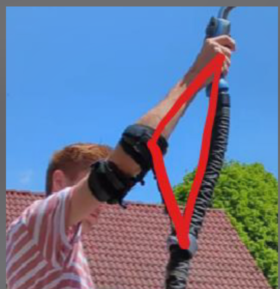


Figure 17: Design proposal R. Conjearts

The second prototype also inspired the design proposal of R. Conjaerts' (2023) where a suspension rope can be switched between two elbow cups for neutral and overhead welding. Conjaerts' cites a measured reduction in wrist torque, although increased cable stifness is still an existing problem that needs to be solved.

3.3.2 Towards FlexGuard

Initial ideation focused on reducing the strain on the wrist, as this was found to be too high (Skelex, 2020). A solution was pursued providing an external torque on the wrist, redirecting the force from the hand to the lower arm.
A wrist brace was suggested by A. A. Nobaveh et al (2020) that can carry the weight of the hand (eases flexion), to support people with musculoskeletal weakness. See figure 18. The torque normally on the wrist joint would be supplied by a compliant mechanism, and transferred to a couple on the underarm.

Figure 18: Prototype wrist support by A.A. Nobaveh et al (2020).

Figure 19: Lo-fi prototype

This idea was adapted to aid welding by carrying the weight of the torch (eases abduction), and by fitting inside a welding glove.

This prototype shows a simple brace that was to be fitted inside a glove, so that it can be donned as easily as a regular welding glove. Upon wearing the glove a spring is deformed providing an upward moment. The spring can rotate around a simple pin, as to not hinder flexion/extension of the wrist.

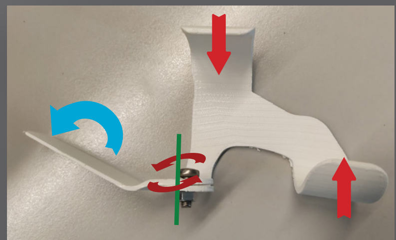


Figure 20: Prototype: Weld support

In using the brace some support could be experienced, although the spring stiffness was not very high in these prototypes, and support was thus limited. Another problem was the ‘sliding’ of the spring over the underside of the hand (ulnar border).
These issues could be solved with a new brace, that could move inwards to follow the movement of the ulnar border.

Figure 21: Helix brace - Can deflect inwards

This brace was then integrated in a MIG welding glove. The helix was glued to the inside of the glove, whilst the spring was supporting the under- outside of the glove. Both parts were connected through a rotating pin.

Figure 22: Concept poster - FlexGuard

The iterative prototyping resulted in a prototype shown in figure 22. Springs with various values for the stiffness could be set in the brace.
It was found there was considerable product latency in the prototype: A hard requirement for a welding glove is easy doffing so it can be thrown off when it gets hot. As a result the helix has the same circumference the glove. This means that when the hand is rotated downward, adduction, the helix first pivots upwards before the spring bends downwards. This effect is greatly increased when the spring stiffness is increased. The spring needs to be relatively short (*~40mm*) since only a part of the ulnar border can be used as you need to be able to grip the torch, and as a result any noticeable difference in effort needed to carry the torch required a very stiff spring.

Figure 23: Wrist support - firmly strapped

When the mechanism is tightly bound against the hand this latency disappears, although this introduces difficulty in donning/doffing and comfort.

3.3.3 Towards CarbonForce

The Skelex-360 is a successful product but it cannot provide a solution to Translas' problem due to two problems:

1. Expensive; the solution is disproportionately expensive to the 8XE fume extractor.
2. Operational range; welding also requires an operational range in neutral position and below the waist.

The ExoForce aims to circumvent these two problems by using a simpler mechanism to carry the weight of the welding cable and torch, and transfer it to the back and hips.

The prototype consists of a carbon fibre rod attached to a steel frame. The dimensions are such that the torch is suspended in front of the welder. To allow for a greater operational range the rod can rotate in the frame, so the torch can freely move in a 180° angle in front of the welder, left to right. Moving it higher would reduce tension in the rod, reducing the upwards force. Moving the torch lower increases the upwards force (requires effort). See figure 25. Moving the torch towards and away from the welder likewise in- or decreases the rod tension.


Figure 24: carbon fibre rod suspending torch.

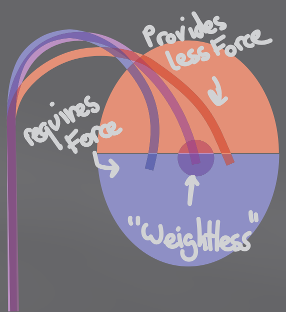


Figure 25: Operational range

The bending stiffness of the rod depends on its stiffness. A rod with a great operational range should have a low stiffness. If the rod has a low stiffness, it needs to be relatively long as a result in order to carry the weight of the torch. As such, there will always be a trade-off between **minimising protruding parts** and **maximising freedom of movement** and **effectiveness.**

An important lesson from this concept is the attachment point on the welding cable. When handling the torch it seems to balance around the handle (Skelex, 2020), which gives the impression that this would be the most comfortable position to suspend the welding torch and cable from. This however introduces another pivot point which interferes with the movement of the ball-and-socket joint. A better position is behind the joint, on the welding cable. This improves the effective maneuverability of the joint between cable and torch, especially in rotations forward (ulnar deviation).


Figure 26: CarbonForce

The CarbonForce shows many promising advantages, but it was fragile and difficult to take to user testing. The CarbonForce concept resulted in a similar cost-effective suspension system (Chapter 3.2.5).

3.3.4 Towards WrapStrap

Concepts similar to 'WeldWing' display a tendency to introduce tension in the welding cable. Suspension cables work best if they are orientated in the direction of gravity. The CarbonForce concept shows that an attachment point behind the ball-and-socket joint can improve the maneuverability of the joint for neutral-to-downward positions, whilst not making neutral-to-upwards rotations considerably more difficult.

The result is an egregiously simple or exceptionally elegant concept direction. A simple strap hangs around the lower arm. The strap features a carabiner clasp, which can be attached to a zip-tie on the welding cable, right before the ball-and-socket joint.

Figure 27: TetherTech.

The weight is suspended from the lower arm. In this position the welder can benefit from the full mobility of the shoulder and elbow, without changing the necessary suspension length between arm and cable. It also shows that the suspension can remain relatively straight for various movement (appendix B). Ulnar deviation is noticeably easier due to the position of the attachment point in relation to the ball-and-socket joint, whilst radial deviation is slightly harder - this effect is not as big however, as the cable still has considerable length to dissipate tensions.

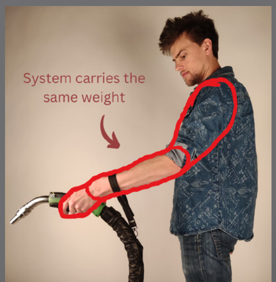


Figure 28: Weight on arm.

The weight on the whole system of the arm is unchanged. Although the variation in length of necessary suspension cable is greatly reduced compared to attachment points further towards the shoulder, the tension in the cable still varies with wrist movement. This means that any chosen suspension length works for a given position and range, but has too much tension (increased pressure, increased discomfort) or too little tension (effectiveness quickly dissipates) for any deviations of this range and position.

As the wrist moment can converge to zero, the torch can feel 'as light as a feather in the hand'. This means that you don't have the grip as tightly, which could directly improve the musculoskeletal health of the elbow joint (Caspers, 2023).

3.3.5 ExoForce and TetherTech

Ideation through prototyping shows two promising but wildly diverging options. The CarbonForce is promising through the ability to take away all weight in an operational range potentially complementary to the Skelex-360 exoskeleton, with a greater simplicity. The fishing rods used in the prototype are too fragile for user testing, so taking this concept forward requires a certain commitment in time and cost. The decision was made to redesign this concept towards a sturdier version. The result is the **ExoForce** exoskeleton. It consists of a steel frame worn on the hips and kept into place with shoulder straps, holding a tool balancer with a pulling force of 5-15N (Rema, n.d.). The cable is directed through several rolling bearings over the shoulder, and goes downwards to attach to the welding cable via a side release buckle. The beam over the shoulder also has a pivot point, so the frame can rotate, following the lower arm when it is moved from left to right.

The WrapStrap is promising through its simplicity, and the ability to take away all weight from the hand. This resulted in the **TetherTech** prototype. It consists of a heavy duty welding glove and a Kevlar strap which can be connected with a side release clasp. The position of the clasp on the glove is chosen so that the cable can hang straight down when attached to the optimal suspension point based on tests with the CarbonForce (Chapter 3.2.3) when holding the torch in a basic posture (Chapter 2.1.2). The strap features a triglide buckle which can be used the attach and fasten the buckle to the welding cable.

Figure 29: TetherTech & ExoForce.

3.4 User testing - Concepts

Three rounds of user tests assess the two concept directions. The first test features four workers in a university workshop, and tests the WrapStrap prototype (Chapter 3.2.4). The second user test features a workbench welder welding window frames. The third user test features two workbench welders, welding metal fences. The second and third user test assess the ExoForce and TetherTech prototypes (Chapter 3.2.5). In addition to testing the prototypes, welders are also asked about their experience with the Translas Fume Extractor torch. The workshop workers have no prior experience with the 8XE, and handle it for the first time during the user test. The workshop welders use a 7XE air cooled torch, which is similar to the 8XE but slightly lighter and more flexible due to a narrower cable. The conclusions on the usability of the Fume Extractor torch are summarised in chapter 3.0. The conclusions on the prototypes are summarised below.

WrapStrap & TetherTech

Positives

1. Weight successfully redirected from 'in the hand' to 'on the lower arm'.
2. The torch is generally experienced as lighter.
3. The attachment system on the TetherTech was experienced as easy to use
4. The spread out pressure on the arm of the TetherTech is comfortable
5. Welders liked that their gloves remained usable for all other working tasks, such as carrying parts or using other equipment.

Negatives

1. Concentrated pressure on the hand of the WrapStrap is uncomfortable.
2. Spread out pressure on the lower arm might introduce increased heat development in the welder.
3. Very difficult to find the right position on the welding cable. If the cable is attached too high there is no tension and no weight redirection. If the cable is too low the tension increases, which introduces discomfort in the best case, and additional muscle strain in the worst case, depending on the orientation and movement of the weld attempted.
4. Even if the right height was found, the tension in the cable still varied a lot, depending on the orientation and movement of the weld attempted.
5. Working height is very important: the welder in the second user test did not think the prototype was very effective (welds: G1/G3, ~chest height), while the welders in the third user test experienced less strain (welds: G1, G2, G3, G5, ~just above waist height), depending on the type of weld and orientation of the suspension points.
6. Welders were concerned not all welds are supported. The welder in the second user test sometimes has to reach around their workpiece, leaving the torch sideways. No support is felt in this orientation. The welders in the third user test did not experience any support during G4 type welds, as they hold the torch sideways.
7. Welders were concerned about the side release clasp hanging down from the glove, that it might get in the way during other working tasks.

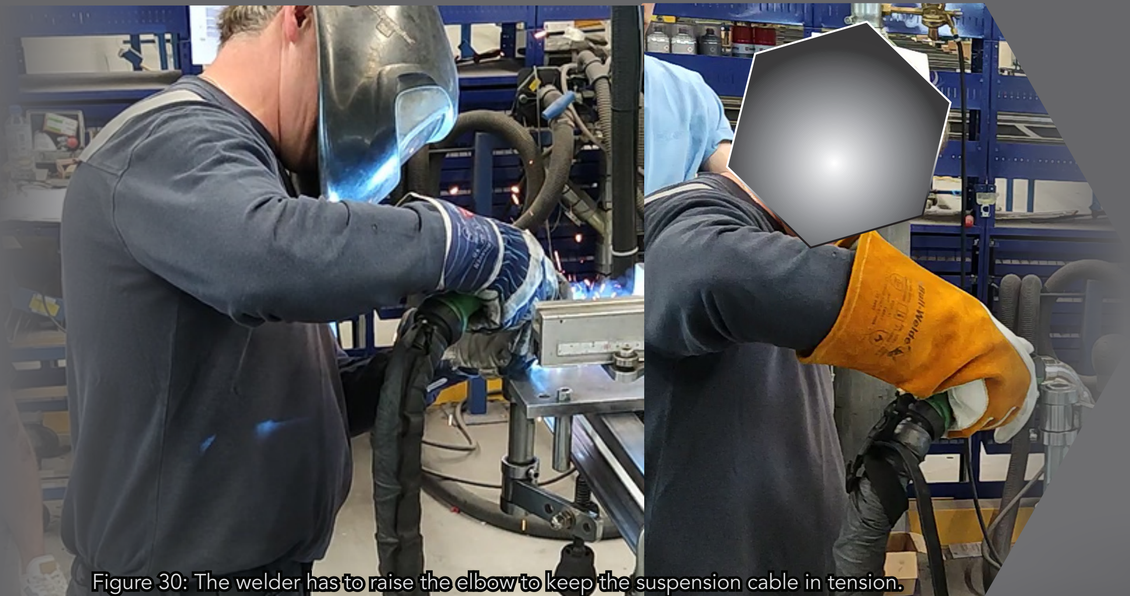


Figure 30: The welder has to raise the elbow to keep the suspension cable in tension.

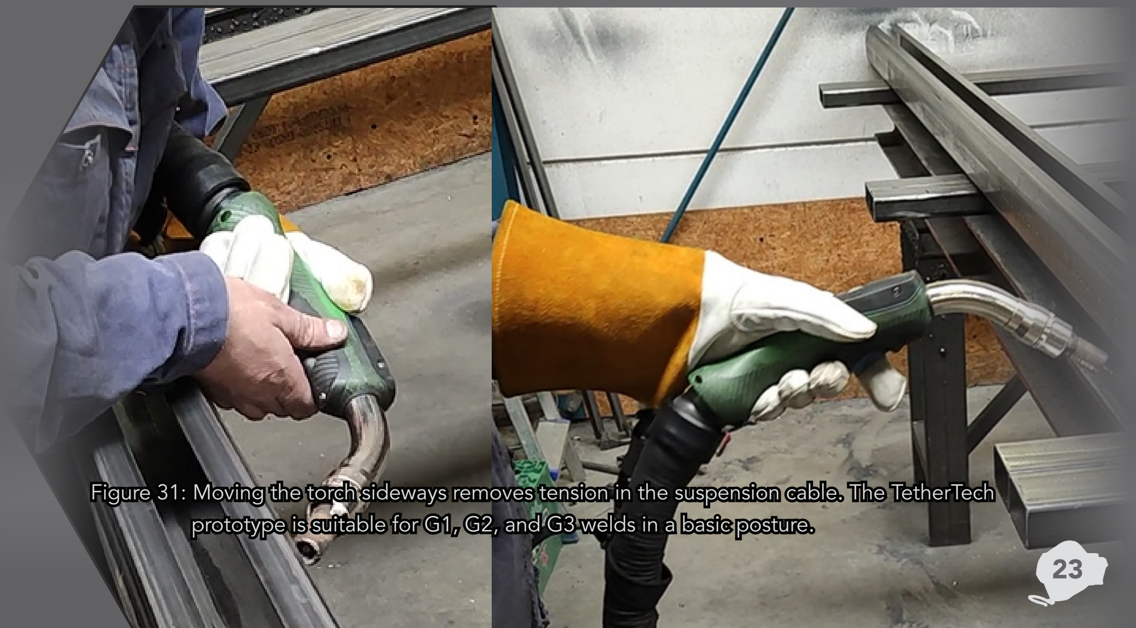


Figure 31: Moving the torch sideways removes tension in the suspension cable. The TetherTech prototype is suitable for G1, G2, and G3 welds in a basic posture.

ExoForce

Positives

1. Very effective at redirecting weight from ‘in the hand’ to ‘on the back’. The welder in the second and third user test specified they felt no weight of the torch when holding it.
2. It is easy to attach and detach the cable to the ExoForce via the side release buckle.

Negatives

1. The prototype was uncomfortable. The metal frame could hurt the shoulder, and the box for the tool balancer was attached too close to the lower back.
2. The prototype is too heavy - it strains the back and shoulders even in the relative short duration of the test.
3. The metal frame is in the way when welding, and also during all the other tasks a welder must do during the workday. The welders in the third user test specified that they have to maneuvre under and around the fences, which would be very difficult to do wearing the exoskeleton. Also manuevring around the storage part of their workshop would be difficult.
4. The welders do not like the hassle of putting on an exoskeleton at the start of their day. Donning/doffing multiple times every day was even more undesirable.
5. The suspension cable of the ExoForce would be in the way during some welds.
6. Operation range is limited. The welding cable needs to be below the shoulder. Especially during the second user test this became apparent, as the prototype was donned wrongly. As a result the frame was angled, and due to the pivoting beam this decreased the operational range. It was not properly usable for the welder in the second user test, as he has to work around shoulder height.

In direct comparison all interviewed welders state that they are a lot more likely to use the TetherTech prototype than the ExoForce. They also stress the importance that the product is simply ‘not in the way’ over the effectiveness. On the other hand, they also state that the TetherTech does not ‘do enough’ to be potentially interesting to them. This, of course, is also influenced by the fact that they do not currently experience the Fume Extractor torches as too heavy as their torches are 1) lighter and more flexible than the 8XE, 2) their welding cables are suspended from above, 3) they weld very short distances, and most of their job consists of preparing and post-processing the welds.

Figure 32: The ExoForce can support the weight, even when the torch is rotated sideways. The frame is already in the way for common welding postures.

Figure 33: ExoForce succesfully move the weight of the torch to the back and shoulder.

The rounds of user testing made clear that the ExoForce concept is not a suitable solution for Translas' problem within the scope and time of this project. Although it can successfully take the weight away from the upper extremities to the shoulder and back for a wide array of welding positions, it introduces various usability concerns about comfort and convenience. These are common problems for exoskeletons in general, and it is probable that these are solvable in the long run. For the specific goal of aiding welders to use the 8XE Fume Extractor torch a solution like the ExoForce will quickly become too complex (expensive) and it is unlikely it can ease the adoption of the fume extractor torches.
The TetherTech concept shows a noticeable improvement in welding ergonomics in some welding positions. The wrist experiences less load, and welders do not have to grip as tightly. Welders noticed the narrow operational range of the prototype, but ultimately are more concerned about how the increasing or decreasing tension on the suspension cable is irritating at best and detrimental to weld quality at worst.

3.4 Converging - 'ExoTether'

The ExoForce has many problems, but operational range ain't one. Inspired by Eberle's SCAMPER method (1972), a final concept is made by 1) combining both concepts, 2) substituting the inelastic strap with the cable of a tool balancer, 3) minimising its dimensions, and 4) reversing the direction of the mechanism from 'welder → welding cable' to 'welding cable → welder'. Figure X shows the initial prototype. Testing showed it to be a clear improvement over both earlier concepts, and it was developed into the final concept and proposed design. The following chapters showcase the final product, and argue their desirability, feasibility, and viability.

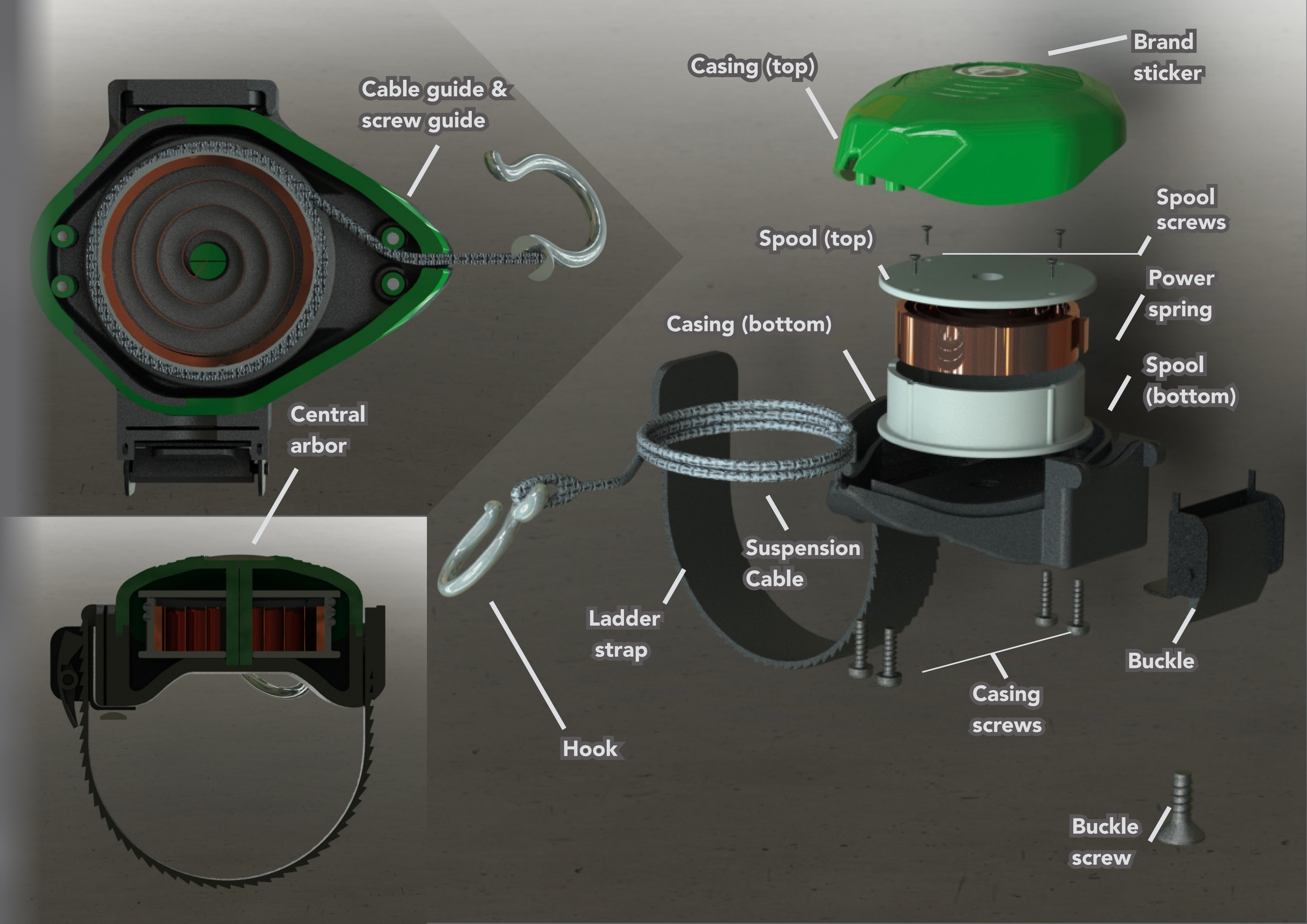
Figure 34: ExoTether. A tool balancer in a 3D printed casing that attached to the 8XE through zip-ties.

4. Delivering

Photo: Denis Corena

AeroGrip

Ultimate Welding Control

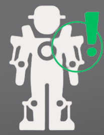

Cable guide & screw guide
Central arbor
Casing (top)
Brand sticker
Spool screws
Spool (top)
Power spring
Casing (bottom)
Spool (bottom)
Suspension Cable
Ladder strap
Hook
Buckle
Casing screws
Buckle screw

4.1 AeroGrip

AeroGrip is an exoskeleton-lite product that eases welding by changing the weight distribution on the upper extremities, improving ergonomics and helping welders ‘be their ultimate’; they can weld safely for longer, with more precision, whilst experiencing less strain. The power spring and suspension cable exerts a *12N* force on the lower arm, and distributes this evenly via the complementary AeroGrip glove. This removes ~55-80% of the weight of the 8XE torch on the wrist, depending on how high it’s lifted. This force is carefully chosen such that it takes away all weight of the welding cable for normal welding postures, and part of the weight of the welding torch, but not so much that it changes the bending characteristic of the welding cable.
Ergonomics are improved through 1) Removing significant strain on the wrist directly, allowing the torch to be moved ‘as light as a feather’, 2) Eliminating the necessity of a tight grip, improving the health of the elbow joint directly (Caspers, 2023), and 3) through the added attachment point on the welding cable, it can be lifted by raising the elbow, instead of only through moving the wrist.
The **AeroGrip Glove** is a minimally altered welding glove, with only an additional leather tab on the underside, featuring a simple grommet to attach the hook through.
All dimensions are minimised so that it does not get in the way during the welder’s workday - the AeroGrip is slightly wider than the 8XE welding cable, and protrudes only *~26mm* above the welding cable.
The **aesthetics** feature geometric shapes to echo the technological fundamentals of Translas and Skelex, which are rounded for comfortable gripping and to minimise the risk of it catching an edge. The colours and texture lines on the product’s face reference the 8XE Fume Extractor torch, and the flowing split line references the new-found air light ease of welding - the result is a visually engaging product matching the products and values of both Translas and Skelex.

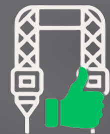
Figure 35: Visual 1:1 scale prototype of AeroGrip || Prototype AG Glove || Simulated AeroGrip

AeroGrip circumvents all exoskeleton usability and comfort pitfalls by not attaching to the body, but to the product.



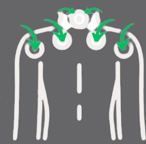
AeroGrip is attached to the welding cable, with it’s minimised dimensions and rounded geometry it is minimally in the way. When the welder needs to do other work than welding AeroGrip is not in the way, like a classic exoskeleton might do. The tab with grommet is barely noticeable.

When in use, AeroGrip is designed around full freedom of movement; moving the lower arm in relation to the wrist is possible since the suspension cable extends with the arm. When not using AeroGrip, it is not limiting movement, like a classic exoskeleton might do.



Donning and doffing is easily done. The hook can be attached/detached with one gloved hand. Although the connection is secure enough due to the geometry of the hook and the fact that the hook is always under tension, it can detached with one movement too.

The tension of the spring exerts a pressure on the lower arm. Since this pressure is divided over the full area of the top of the AG Glove, this pressure is not uncomfortable. There will be some added heat build up, but AeroGrip is not firmly attached to the welder like a regular exoskeleton; the AG gloves can regularly and easily be taken off.



To make AeroGrip as simple as possible, standard parts are used as much as possible. Ladder strap and buckles are readily available as sets, just as metal hooks, and can be designed around. AeroGrip features. Standard fastening options are used, such as ferrules for cable, screws for plastics, and a grommet for a hole in the leather tab of the AG Glove.

AeroGrip can be held in the hand with just a thumb and index-finger. Maneuvering the torch is light, and can be done with a lot of control. Lifting can partially be done through lifting the arm, as AeroGrip will help the welder lift.

AeroGrip is integrated with common welding equipment. This plays its part in not inconveniencing the welder, to ease adoption by welders, but also improves the business case considerably.

4.2 Numerical Analysis

Using the numerical model (Chapter 3.2.2) a quick comparison can be made between the strain with and without AeroGrip. For the model the suspension cable is assumed to be in the direction of gravity. This results in the following formula's:

$$M_W = r_{CW} \times (F_g - F_A) \qquad M_S = r_{CS} \times (F_g - F_A) + r_{AS} \times F_A \qquad \text{(6a, 6b)}$$

Where M_w and M_s are the joint moment in wrist and shoulder respectively. r_{CW} and r_{CS} are the position vectors from CoM to wrist and shoulder respectively. r_{AS} is the position vector from the AeroGrip suspension point on the lower arm to shoulder respectively. F_g is the weight of the torch and cable, whilst F_A is the force of the spring in AeroGrip, *12N.*

Table 17: Joint moments - modelling results.

	Shoulder moment - Total [Nm]	Wrist - Abduction [Nm]	Wrist - Pronation [Nm]	Wrist - Flexion [Nm]	Wrist - total [Nm]
Basic posture	2.3	0.70	0.24	-0.31	0.80
With AeroGrip	2.13	0.16	0.069	-0.0055	0.18
Extreme posture	12.8	0.56	-0.52	-0.07	0.77
With AeroGrip	12.1	0.23	-0.028	-0.21	0.32

The model predicts slight improvements for the shoulder joint in both postures, and ~70-80% reduction for abduction and total wrist moments in a basic posture, and ~35-40% reduction in an extreme posture. This is because the welding cable is lifted higher in an extreme posture, increasing the weight, such that the spring cannot redirect all forces.
The suspension cable is assumed to be in direction of gravity. This is accurate enough for predicting abduction forces, as even ±25deg only reduces the effective spring force by 10%.

Welding static loads are generally within safe magnitudes, it is difficult to argue welders can work safely for significantly longer safely in regards to shoulder joint health. Using Potvin's equation (Chapter 1.4) welders can work safely 20% longer, in regards to the wrist.

4.3 User Test - AeroGrip

Two user tests verify the function and desirability of AeroGrip.
For this purpose a functional prototype was made with a power spring from a tool balancer. A casing without axis and spool were 3D-printed at 140% scale. A *10mm* steel axis was hammered into a hole with the same dimensions on a steel *2mm* plate. The underside was welded together, and ground down to a flat surface. A slit was sawed of *~20mm* in the axis for the spring to go through. A Dyneema cable was put through a hole in the spool and held into place with a double knot. The spring was fitted in the spool, with enough space left over for the Dyneema knot to minimally interfere with the movement of the spring. The steel axis & plate were attached to the casing (top) using epoxy. Once dry the spring in the spool is put through the axis - rotating the spool now winds the spring. *2m* of dyneema cable was rolled around the spool. The casing was closed, with the cable through the slit, and fastened using 4 m3 screws. Pulling 1m of cable out of the slit preloads the spring, and tying a double knot prevents the cable from going back into AeroGrip. The cable was looped through a metal hook, and through a ferrule. Compressing the ferrule holds the hook in place and prevents the cable from going through the cable slit. Two velcro bands were sewn on the casing to attach to the cable. Regular (lighter) MIG welding gloves were cut at the seam at the underside, and two leather tabs were attached, sewn together, and a grommet put through.

Figure 36: Functional 1.4 scale prototype of AeroGrip.

Two general workshop workers with regular welding experience were asked to simulate flat, horizontal, vertical, and pipe welds, for a duration of 10 minutes, equally divided with and without AeroGrip. During which they were interviewed on their physical experience. Users were asked, among others, 1) to describe what they felt in their wrist, elbow, shoulder, and back, 2) how much control on the weld they have, 3) which types of welding are influenced most using AeroGrip 4) whether they foresee general problems with AeroGrip, and 5) whether they want to use AeroGrip when welding. Appendix C shows an excerpt of the second user interview, and important comment from the first.

The spring is slightly stronger than AeroGrip's designed spring. This results in AeroGrip pulling the cable slightly towards the welder's lower arm. This can create additional flexure points, and does not reflect AeroGrip's behaviour. To circumvent this a small weight is attached to the cable of *300g*. This is also a common strategy to research fatigue effects through shorter, high intensity activity. (e.g: Watanabi et al., 2016). After the test users were asked to use the prototype without the added weight, and asked whether they think differently about their given answers. In both cases the employees stated they think the same.

Figure 37: User tests with workshop employees.

Welders both experienced considerably less strain on the wrist, and even experienced less strain on the wrist and shoulder. "I don't feel it on my back. It's more relaxed." The reason they both gave is that they do not have to lift the cable solely by rotating the wrist, but they can also use their shoulder and elbow - raising their elbow lifts the welding cable too. They felt more in control of their movements "it feels like it helps with the movement", as their wrist did not carry a load. They describe the effect as the load being equally divided over the whole area of the glove, instead of everything in the hand and on the wrist. They had some difficulty attaching the hook with gloves on, as it requires a little practice. It was not described as frustrating however, and the attachment felt secure throughout all welds. One employee compared welding without AeroGrip as playing badminton, as all lifting has to come from the wrist, whilst welding with AeroGrip is like playing tennis, where you can use the elbow.

One of the workshop employees is responsible for procurement. He stated interest in such a product citing multiple employees with back and shoulder complaints, stating it would help their health, and he is willing to pay €300,-.

Testing shows that AeroGrip works best for flat welds (similar to 1G), and works well for horizontal/circular (similar to 2G), and vertical (Similar to 3G) welds. It can ease overhead welding, but it requires the position of the AeroGrip to be changed and the work remains straining. AeroGrip works best for postures where the lower arm remains straight, as these keep the suspension cable vertical the best.

4.4 Feasibility

AeroGrip is actuated by a Power Spring. Common applications are tool balancers and cable reels. Power Springs can provide considerable force in a small package. Their characteristic can be altered easily by changing the thickness or height of the spring.

The spring is designed for an actuating force of *~12N*, but this requires a slightly stronger spring. Friction on the steel-on-steel contact of the spring itself, PA-6 on PA-6 contact between the arbor and spool, and Kevlar on PA-6 contact of the cable on the casing. The friction forces in the spring are included in the spring characteristic a supplier provides, and the second one is negligible through the low speeds and forces. The Kevlar cable is redirected twice: at the cable guide fastening cylinder, and the cable slit. The friction forces can be derived from the 'redirection' angle, which is dependent on the distance between spool and guide, given by:

$$\phi = \sin\frac{r_{sp}}{d_g} \tag{7}$$

A second factor is the redirection of the cable slit, which is estimated to be around $\gamma=30°\pm20°$, as it realistically varies whilst welding. Computing the output pulling force with the Capstan friction equations (Mikrocentrum, 2019) one can estimate the output force T_{out} with:

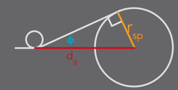


Figure 38: Sketch angles

$$T_{out} = \frac{T_{in}}{e^{\mu_1\phi + \mu_2\gamma}} \tag{8}$$

Where T_{in} is in the force of the spring on the spool in Nm, μ_1 the friction coefficient of Pa-6 on Pa-6, estimated to be $\mu_1=0.2$ (The Engineering Toolbox, 2004), μ_2 the friction coefficient of Kevlar on Pa-6 which cannot be readily found, but is assumed to the friction coefficient of Kevlar on aluminium at low contact pressure, $\mu_2=0.2$ (Brown & Burgoyne, 1999).

Figure 39 shows simulated data of the spring, cable, and output forces. A spring force of *15N* is shown by the dotted line. The green line shows the effective tension in the cable after the guide cylinder. This varies with the chosen distance from arbor to guide, and is *~30mm* for AeroGrip. The blue and red line represent the change in output force depending on the minimal and maximal deflections of γ. The graph shows that a spring with output force *15N (T=0.3Nm)* gives an output tension force of *12N*.

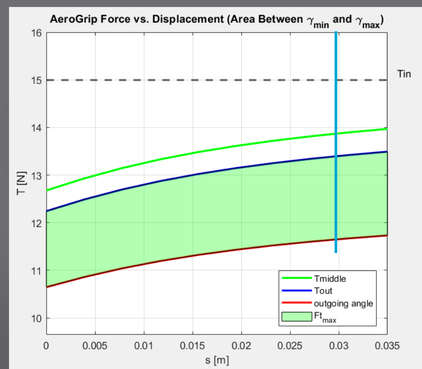


Figure 39: AeroGrip tension vs guide distance.

The AeroGrip powerspring is based on the characteristics of a Vulcan Spring:

Table 18: Chosen Spring (Vulcan Spring, 2023)

Spring	Torque	Arbor diameter	Number of turns	Spring outer diameter	Height
SCP13G59VS	0.30 Nm	6.4 mm	17	38mm	12.5 mm

The spring's casing is *~20mm*, resulting in an internal force of *~15N*. A height of *12.5mm* can result in a minimally protruding product. The spring can still be optimised in reducing the number of turns; If only the middle part of the spring characteristic is to be used, using 5 rotations to preload the spring, and only using the middle 7 rotations, a cable extension of ~π*40mm*7 = 880mm is possible. As only ~200mm is necessary to give the lower arm full range of motion from the wrist, Appendix B, a slightly smaller spring should be possible.

The casing has base material PA-6 30% glass-filled. Together with the considerable wall thickness of *3mm* this will result in a product that feels sturdy and can resist the general rough handling that happens in a workplace. These are based on Translas' experience with their torches in a welding environment. The wall thickness is perfect for the arbor, which is an axis divided into two half-cylinders with a thickness of *~3mm*. A torque of *0.3Nm* is divided over the parts of the axis, resulting in *32.6MPa* von Mises stress on the base, which is well below the fatigue strength at 10^7 cycles, *58.2MPa (Ansys GRANTA Edupack, 2023)*. In the simulation the axis is only fixed at the base, but in the casing it will be kept together by a slot in the base, increasing the safety factor.

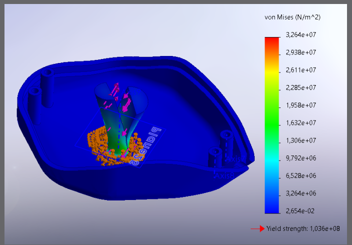


Figure 40: FEM axis / arbor.

The spool is made from the same material, but has a wall thickness of 1.5mm, as it's protected by the casing. PA-6 has a low coefficient of friction, is self lubricating, and has good wear resistance.

The cable is made of Kevlar, as it is a flame retardant material, strong and durable, and does not cut into the casing, like a steel cable would.

Hooks are readily and widely available in all sorts of sizes and shapes. A shape is suggested where a small hall can be used to attach the cable to the hook. The hook closes completely, so that the Kevlar cable cannot get stuck in a groove. The hook is open, so that it can easily be attached and removed. The hook rolls outward, so it's easier to attach it to the glove.

Figure 41: Hook

The Ladder strap is made from Pa-6, which is flame retardant and suitable for a welding environment.

The AG Glove is functionally the same as a regular welding glove, and as such can be easily thrown off when required, even when the suspension cable is attached. This makes it safe and convenient.

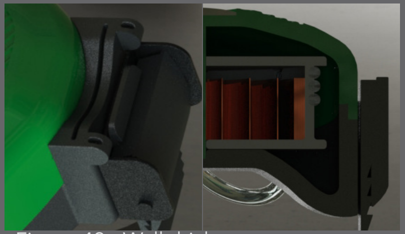


Figure 42: Wall thickness

AeroGrip is designed with injection moulding in mind. The model has a nominal wall thickness of *3mm*. Some places have thinner walls, but never a larger wall. Fillets of 3mm are used on most edges, although reasonable fillets are everywhere. On the buckle platform a small slit is added so that the wall thickness does not exceed *3mm*.

Features of the injection moulded casing include 1) a split line intersecting the cable slit, so the mould does not need sliders, 2) a lip-groove structure for straight fastening, and 3) texture ribs resembling the 8XE torch.

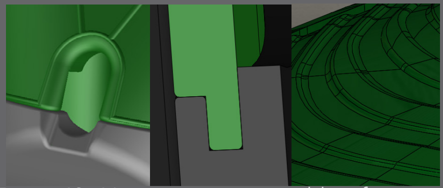


Figure 42: Various injection moulding features

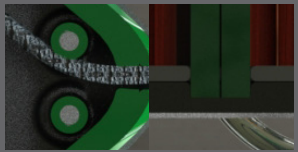


Figure 43: Various features

The casing features fastening cylinders with a hole for the standard screws for plastic. The cylinders at the front have a double function as a cable guide. In the bottom casing a slot is found for the axis to increase life cycles.

These buckles feature a simple pivoting lever pushed on the strap by a small spring, preventing movement in one direction, but not in the other. The buckles generally feature two small protrusions to prevent rotation. Two slits in the casing use these to hold the buckle in place. The buckle fits on the frame, where it can be fastened with a screw.

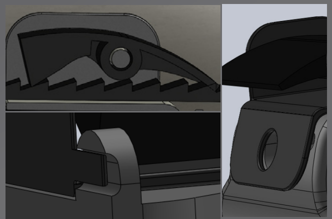


Figure 44: Ladder strap buckle

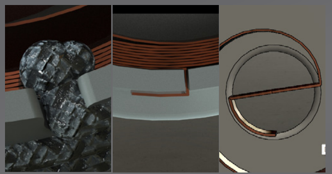


Figure 45: Spool features

The spool features a slit for the Kevlar cable to be locked behind, and slit for the spring to lock behind. The middle of the spring can be locked in the axis or arbor.

If all parts are in position in the spool, and the spool is attached to the axis with the spring, the cap can be screwed on the spool. Standard screws ore used. The casing has slots to integrate the spool, whilst the spool uses chamfers. The ladder strap is attached via a tight press fit. A barb can be added to improve this connection without complicating the mould.

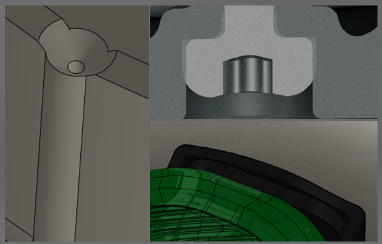


Figure 46: Fastening features

4.4 Viability

Table 19: Bill of materials

Part	Material	Type	Quantity	Cost (total)
Casing	PA-6 30%GF	Custom	1 pcs	€3,-
Spool	PA-6 30%GF	Custom	1 pcs	€1,-
Spring	303 Spring Steel	Standard	1 pcs	€0.25
Suspension cable	Kevlar	Standard	1 m	€0.76
Hook	Steel	Standard	1 pcs	€0.30
Ferrule	Aluminium	Standard	1 pcs	€0.08
Ladder strap	PA-6	Standard	1 pcs	€0.40
Buckle	Steel, coated	Standard	1 pcs	€1.60
Casing Screw	Steel	Standard	4 pcs	€0.32
Buckle screw	Steel	Standard	1 pcs	€0.20
Spool screw	Steel	Standard	4 pcs	€0.60
AG Glove	Leather	Custom	1 pair	€5,-
Total				€13,60

The cost consists of the financial burden to get the part made and/or delivered to Translas in Nieuwegein, where assembly takes place. The price assumes a reasonable Minimum Order Quantity. Translas and Skelex both do their assembly at their own workplaces, although Translas has larger infrastructure in place consisting of a larger workshop with various machines and assembly lines. This plan is written for this context.

Table 20: Assembly plan

#	Details	Estimated time [s]
1	place the spool and spring on the axis. The spring comes with a protective band - remove it after the spring is in the spool.	90s
2	Knot the end of the cable, and put through the slit on the spool. The rope and spring can be locked in place by attaching the spool cap using the 4 screws.	70s
3	roll ~1m around the spool. It is not necessary to wind the spring now. Make sure to roll it in the same direction as the spring rotates.	40s
4	Place the rope over the guide and through the slit. Click the halves together, making sure the cable does not fall into the slit. Screw the casing shut.	120s
5	Pull the rope for 600mm, leaving ~400mm in AeroGrip. Use the bench vise to lock the cable in place. Make sure not to lose grip, or the cable might shoot into AeroGrip.	50s
6	Cut off some rope to make it easier to work. Pull the rope through the ferrule, the hook, and back through the ferrule. Clamp it in place close to the vise.	180s
7	Attach the buckle and ladder strap using the screw and press fit	50s
Total assembly time		600s

Assuming wages of €45,- per hour (Translas, 2023), this introduces assembly costs of €7.50 per product.

A reasonable consumer price was set on €100,- . based on Translas' experience in selling welding technologies, and assumes AeroGrip to provide a tangible improvement both in welding ease and ergonomic health, although user tests suggest a higher price of €300,- might be possible still. Translas currently primarily sells gloves in the higher glove segment; €10 - €15. When selling to companies with high order quantities it is reasonable to assume a price of €10,- for the AG glove is a high estimate. A consumer price of €7,50 is more reasonable estimate. The market size of the AeroGrip can be based on the market size of the 8XE torches. It's a reasonable assumption 10% of welding companies interested in 8XE torches are interested in AeroGrip - this forecasts 400 AeroGrip systems to be sold over the course of three years. Since welders use around two pair of welding gloves per month on average, every AeroGrip sold leads to a 'subscription' of AG Gloves from that point onwards.

- Estimates for investments of moulds (€24 000,-), MOQ parts (€8 100,-), potential patent (€8000,-), and 3 months of additional R&D (€43 000,-) are estimated.
- The business model uses a subscription type model through the integration of special welding gloves. These effectively add exponential growth to profits.
- A reasonable production cost is calculated through costs of part and assembly costs.
- Taxes of 25.8% are taken into account

Both cases showcase a profit within a reasonable time frame of three years.

Figure X shows the cumulative cash flow with a consumer price of €300,- per AeroGrip and €10,- per AG Glove if 408 are sold over a three year period. This amount assumes that 10% of 8XE users are interested in using AeroGrip.
The 8XE is a rather niche product, but AeroGrip does not have to be. With slight additional development on the attachment point to the welding cable AeroGrip can be suitable for welders in general.
Building a business case on all customers of Translas, and again assuming 10% of welders are interested in AeroGrip, the product can turn a profit earlier with more reasonable prices. See Appendix D.

Table 21: Business cases - summary

AeroGrip price	Glove price	Pcs sold in 3 years	Profit after 3 years
€300,-	€10,-	408	€27 000,-
€100,-	€7,50	1583	€41 000 ,-

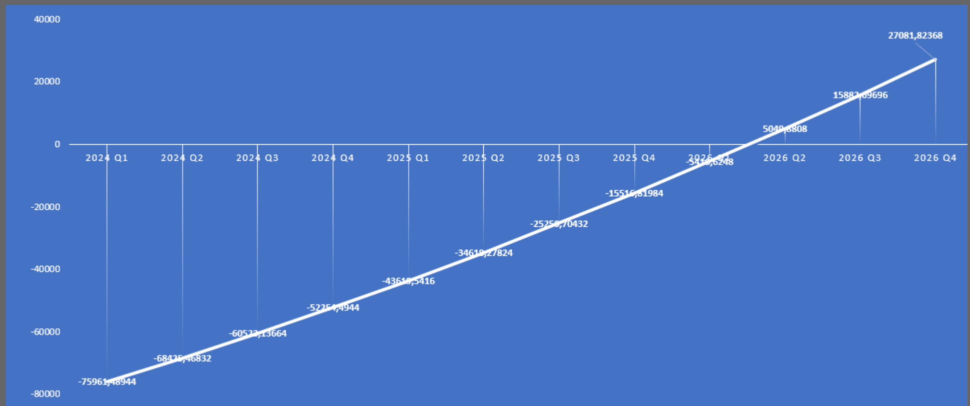


Figure 47: Business case 'Low volume, high price'

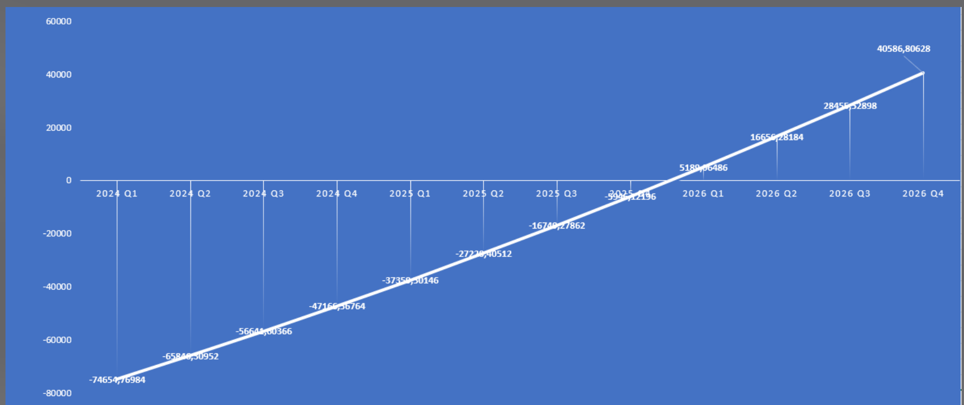


Figure 47: Business case 'higher volume'

5. Finalising

Photo: Hoang NC

5.1 Conclusions

AeroGrip aims to embody an exoskeleton-like product that 1) eases welding, 2) is convenient, and 3) can improve welding ergonomics, and this is successfully attained:

AeroGrip eases welding, and can improve ergonomics

- Simulated data shows a reduction of 55-80% of weight on the wrist, distributing it over the lower arm via the AeroGrip, predicting welders to generally be able to weld safely 20% longer, in regards to the wrist.
- User tests show significant relief of the wrist during welding. Welders experience an evenly distributed weight on the lower arm instead of a concentrated weight in the hand, and expect "less fatigue during longer welding sessions".
- Welders experience that the torch does not have to be gripped as tightly. This can improve the musculoskeletal health of the elbow joint.
- When welding welders lift the cable through radial deviation, "putting a lot of weight on [the] wrist when controlling the handle". With AeroGrip this is taken away.
- Welders state to feel more in control of their weld, stating it's easier to weld straight for longer periods, or do fine movements whilst welding upwards. Flat, circular welds can be done longer without repositioning.

AeroGrip is convenient

- AeroGrip is integrated with welding gloves. As no extra harnesses or add-ons to the body are necessary, multiple exoskeleton usability pitfalls are avoided.
- AeroGrip attaches to the welding cable, leaving the welder free to do any work using the gloves unhindered. The hook is designed for easy detaching, whilst the required security is maintained.
- Dimensions are minimised. A commercial standard spring with the required spring characteristic is placed in a spool and casing with minimal extra space. As such, it minimally interferes with welding work.
- Due to the chosen position of attachment point on the lower arm the length of the suspension cable varies minimally, minimizing dimensions and resulting in less variations in spring tension. Additionally, the suspension cable is short and is minimally in the way.
- AeroGrip does not change the bending characteristic of the welding cable; it does not introduce new flexure points which get in the way, due to the attachment point on the welding cable a short distance from the torch.
- The singular hole in the AG Glove as well as the fixed spring tension results in an easy plug-and-play solution. Welders have to do minimal set-up for AeroGrip.
- The ladder strap and buckle provide an easy way to attach the torch to the 8XE welding cable, and reposition if desired.

Additionally, AeroGrip aims to be 1) desirable, 2) feasible, and 3) viable. This is succesfully attained:

AeroGrip is desirable

- User tests show that working with AeroGrip is preferable to working without AeroGrip for a wide array of welding positions (Flat, horizontal, Vertical, Flat circular and horizontal circular)
- Numerical analysis and user tests show that AeroGrip improves welding ease and safety.
- Design is optimised for maximum convenience, and user tests show that AeroGrip is minimally in the way.

AeroGrip is feasible

- The actuating power spring is based on a commercially available standard power spring.
- The plastic parts are suitable for injection moulding through constant wall thickness, fillet radii, and draft, and is further optimised for simple moulds without sliders through the chosen split line and orientation of bolt slots.
- Critical parts are calculated for fatigue effects, and friction is taken into account for the required spring characteristic.

AeroGrip is viable

- Required custom parts is minimised so that investment costs can be reduces.
- The business model uses a subscription type model through the integration of special welding gloves. These effectively add exponential growth to profits.
- A reasonable production and investment costs are calculated, and a reasonable consumer price is estimated based on Translas' experience, and losses due to musculoskeletal disorders.
- Two business cases with different strategies are developed, both profitable within a three year period.

There are various miscellaneous requirements that have to be met. Appendix E.

5.2 Recommendations

This document contains all necessary information to bring AeroGrip towards a Minimum Viable Product, and I **recommend Translas and Skelex to bring AeroGrip to market,** as it's shown to be a desirable, feasible, and viable design. Some tests are required:

Tests

- Set up a focus group of ~5 welders that use the heavier welding torches, that are willing to pilot the AeroGrip prototype for several hours, to verify the author's findings on increased welding ease, precision, and comfort, as well as usability on a larger scale in a real welding environment.
- Use this focus group to explore options to combine AeroGrip not with the welding glove, but with R. Conjeart's arm cups (Conjaerts, 2023). Improved relief on the elbow and shoulder might be achieved at the cost of a changed bending characteristic of the cable and more complex user experience.
- Set up an 'exoskeleton parkour' simulating welding postures. Measure physical, fatigue, and discomfort related variables. Measuring parameters such as muscle activity, locally experienced discomfort, and endurance time work task can provide evidence of AeroGrip's value to welders and policy makers.

It is recommended to **pursue the business case of a lower price and higher volume**, as this is a more realistic scenario. Some developments are recommended to increase the success of AeroGrip.

AeroGrip development considerations

- Explore the suitability of the ladder strap and buckle to attach to the welding cable. The regular 8XM cable is incompressible, which might result in AeroGrip slipping. If it is not suitable it is recommended to continue development on AeroGrip so it fits both torches.
- Explore options in regards to different spring tensions. User tests suggested that AeroGrip can also enhance welding with lighter torches. It is probable that simply putting a weaker spring in the existing AeroGrip will make it suitable for lighter welding. If AeroGrip proves to be small enough for these torches already, minimal investment is needed to expand this market as springs are standard parts.
- Translas believes welders do not want any configurability on their products, based on their experience with fume extraction and protection gas parameters often being wrongly configured. However, all welders this author has spoken to stated they do appreciate configuration options. For AeroGrip I urge Translas and Skelex to consider an axis that can rotate, so AeroGrip's spring characteristic can be configured slightly.

This collaboration between Translas and Skelex is beneficial to both parties as they complement each other, and **I recommend both parties to continue this collaboration.** Translas is pivoting towards cutting-edge technologies supporting welder health. A focus on musculoskeletal health fits with this business strategy, and exoskeletons and exoskeleton-like products can play an important part. Here Skelex has a lot of experience, especially with usability and comfort pitfalls.

- Neck complaints are prevalent due to the heavy welding mask. This provides a promising product direction

To Skelex and Translas individually I have the following recommendations.

Skelex

- Continue with the focus on standardising parts of the Skelex-360. The current price is high, and Skelex is at risk of being out-competed as larger companies are reducing the price of their products at a fast rate. Reducing the price of the Skelex-360 should be Skelex' primary focus.
- Continue investing in the R&D team, since "At the core, Skelex is an R&D Company" - G. Genani (VenturesOne, 2021). During the internship Skelex' ship was sailing with a bare-bones crew. Skelex needs employees to redesign parts to reduce costs, and provide value to various companies such as Translas through new technologies.
- In the development process of new products I recommend Skelex to try to design around standard parts as much as possible. This can significantly reduce production costs. Covers, levers, bolt, or hinges often don't have to be custom made.
- The CarbonForce and ExoForce concepts are both promising, and cost-effective technologies to develop further. They are fundamentally different from the Skelex-360 as they work on the tool directly instead of on the body, which has a potential health advantage (Caspers, 2023) . The Hilti-01 is actuated by a tool-balancer type mechanism, and might be the reason why its price can be so low.

Translas

- Invest in R&D. Although Translas is a larger company, its R&D team consists of one employee. If Translas wants to develop more technologies focused on welder health it is recommended that a larger design team is maintained.
- Consider drastic redesign options of the 8XE extractor torch, per chapter 3.1. All usability complaints can be traced back to the large fume extractor cable, and the way it is connected to the torch through the ball-and-socket joint. Having a separate fume extractor cable can potentially reduce stiffness and reduce usability complaints. This eliminates the possibility of the ball-and-socket joint with dis-coupled cable movement from the torch, but I urge Translas to explore this direction nonetheless.
- Do the bending stiffness test in Appendix A with a welding cable bundle without torch and attachment casing to properly understand their product's specifications.

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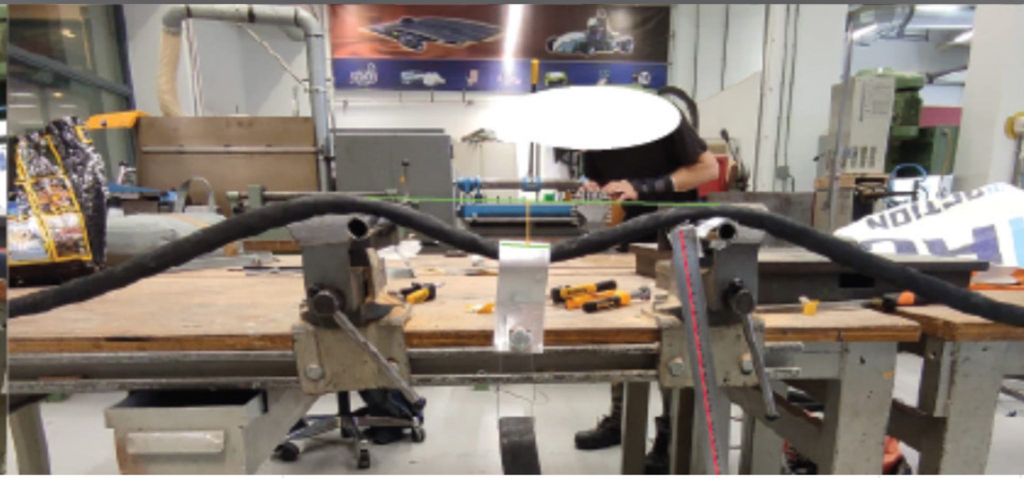
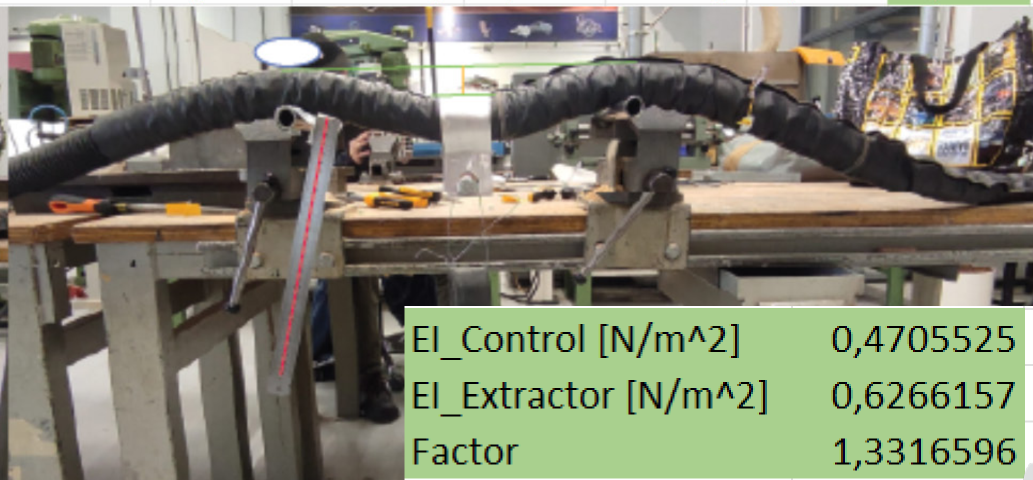
Appendix A - Bending Stiffness 8XM vs 8XE

To research the bending stiffness of the 8XE welding cable a bending stiffness test was set-up, based on a three-points bending test. The welding cable was set up between to static pins, and a known weight was hung on the middle of the cable. Pictures were taken and analysed using Illustrator to measure the distances. I ruler was put in the frame at the same depth as the objects. There are severe limitations to this test due to the fact that the torch and cable ending is still attached to both welding cables, and are lying on a table. There is also considerable friction on the static pins, which should be rolling pins in a proper three-point bending test. Still, as a comparative test it shows that the 8XE cable is significantly stiffer than the regular 8XM torch. It can also give a reasonable first estimate of the bending stiffness EI of the 8XM as 0.62 Nm^2



			No load				loaded				
	L [pt]	L [m]	C_Ruler [pt]	factor	d0 [Pt]	d0 [m]	C_Ruler [pt]	factor	d [pt]	d [m]	dtot [m]
Control	161,7	0,3918417	123,8	2,4232633	6,1	0,01478	113,7	2,63852	18,8	0,0496	0,06439
Extractor	129,5	0,392821	98,9	3,033367	5	0,01517	111,2	2,69784	12,3	0,03318	0,04835



EI_Control [N/m^2]	0,4705525
EI_Extractor [N/m^2]	0,6266157
Factor	1,3316596

Appendix B - Variations in positions vectors for different postures.

	1	2	3	4	5	6		L Torch [mm]		
BLUE [pt]	22,19	23,33	23,98	24,47	25,03	24,15		190		
RED [pt]	5,79	5,8	5,67	5,11	4,46	4,99				
ORANGE [pt]	13,74	14,29	13,42	12,94	12,42	12,68				
YELLOW [pt]	23,22	23,59	23,08	25,22	22,79	23,08				
D-GREEN [pt]	23,22	23,79	19,35	17,77	17,53	18,71				
L-GREEN [pt]	28,08	27,48	22	18,45	17,99	19,47				
TURQUOISE [pt]	36,05	34,49	28,19	23,92	22,03	23,87				
Factor	8,562416	8,144021	7,923269	7,76461	7,590891	7,867495				
BLUE [mm]	190	190	190	190	190	190		Mean [mm]	Max-Min [mm]	Ratio
RED [mm]	49,57639	49,66201	48,5489	43,75394	38,18837	42,72645		45,40934355	11,47363677	0,252671276
ORANGE [mm]	117,6476	122,3569	114,9076	110,7977	106,3452	108,5714		113,4377347	16,01171699	0,14114983
YELLOW [mm]	198,8193	201,9874	197,6205	215,9441	195,1374	197,6205		201,1882229	20,80666967	0,103418925
D-GREEN [mm]	198,8193	203,6999	165,6827	152,1541	150,0991	160,2028		171,7763257	53,60072105	0,312037883
L-GREEN [mm]	240,4326	235,2952	188,3731	157,9766	154,0379	166,7102		190,4709329	86,39477242	0,453585075
TURQUOISE [mm]	308,6751	295,3177	241,3745	204,813	188,63	204,3849		240,5325222	120,0450653	0,499080392

Appendix C - Final user test, second interview

Do you feel relief? Please describe what you feel.
If Im completely honest.. How can I describe it. It's going a little bit too much like this, it's pulling too much, and it doesn't seem to work.
Ah, I see - it's bend around the cable. Like this? [Rotating AeroGrip so its on top of the welding cable.
Ooh- look. Yes that definitely relief. (Flat weld)
Now I come at a point where I start feeling it again. If I weld too high. And now I start feeling it again in my back - [I'm a] back patient. (Torch going above shoulder height) (vertical weld) But I do think it's definitely an improvement compared to without. Especially with the flat weld.
And what about these welds without AeroGrip?
Yeah then it is that you have to lift the cable more. Actually, the end of the torch should be connected to something, like it's connected to the machine.
I'll put the end of the torch in a vise
Yeah see, now you have that it hangs more, like in the real situation. And then when you put on the thing - now the weight is distributed here. [lower arm where the glove is]
Yes - this is it! Totally works. Especially when it hangs in the vise, then you really feel how it helps with lifting. Also the vertical lifting is a lot better too.
And how is it on the elbow? Or shoulder?
Oh I didn't really pay attention to that. Was more focused on the wrist, and how it helps to balance this movement [Small rotations whilst moving upwards]
Do you feel like you can work more precisely?
Yes, because you don't have 'this' [lifting the cable, showcasing how it pulls the cable down, rotating the torch backwards, which you have to carry with the wrist]. When im TIG welding I use these weights to create a guide for my hand so the cable is not in the way - with this I think I can move straight without such an arm guide.
So yeah, I like it. It's definitely an improvement. Especially this height actually [vertical weld, shoulder height. elbow straight angle, lower arm forward]. I don't feel it on my back. It's more relaxed. But if you go too high, I do start feeling it. [Elbow higher than shoulder, high flat weld] But that's of course not very ergonomic working anyway.
Would that be better without?
Well no, without it would be even worse of course. Because then you have to do everything with the wrist
And what about round welds. I set up some larger cylinders here
Yeah.. It feels like it helps with the movement. Because you have to pull the cable with you, and the cable helps with that. You can also do more of the weld before having the reposition. So also that's better
Do you feel like the suspension cable would be in the way sometimes?
Hmm.. I don't think so. Because it's always below the lower arm. I never weld overhead. And I would never weld like this [rotating torch 90 degrees from the wrist
Would you want the cable to be further back? That it hangs on your elbow maybe?
Hmm.. What I could recommend is that you can change the load. If we want to use it here, because I do think it's an enrichment, the tension has to be less.
What I really like is also that during movements like this [radial deviation, rotating forward] , you can lift with your lower arm instead of your wrist.
Actually - if this is on the market I would, I'm the guy in charge of procurement here, I would purchase these as an enrichment in the workplace. To work more ergonomically
What would you expect to have to pay for it?
Oh that I don't know. I also don't really care about these things, if it can improve the health of my colleagues. So I dont know. But yeah, that's also hard to say - because if you only sell a 100 a year, it will be a lot more expensive than if you are mass distributing the things.
But would you be hesitant to pay a hundred euros?
No. I think..I would even pay 250 - 300 euros for it. Yes, because you really feel an improvement in the ergonomics, and I think you can invest in that. That's also why I purchased these overpressure masks. At first they said, we don't want that', but now they say, 'okay it is useful after all'. I have three colleagues here with back problems - and I think this will make welding more fun, that you can weld for longer without pain. So it is worth the money.

Comments User test #1

"Yeah this is almost no weight. Without this all the weight is on the wrist. And now it's distributed over this area, the glove. It's like the difference between badminton and tennis, where you do badminton with the wrist as the racket is so light - but tennis you have to do with your elbow, as the racket is heavier.
So you only have to aim with your wrist, so to speak. Instead of doing all the lifting also.

I think as a combination it will give the benefits of extracting the fumes and not having all that weight go trough your wrist.

the torch handle is workable but the hose is putting a lot of weight trough my wrist when controlling/holding the handle in the different welding positions.

Appendix D - Business case

Consumer price [eu]	100
Tax (%)	25,8
Profit margin (%)	20
Risk mitigation (%)	0
AeroGrip Production cost aim [eu]	54,2
Profit per AeroGrip [eu]	20
Consumer price	7,5
Tax (%)	25,8
Profit margin (%)	7,533333333
Risk mitigation (%)	0
AG Glove Production cost aim	5
Profit per AG Glove	0,565
Assembly time/product	0,166666667
Wage/hour	45

*welders use two pairs of gloves a month

Part	Quantity	p.p.p.	Price	Details		Investments for first	1000
PA-6 Casing Top part	1	1,5	1,5	Injection moulding - Mould A		1500	
PA-6 Casing Bot part	1	1,5	1,5	Injection moulding - Mould A		1500	
PA-6 Spool	1	0,5	0,5	Injection moulding - Mould B		500	
(PA-6 Spool Cap	1	0,5	0,5	Injection moulding - Mould B		500	
Power spring	1	0,25	0,25	External supplie	https://www	250	
Kevlar cable D=3mm (	1	0,76	0,76	External supplie	https://www	760	
Hook	1	0,3	0,3	External supplie	https://www	300	
Ferrule	2	0,0756	0,1512	External supplie	https://www	151,2	
Ladder strap	1	0,4	0,4	External supplie	https://www	400	
Buckle	1	1,6	1,6	External supplie	https://www	1600	
Casing inserts	4	0,08	0,32	External supplier		320	
Screws m5	1	0,2	0,2	External supplier		200	
Spool inserts	4	0,15	0,6	External supplier		150	
Glove+hole (pair)	1	5	5	External supplie	https://www	5000	
			13,5812			8131,2	
						8,1312	

Time		2024 Q1	2024 Q2	2024 Q3	2024 Q4	2025 Q1	2025 Q2	2025 Q3	2025 Q4	2026 Q1	2026 Q2	2026 Q3	2026 Q4
Units sold (AeroGrip)		132	132	132	132	132	132	132	132	132	132	132	132
Units sold (AeroGrip) - cumalitive		132	264	396	528	660	792	924	1056	1188	1320	1452	1584
Units sold (AG Glove)*		792	1584	2376	3168	3960	4752	5544	6336	7128	7920	8712	9504
Units sold (AG Glove) - cumalitive		792	2376	4752	7920	11880	16632	22176	28512	35640	43560	52272	61776
Cash flow in (AeroGrip)		13200	13200	13200	13200	13200	13200	13200	13200	13200	13200	13200	13200
Cash flow in (AG Glove)		447,48	894,96	1342,44	1789,92	2237,4	2684,88	3132,36	3579,84	4027,32	4474,8	4922,28	5369,76
Variable costs	Assembly costs	-990	-990	-990	-990	-990	-990	-990	-990	-990	-990	-990	-990
	Transport costs												
Risk mitigation (%)		0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
Investments	Moulds	-24000											
	Materials for first 1000	-8131,2											
	R&D 3 months	-43000											
	patent	-8000											
Risk mitigation		-660	-660	-660	-660	-660	-660	-660	-660	-660	-660	-660	-660
Taxes		-3521,05	-3636,49968	-3751,95	-3867,4	-3982,85	-4098,3	-4213,75	-4329,2	-4444,65	-4560,1	-4675,55	-4791
NET - cash flow		8476,43	8808,46032	9140,4905	9472,52	9804,55	10136,6	10468,6	10800,6	11132,7	11464,7	11796,7	12128,8
Netto cash flow _ cumalative		-74654,8	-65846,30952	-56705,82	-47233,3	-37428,7	-27292,2	-16823,6	-6022,91	5109,76	16574,5	28371,2	40500

Appendix E - Program of Requirements

Requirements			
Category			
Eases welding	Reduces muscle strain	User tests	
	Improves manueverability of the torch	User tests	
	Decreases fatigue	User tests	(more long scale testing required)
Improves ergonomics	Reduces joint moments	Numerical model, user tests	
is convenient	Easy to attach to the welding cable	Hook is simple	
	Easy to attach to the AG Glove	Hook is simple	
	Easy to take of the AG Glove	It's a normal welding glove	
Minimal protruding parts	AeroGrip is small height 26mm, widt ~60mm	Size is optimised, small enough	
	No (big) hard components on the glove	Grommet is small and not in the way. Tab is minimally in the way	
is feasible	Can be assembled efficiently by one person	Assembly plan	
	Casing and spool can be injection moulded	Constant wall thickness, fillets, draft, holes/slits one direction, so simple mould	
	Many standard parts	Designed around standard parts	
	Spring can exert necessary force	Vulcan Springs	
is desirable	Eases welding	User tests	
	Improves ergonomics	User tests, numerical model	
	Is convenient	User tests	
	comfortable	Welding Glove is comfortable, divided pressure is comfortable.	
	Should not slip	AeroGrip Can be firmly attached to the compressible 8XE cable.	
	Usable for various welding postures	Yes, best for flat, good for horizontal, vertical. Vertical pipe welds are difficult (That means the pipe is horizontal ;))	
	AeroGrip should be light	Casing and spool are 40g, making the whole system less than 100g.	
is viable		Profitable withint 3 years	
is integrated with welding equipment		Integrated with glove	
	inflammable	All materials have 'flame retardant' rating or better	
Safety	inconductive	Only the hook and spring are conductive. The spring is encased in PA-6, and the hook is connected with a unconductive kevlar cable.	
	Thrown off within 1 second	Like a normal welding glove, the AG Glove can be thrown of within 1 second	
	Hook does not detach unexpectandly	The shape of the hook prevents unexpected slipping	
	Durable for 200 000 cycles (260days x 8 hours x 100 cycles)	Axis: yield strength at 10^7 cycles >> torque on axis || Power Springs typically can withstand 500 000 cycles (SpiroFlex, 2020) || Kevlar cable is strong and durable. The casing does not cut into it due to the fillets.	
Durability	withstands rough handling by welders in the workplace	3mm PA-6 30% GF is a proven material and geometry for use in a welding environment (Translas, 2023)	
Design drivers	Freedom of Movement	Suspension cable moves with welder movement, can easily be detached	
	Simplicity	Many standard parts	
	Minimal contact points	AeroGrip attaches on the welding cable, and only a cable attached to the body	
		As small as possible.	

Appendix X - Stiffness simulation: Internal vs External cable

The inner cables for electricity+water influx, steel supply, and water efflux are measured to be 12, 12, and 7.5 mm. If we assume the chosen effective area of the fume extractor cable should not change to keep the same extractor behaviour, we can calculate the diameter of an 'external' fume extractor cable in stead of an 'internal'. Although of course only minimal decrease in diameter can be achieved, 50 --> 47.5 mm, this has huge consequences for the bending moment of the geometry, since this scales to the fourth power. Simply going from an internal to an external fume extractor cable, the stiffness of the welding cable decreases by 20%.

$$I_x = \frac{\pi}{64}(D^4 - d^4)$$

```
D_cable = 0.050 ;       %m  Diameter cable
D_tube = 0.012 ;        %m  Diameter tube, zitten er twee in: 1 voor stroom/water toevoer, 1 voor staal toevoer
D_water= 0.0075 ;        %m Diameter water afvoer kabel, zit er 1 in

t= 0.003; %m thickness fume extractor cable

A_cable = (pi*(D_cable/2)^2) ; %m^2
A_water = (pi*(D_water/2)^2) ; %m^2
A_tube = (pi*(D_tube/2)^2) ;   %m^2
A_fume = A_cable - 2*A_tube - A_water;  %m^2

D_FumeOnly = 2*sqrt(A_fume / pi) %m


I_old = pi* (D_cable^4-(D_cable-2*t)^4) / 64;
I_new = pi* (D_FumeOnly^4 - (D_FumeOnly-2*t)^4) / 64;
ratio = I_new/I_old
```

```
D_FumeOnly =

    0.0464


ratio =

    0.7895
```

AeroGrip is a exoskeleton-lite design that can be fitted on the 8XE Fume Extractor torch. A hook can be pulled out of AeroGrip, and conveniently attached to the complementary AG Glove. This otherwise normal welding glove has a grommet (hole) attached to a small tab hanging below. The hook, attached to a Kevlar cable, is connected via a spool to a Power Spring, reeling the cable back into the AeroGrip. This lift the welding cable up on the welder’s lower arm, leaving the torch **as light as a feather in their hand.**
As a result welders can work with less effort, with more control, and with improved musculoskeletal health.
This Master Thesis report describes the process of design and engineering from start to finish, and assesses the quality of the result through desirability, feasibility, and viablity.