BACHELOR'S DEGREE PROGRAMME

Innovation and Product Management

Design of an exoskeleton to enhance performance and reduce musculoskeletal injuries in firefighters

SUBMITTED AS A BACHELOR THESIS

to obtain the academic degree of

Bachelor of Engineering of Industrial Design and Product Development

by

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Thesis supervisors

FH-Prof. Dr. Markus Kretschmer and Prof. César García, University of Zaragoza

PREFACE

I would like to express my gratitude to my supervisors: Dr. Markus Kretschmer, University of Applied Sciences of Upper Austria, and Prof. Titular César García, University of Zaragoza. As well as to Eduardo José Sánchez, Fire Chief of Zaragoza, Dr. Christian Zehetner, University of Applied Sciences of Upper Austria, family, and friends. Your support, guidance, and encouragement have been invaluable in the completion of this thesis. I am humbled by the opportunity to contribute to the field of Engineering of Industrial Design and Product Development, and I hope this work inspires further research and understanding.

María Soldevilla García

SWORN DECLARATION

I hereby declare that I prepared this work independently and without help from third parties, that I did not use sources other than the ones referenced and that I have indicated passages taken from those sources.

This thesis was not previously submitted in identical or similar form to any other examination board, nor was it published.

This printed thesis is identical with the electronic version submitted.

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María Soldevilla García

Wels, June 2023

ABSTRACT

Firefighters have an immense dedication and commitment to the well-being of others, but unfortunately their job comes with a number of risks and injuries, from burns and inhalation of toxic gases to overextensions and strains. In the present time, there are many who research, test, and create different products and systems to enable them to enhance their skills and sustain peak performance. Although nearly none prioritize assisting firefighters in performing their duties with reduced physical exertion or mitigated risk of injury.

Therefore, this Final Degree Project has centered around the development of a product that empowers firefighters to enhance their skills and capabilities maintaining the expected level of performance, all while minimizing or even eradicating the possible injuries. In addition, this project is situated within the ergonomic hazards and centers on identifying and acknowledging potential health and safety concerns in the workplace.

The development for the final product has been focused on the analysis of a designed online questionnaire to firefighters from Spain and Italy, medical studies, workers feedback, and investigations related to the subject. Moreover, for the functional and formal development, an analysis of existing products and mechanisms was realized as well as structural, functional and usage analyses. Furthermore, a virtual simulation has been executed to verify the accurate and proper functionality by studying the results of the performance, additionally to a physical prototype to validate the mechanism and product design.

To conclude, this thesis has focused on the design of a mechanical exoskeleton which consists of three elements with independent use which attach to the user´s arms, legs and back. It reduces the musculoskeletal disorders and associated injuries that can arise from uncomfortable positions when repetitive strenuous lifting, resulting in a decrease of approximately 55% in the effort needed by the user to perform its movements.

CONTENTS

1 INTRODUCTION

In the face of emergencies that occur without warning, an extraordinary group of people emerge to become the heroes of our communities. They are the First Responders who embody dedication, resilience, and compassion in the most difficult circumstances. From natural catastrophes to accidents and critical situations, they are the first ones on the scene to arrive, ready to offer help and support in times of distress. The different types of First Responders put their lives on the line to save others, and even though each requires specific training, they all respond effectively to a wide range of emergency situations. Thanks to the opportunity that my co-director, César García, gave me for collaborating in the D4S Research Project, University of Zaragoza, this research project has focused on firefighters who receive extensive and continuous training in first aid and rescue.

When the alarm bell rings, their hearts race and they head towards the danger from which most instinctively flee. Their bravery knows no bounds and their work ranges from extinguishing flames to helping with hazardous materials, traffic incidents, medical emergencies, floods and even the stereotypical rescues of cats from trees. Each day they must be quick, efficient, selfless and risk their lives to protect ours. Their bravery and compassion leave an imprint on our humanity and therefore, as recipients of their untiring help and unwavering dedication, it is our responsibility to reciprocate their acts. Unfortunately, their work carries risk, and they are susceptible to various injuries from burns, inhalation of toxic gases, asphyxiation, structural collapse injuries and mental illness from exposure to traumatic situations, constant pressure, and stress. Ironically, First Responders are called in to prevent personal injury and it is often them who are injured on the job.

Nowadays there are many who research, test, and develop different products and systems, which try to make it easier for firefighters to develop their skills and abilities, and continue to function at the highest level in which they are required to.

Some examples are the use of virtual and augmented reality, sensors, mobile devices, and robotics, although almost none focus on helping the firefighter to perform their activity minimizing the physical effort or risk of injury they may have.

Following the study *"United States Firefighter Injuries in 2021"* (Richard Campbell and Shelby Hall, 2022), we note the high number of firefighter injuries in the US in 2021, and it shocks to observe that there has been no real research or effort to reduce these numbers. During that year, there were "64.875 on-duty injuries […] and the leading cause of most of them was overexertion or strain. This accounted for almost 2 out of every 5 injuries in the fire department" (Richard Campbell and Shelby Hall, 2022, p.4).

For all these reasons, this Final Degree Project has focused on the design of a product that allows firefighters to develop their skills and abilities and continue to function at the same level they are required to, while minorizing or even eliminating the likelihood of harming themselves. In other words, this project has focused on the design of a product whose objective is to increase human strength or, simply put, to decrease the physical effort required for firefighters to perform different movements.

This thesis is contextualized in ergonomic risks and focuses on the identification and recognition of potential health and safety issues in the workplace. This is done through risk assessment, accident analysis, worker feedback and compliance with applicable rules and regulations. As a result, it effectively reduces them and ensures a safe and healthy working environment for all employees and those around, minimizing any potential hazards or risks that may arise.

In this work a product has been developed to reduce the musculoskeletal disorders and related injuries that awkward postures, repetitive movements and heavy lifting can generate in the worker´s health.

For its ideation and development, opinions, experiences, and comments have been collected directly from the user. Active listening, analysis of the different aspects of their work environment, different situations and body positions and knowledge of the environmental and interaction requirements have allowed the development of a prototype whose validity has been carried out with simulation programs that have tested its response. This Final Degree Project is structured in three parts:

Firstly, a theorical research was carried out. Its methodological approach was, on one hand, the collection of data from primary sources by the design of an online structured questionnaire, which was distributed among the different fire departments in Spain and Italy, with the collaboration of participants in the D4S Project. This analysis has allowed to know exactly their real needs, the repetitive moments they carry out in their emergency exists and body parts that are most frequently and intensely affected. On the other hand, documentation work was carried out from secondary sources and analyses to deepen the subject from different perspectives: structural, functional and of use.

Secondly, based on the ideas and groups evaluated in the previous step, three concepts were sketched and developed following the established PDEs. These different, clear, consistent, and viable concepts were then analyzed and evaluated by Eduardo José Sánchez, Fire Chief of Zaragoza, to obtain feedback, selection of one of them, and where appropriate, suggestions for improvement.

Thirdly, the formal and functional development of the selected concept was carried out analyzing other existing products, different solutions for the functionality and defining both the production processes and the product materials. Finally, a test simulation was realized to confirm the functionality of the final product, using the Open Modelica Software.

To conclude, it should be noted that in each of the steps, there has been a collaboration of the real future user of the product and people with high level of knowledge in the developed subject. This co-creation and participatory design were a priority in this research work, protecting their privacy and confidentiality in relation to the collected data.

2 CALENDAR

This calendar serves as a comprehensive overview of the timeline of the project. It outlines the planned activities and organized execution [see Fig. 1 on page 4].

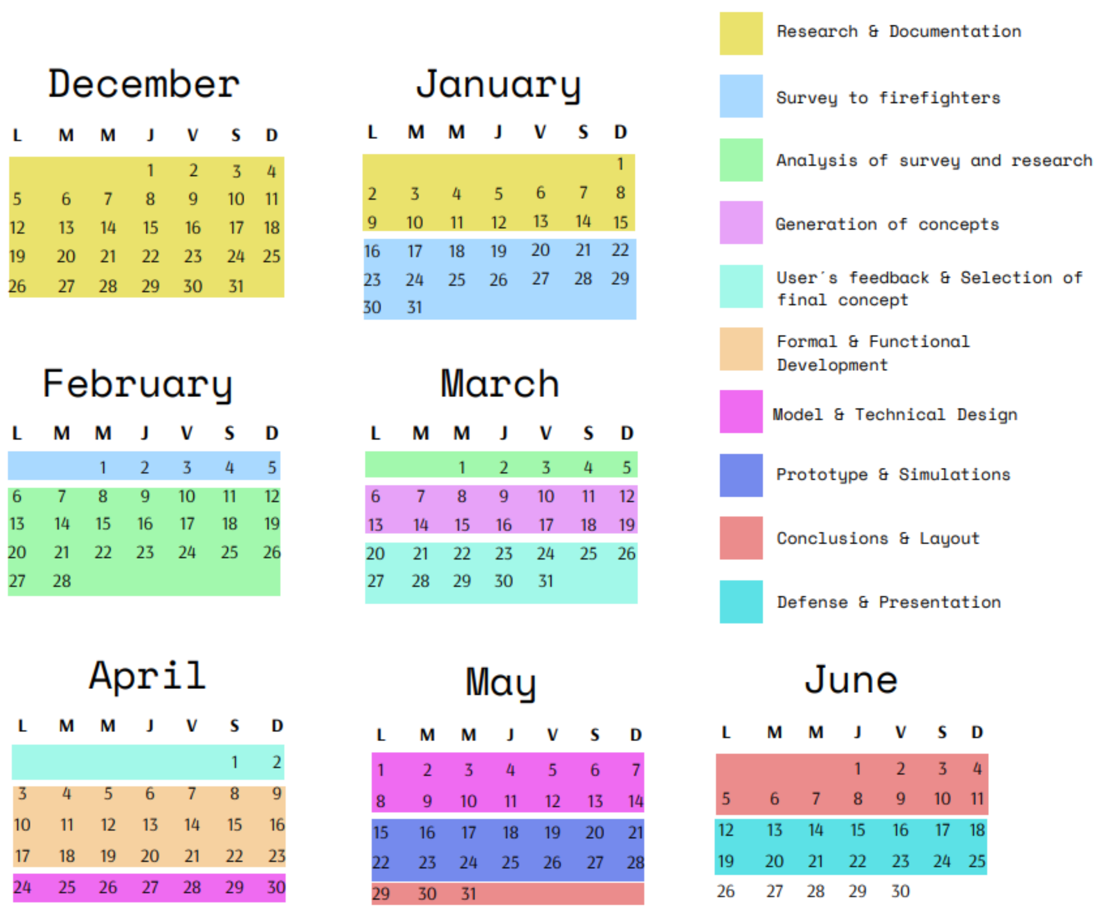

Fig. 1: Calendar

3 METHODOLOGY

Many sources have been utilized to obtain the information for later be used in the subsequent analyses and development of the project.

Firstly, in the earlier steps of the thesis, a first research has been executed with secondary sources to obtain a general idea about the context and existing products and services whose objectives were focused on the aid for firefighters. For it, both web pages and studies were analyzed and allowed to have a clear idea about the problem that had to be addressed.

Secondly, a qualitative research has been carried out with a primary source; an online questionnaire addressed to firefighters from Spain and Italy. With it, several movements, positions, and situations were determined for the posterior research and definition of the focus of the project.

Furthermore, in each one of the following phases, secondary sources were used to continue the analyses, obtain further information, and allow the development of the project. These consist of the combination of both web pages and studies. In addition, it should be noted that in many of the phases, feedback has been received from the future user and faculty, and each section has been reviewed with the thesis supervisors to confirm its correct completion.

To conclude, all sources can be found in the section 10. References/Bibliography on page 62.

4 INFORMATION AND DOCUMENTATION PHASE

4.1 PRELIMINARY INVESTIGATION

Due to the collaboration with the D4S Research Project, University of Zaragoza, the user on which the project had to focus and for whom a solution had to be developed, was already determined. These are the firefighters; highly trained professionals who respond to emergencies involving fires and other hazardous situations.

To commence the project, a preliminary investigation has been developed. From products that have been designed specifically for firefighters to those in relation to develop similar functionalities, have been analyzed for obtaining an initial context and knowledge about the existing investigations. In order to carry out this research, after investigating different companies and researchers that belong to the same sector of investigation, those that have been developed by the well-known RESPOND-A-Project have been the focus of the research.

RESPOND-A Project "aims at developing holistic and easy-to-use solutions for First Responders by bringing together the complementary strengths of its investigators […]" (RESPOND-A, 2020). The RESPOND-A system and components focus on three main groups: Firefighters, EMS (Emergency Medical Care) and Civil protection and Police, therefore after investigating their product range, those related to firefighters that have been found as more interesting and that have led to the development of the project. These go from augmented and virtual reality, sensors, wearables and mobile devices to robotics and unmanned vehicles.

Most of these products, apart from others that are being developed by other researchers, focus on allowing firefighters to develop their abilities and skills and continue functioning on the same level they are required to. The startling observation is that hardly any of these products really focuses on helping the firefighter to realize its job while minorizing the physical effort or risk of injuries.

Firefighters must realize all different actions and they must be quick, efficient, and safe while performing them. They face all kinds of different challenges and they do protect society against all these dangers, but most of the time they are the ones who end up affected by injuries too.

One of the statistical studies that has become the focal point due to its results related to this lack of assistance and high probability of the user´s injuries is "United States Firefighter Injuries in 2021" (Richard Campbell and Shelby Hall, 2022).

If we observe the number of injuries on firefighters in the USA, on the year 2021, we could be impressed of how many of these first responders have been injured and how there hasn´t been a real research or effort for decreasing these numbers. "64.875 firefighter injuries occurred in the line of duty during that year and in addition to injuries, there were 20.900 documented exposures to infectious diseases and 17.050 exposures to hazardous conditions. The leading cause of fireground injuries was overexertion or strain. These accounted for nearly 2 of 5 injuries on the fireground" (Richard Campbell and Shelby Hall, 2022) [see Fig. 2 on page 7].

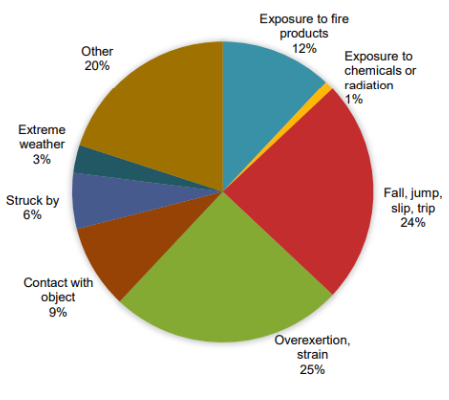

Fig. 2: Fireground injuries by Cause: 2021

Therefore, this project has focused on the development of a product that allows firefighters to develop their abilities and skills and continue functioning on the same level they are required to, while minorizing or even eliminating the probability of harming themselves. It focuses on recognizing health and safety issues at work and deal with them to minimize the degree of hazard or risk, always ensuring their personal safety and the safety of others.

In other words, this project has focused on the design of a product whose objective consists of augmenting the human strength or simplistically, decreasing the needed effort for realizing different movements for firefighters.

4.2 ONLINE SURVEY

Due to the opportunity of working with the D4S Research Group, University of Zaragoza, the contact with several firefighters from around Europe, especially from Spain and Italy has been possible.

To find information about their actual needs, movements they continuously realize and the body parts that are mostly affected, a survey was sent to them in the earlier steps of the project. In this survey they were asked about their age, service they belong to, situations in which they would have liked an external help, physical movements that involve the most physical effort, body parts affected, physical injuries they had and if they were willing to use an exoskeleton or product to aid them realize their job. This questionnaire can be seen in section 1.1 Online survey in the Appendix on page 1.

After a few weeks, the results and comments from 83 people from Spain and 11 from Italy, making it up to 94 people in total were gathered. After analyzing each one of the questions with the variety of selections, see section 1.1 Online survey in the Appendix on page 1, the conclusions for each one of the questions are the following.

The majority of the results were from men (98.94%) between the ages of 35 and 54 (65%). Focusing on Spain, the answers came from different autonomous communities, but the greatest numbers were on Aragón (46.4%), Andalucía (15.2%) and Castilla y León (13.2%). From the Italian survey, all the answers came from Vigili del Fuoco (Italy).

88.3% knew what an exoskeleton is, 42.55% confirmed they would wear one to realize their job and 54.25% would be willing to try it to check its efficiency. Apart from it, when they were asked about if an exoskeleton would be efficient for all of their colleagues, the majority (51%) said that it depended on the job position and the activities they must realize and 29.78% answered "Yes, for all of them".

These main percentages can show us how nowadays exoskeletons are getting more developed and introduced into different services. Depending on their functionality and aesthetic aspects, some of them could actually be really useful for the realization of the user´s job. In the contrary, an important aspect is that because of the variety of activities that firefighters must realize each day, the same exoskeleton won´t work for every single one of them because of the requirements, time to function and need of use. Therefore, the designed product had to focus on aiding the user for realizing some specific movements and provide help to certain body parts. To know which ones we had focus on, the conclusions of the next questions were helpful.

When they were asked about in which different situations they would have liked to use an external help such as an exoskeleton or a robot, the answers that most stand out were: "When carrying the victims in your arms" (26.4%), "Moving obstacles" (21.35%) and "Going up stairs" (19.66%). After proposing them several situations, they were also able to write down others if they would like. Surprisingly, most of the answers (46.8%) were related to holding really heavy objects like: tools, victims, the hose or landslides. In addition, they also included going up and down the stairs while holding all the objects explained before (26%).

The next question focused on what physical movements usually involve the most physical effort for them. The ones that were voted the highest were: “Keep still while holding a heavy object” (31.28%), “Holding up some object” (27%), “Go up and down the steps” (12.27%) and “Grab something from the floor” (11.04%). Because of these continuous and tiring movements, the body parts which they feel most affected by the physical effort are: “Back” (25.28%), “Lumbar” (23.83%), “Knees” (13.47%), “Arms” (13%) and “Shoulders” (11.9%). Apart from this question, they were able to write about some physical injuries they have ever had because of their job describing how it happened and in what part of the body it occurred. Astonishingly, most of all the answers contained “Low back pain” (38%), “Back pain” (30%) and “Knee sprain” (36.1%). The first two were mostly influenced by overloads while the knee sprain happened because of a bad gesture or falling when jumping. Therefore, there could be two focuses for the project. The first one, blocking the free movement of some extremities to avoid a bad gesture like the knees or enhance greater strength or help in the movement of parts of the body such as back or lower back to perform different activities.

After focusing on the movements and need of functionality, the last question focused on what product aspects would they value more in order to use an exoskeleton in their work. The answers that were the most voted are: “Facility to put it on and off” (25.1%), “Ergonomic” (16.35%), “Increase strength” (9.12%), “Facility of transport and storage” (8.36%) and “Simple mechanism” (7.6%). These main values had been taken into consideration when designing the next concepts.

Finally, at the end of the survey there was an open space to write any comments, opinions, or suggestions. Some of the most interesting ones were: “Allow free movement”, “Economic”, “Focus it to specific activities” and “Addition of visibility or oxygen”.

In conclusion, as we can observe in the last results, our user needs focus on having an external help to increase the strength and reduce the injury risk on the body parts like back and lumbar. Because of the continuous movements and holding heavy objects, these body parts are really affected and end up overloaded and reducing the efficiency of our user´s work. Therefore, the next step consisted of a research of different existing products that function for the same or related problem to understand their functionality, composition of elements and to find different ways to satisfy the user´s needs.

Although, before starting with this research, an online Meet meeting with Eduardo José Sánchez, Fire Chief of Zaragoza was executed to share the results from the survey, obtain a face-to-face response and design proposals.

He explained how firefighters have an “imaginary box” that goes from their shoulders to their hips and “any movement that has to be done inside that box is not going to require a high effort or cause any injuries, while using an ergonomic posture […]. But when the movement requires any extremity to go out of that box, then that´s the moment when the user will require an external help, in this case our product” (Eduardo José Sánchez, March 2023). He focused his speech on the mountain bags, how they transfer all the weight to the hips and lower back to have a higher stability and reduce the fatigue. He insisted on developing a product that could work similar to this one, and even proposed the transfer of the weight to the ground in some way.

4.3 SEGMENTATION BY TYPE

Once the meeting was realized and the ideas and requirements analyzed, the research of existing products started. To solve these sorts of problems, the type of product that has been selected to serve as an aid for the different situations is the exoskeleton: “A robotic exoskeleton is a mechanical device worn by a human being for certain purposes or applications. An exoskeleton is generally considered to be a hard mechanical frame with joints that allow movement of the human operator, and their main classification is between motorized and passive exoskeletons” (Iberdrola, 2022).

During this research, the focus was on 3 different types of exoskeletons, related to the survey results and the meeting with specialists commented before. These were the following: exoskeletons for supporting heavy tools, exoskeletons for holding objects while lifting the arms and exoskeletons for lifting objects from the ground.

Four existing products have been selected for each one of these types and are summarized in the following sections:

- Exoskeletons for supporting heavy tools

“Tool-holding exoskeletons are composed of a spring-loaded arm that holds a heavy tool on one end and is connected to a lower-body exoskeleton and a counterweight. The weight of the tool is then transmitted to the ground. These exoskeletons are usually passive and sometimes contain only one joint, which is sufficient to provide weight support” (Jean Thilmany, 2023).

> FORTIS

FORTIS [see Fig. 3 on page 13] is a passive tool holding exoskeleton made by Lockheed Martin.

It takes the weight of a heavy tool and sends it directly into the ground, bypassing the user´s body. “The tool is usually held in a gimbal to allow for rotation and flexibility and the gimbal is then connected to a spring-loaded arm […]. Its main objective is to reduce fatigue and improve worker safety while handling heavy tools. It is also great for improving the worker efficiency as long as they stay within a relatively small area and need to use a large tool such as a grinder” (Exoskeleton Report LLC, 2023).

Fig. 3: FORTIS

> ExoHeaver

ExoHeaver [see Fig. 4 on page 13] is a passive and active tool holding exoskeleton made by ExoMed.

“It uses a spring-loaded arm to support large loads, such as a grinder or a drill at variable heights. The load is transferred through the rigid frame into the ground […]. This unusual combination of passive and active components creates a new class of semi-passive exoskeleton devices, combining free-to-move, locking, spring-loaded and actuated components in one fully integrated wearable ergonomic solution for workers” (Exoskeleton Report LLC, 2023).

Fig. 4: ExoHeaver

> X-Arm

X-Arm [see Fig. 5 on page 14] is a passive, third arm, tool holding exoskeleton composed of aluminum and fabrics and made by Exorise.

"It has been designed to support an instrument at nearly any height or length and is meant to work with instruments that weight between 2 to 40 kg" (Exoskeleton Report LLC, 2023). The weight of the object is meant to flow through the exoskeleton´s spring arm, and through the frame directly into the ground removing a significant amount of weight from the back and shoulders concluding into a reduced fatigue and fewer musculoskeletal injuries.

Fig. 5: X-Arm

> Ekso ZeroG

Ekso ZeroG [see Fig. 6 on page 14] is a zero-gravity arm made by Eksobionics.

"It is able to hold heavy tools atop aerial work platforms, scissor lifts and scaffolding. It´s a spring-loaded robotic arm that can transfer the weight of heavy tools to its base, and then into the ground" (Exoskeleton Report LLC, 2023). Zero gravity arms are designed to relieve the pressure and weight load from the worker´s limb, providing physical support through an entire range of motion. Also, they allow tools to hang in the air wherever they are left by the worker when they remove their hand.

Fig. 6: Ekso ZeroG

- Exoskeletons for holding objects while lifting the arms
  - Ottobock Shoulder

Ottobock [see Fig. 7 on page 15] shoulder is a passive exoskeleton made by Ottobock.

"It supports the arms during strenuous overhead work, while feeling like a natural extension of the body and absorbs the potential energy from the user´s upper extremity and stores it in a spring and cable system. The device continuously releases this stored energy to reduce the effort required to raise the upper extremities. This storage and release of energy significantly relieves strain on muscles and joints, allowing over-the-shoulder activities to be performed comfortably" (Ottobock, 2023).

Fig. 7: Ottobock Shoulder

- Eksovest-EVO

Eksovest-EVO [see Fig. 8 on page 15] is a passive exoskeleton made by Eksobionics.

"This exoskeleton technology takes away the strain and risk of overexertion while keeping the user comfortable and upright. Its patented stacked-link structure seamlessly follows the user´s arm and elbow through the full range of motion while providing proper joint alignment through repetitive movement" (Eksobionics, 2023). It can reduce worker´s fatigue, improve its health and endurance and prevent workplace injuries, among others.

Fig. 8: Eksovest-EVO

> PLUM

PLUM [see Fig. 9 on page 16] is a passive exoskeleton made by HMT.

"It´s specially designed for repetitive handling and manipulations using the arms. It is meant to reduce the weight on the arms, shoulder and back and its objective consists of reducing the risk of musculoskeletal disorders of the upper limbs without discomfort and without constraint for the operator. Unlike most shoulder-support passive exoskeletons, the PLUM provides support directly to the arms, a little bit past the elbows" (HMT France, 2023).

Fig. 9: PLUM

> EXO-01 Overhead exoskeleton

EXO-01 Overhead exoskeleton [see Fig. 10 on page 16] is a passive exoskeleton made by HILTI.

"It helps relieve strain on shoulders and arms during overhead installation work and has freedom of movement; provides dynamic support without restricting the range of motion of arm and torso. It does not need batteries and has no motors" (Hilti, 2023).

Fig. 10: EXO-01

– Exoskeletons for lifting objects from the ground
    > LG CLOi SuitBot

LG CLOi SuitBot [see Fig. 11 on page 17] is an active exoskeleton made by LG.

“It is meant not to help humans walk but to augment lower body strength for people who need to lift heavy objects from the ground. These often lead to back and leg injuries that the SuitBot can help prevent. It includes too a bit of Artificial Intelligence to learn from the wearer´s habits and optimize power and movement” (Torres, 2018).

Fig. 11: LG CLOi

    > Ottobock Back

Ottobock Back [see Fig. 12 on page 17] is a passive exoskeleton made by Ottobock.

“This exoskeleton works according to a biomechanical principle: the load is taken off the lower back and transferred to the thighs with the help of the exoskeleton´s support structure. The energy storage absorbs force when bending and release it again when lifting, which significantly reduces the back muscles forces” (Ottobock, 2023). It takes a really short time to put it on and off and it has been designed to fit both men and women.

Fig. 12: Ottobock Back

> Muscle Suit Every

Muscle Suit Every [see Fig. 13 on page 18] is an active exoskeleton made by Innophys.

"It is an assistive suit that works using air pressure and it has been designed to lighten the load on the users back at work helping with daily labor-intensive activities" (Innophys, 2023). The user can simply fill it with air using the supplied pump, it does not need electricity and has no difficult maneuvering so anyone can use it. In addition, the product stands against water and dust.

Fig. 13: Muscle Suit Every

> Exoback

Exoback [see Fig. 14 on page 18] is an active exoskeleton made by RB3D.

"It is an active lumbar assistance exoskeleton, aimed at reducing the operator´s efforts and therefore the potentially associated musculoskeletal disorders. Also, the double-jointed hip allows the user to follow the movements without any discomfort and in total freedom" (RB3D, 2023). It provides more strength by motorization with an electric cable actuator, more safety by reducing the musculoskeletal disorders, more comfort because it only takes around twenty seconds to get fitted out and more support on the shoulders, waist, and thighs.

Fig. 14: Exoback

4.4 ANALYSES

Following the earlier research, the next step consisted of analyzing several of these products from different perspectives: structural, functional and usage.

4.4.1 STRUCTURAL ANALYSIS

The first analysis that was developed is the Structural Analysis. In it, two products of each type, the most interesting and useful for the development of the project, except for the first one for which three were analyzed, have been decomposed into levels with the highest detail.

The selected products from the first type are: FORTIS, Ekso ZeroG and X-Arm. From the second one: Ottobock Shoulder and PLUM and finally from the third one: Exoback and LG CLOi SuitBot.

As we can observe in the section 1.2 Structural Analyses in the Appendix on page 14, each one of these products have been decomposed to a small detail focusing on their body attachment and mechanism. Most of them have symmetry of elements, in both arms or legs and depending on their functionality and motion, each one of them have a similar but different composition.

In relation with the body attachment, the majority are composed of a shoulder harness, pelvic belt, and chest strap. This way, the product can be attached to the user in the most adequate and comfortable way, transferring its weight to the whole body and allowing the user to move with the product as one. In the other hand and in relation with the mechanism, depending on its main objective and function, each one of them are composed differently. Although, the majority are made of a combination of bars which are connected by rotating joints and include measurement adjustments to adapt itself to the user and lock latches to fix the bars between each other for a correct functionality.

With these analyses, a higher knowledge about the composition of these different products, the relation between elements and the necessary aspects for a correct functionality was achieved.

4.4.2 FUNCTIONAL ANALYSIS

Once each of the products had been decomposed into their elements, it was necessary to study their function in detail, segmenting the primary and the secondary functions. In addition, there was an observation of which elements oversee each aspect, their differentiation depending on their importance and identification of new ways or improvements to realize the same functions. As we can observe in the section 1.3 Functional Analyses in the Appendix on page 26, each one of the products has been analyzed in detail defining their primary, secondary and performance functions which include: technical, usage, security and sometimes esthetic functions.

As a conclusion, most of the technical functions consist of attaching the product to the user or allowing the connection between elements. For the first function, most of the needed elements are pelvic belt, shoulder harness, back cover, leg strap, among others. In the other hand, the elements required for the second one are specially tool attachment or arm connection.

In relation with the usage functions, the ones that most appeared are weight transfer; realized by the metallic bars connected within each other and the pelvic belt, weight transfer directly to the ground or support weight of arms. With respect to the security functions, they mostly consist of providing stability to the user. Because of the weight and size of most of the products, for the user to be able to realize its action, it is important to include an element to counterbalance the weight and help the user. Another interesting function is to ensure the connection between elements. Due to their weight and their complex relation between each other, it is necessary to include several components to fix that connection and this way avoid possible user injuries or incorrect functionality of the product. Finally, some of them do have esthetic functions like facilitating its storage with a hanging rope.

To summarize, each one of these functions and the way they have been analyzed, have been useful for the development of the future product. It has allowed to understand with higher knowledge the functionality of the existing products, their components and what is necessary, what could be improved or even eliminated.

4.4.3 USAGE ANALYSIS

Subsequent to both the structural and the functional analyses, a study of the usage of these products and the interaction they have with the user has been realized.

The analysis of use, user and environment serves especially for the evaluation of the products in their environment, with the aim of product conception, comparison and differentiation within each other. In addition, this analysis makes it possible to specify various concepts as to how to meet the user´s requirements and needs. In fact, the best way to carry out this analysis is to perform it “in situ”, i.e. in reality to be able to see the product in operation, as well as the relationship with the user and what sensations it provokes. Unfortunately, this analysis couldn´t be done in reality to study their interaction, but it has been possible to idealize and analyze the situations.

For each one of the products, there has been an analysis about the modalities of use and identification of environmental conditions and the environment of use. Additionally, the sequence of use to observe the different steps and possible problems that could appear in each one of them. See section 1.4 Usage Analyses in the Appendix on page 29.

In conclusion, as we can observe in the different analyses, there has been an identification of different problems which had to be studied afterward and solved during the development of the design. Specially, most of these products occupy a big space for their storage, take time to attach them to the user or even need an external help to put them on correctly, and need a good maintenance of their different components and connections to maintain the correct functionality of the product.

5 DEVELOPMENT PHASE

5.1 USER CASES OF THREE CONCEPTS

After accomplishing each one of the analyses, there was a higher knowledge about the existing products that are used in similar situations, their components, functionality and way of interacting with the user, among others. Due to this, the next step consisted of designing three different concepts for our main user that were developed eventually. These concepts had to focus on the same objective but differentiate from each other in relation with functionality, situation of use and conceptualization.

Based on the results from the surveys and the analyses that had been executed, the 3 concepts that were developed are the following:

- Exoskeleton for holding hose in case of fire.
- Exoskeleton for holding axe and using it for cutting.
- Exoskeleton for continuously collecting debris after a building collapse.

Before devising each one of these concepts, it was required to realize a series of user cases for each of these concepts. In them, the specific situation they would be used on was defined, as well as the analysis of all the different steps taken on to find the different main aspects that the product should fulfill. With the use of this cases, it may appear moments or circumstances that could lead to a type of design and this way there is a better understanding of the needed interaction between the user and the product.

After realizing the user cases, see section 2.1 User cases in the Appendix on page 36, there were a few aspects that really stand out and they introduced a way in which the designs had to focus on. Specially, for the three concepts, there was a real need of lightweight designs, facility of its attachment to the user and efficient way for their storage. Also, the need of being able to attach them without the need of an external help and not disturbing in the user´s movement or being an extra weight.

5.2 PRODUCT DESIGN SPECIFICATIONS

In advance of designing each concept, it was necessary too to define the requirements that each one must follow. Some of these are functionality, user, maintenance, materials and ergonomics. This way, each concept had a main base for being able to work correctly and satisfy the user´s needs. It should be noted that the majority of these requirements were chosen from the results of the previous survey and the conclusions of the analyses.

- Exoskeleton for holding hose in case of fire
  - Functionality: Support the hose in a static position transferring its weight to the ground.
  - User: Firefighter
  - Context: In situations in which a hose is needed during a long period of time in an emergency moment.
  - Service life: Durability. Because of the price and complexity of these products, it is necessary that they can perform their activity during a long period of time, without having to be replaced or have a constant maintenance.
  - Commissioning: Facility to put it on and off; instant attachment to the user´s body and ready for its use. Also, quick adaptability to the different tools that could be used in these certain situations.
  - Maintenance and materials: Need of anticorrosion and resistant materials. Should function correctly at all times and no need of continuous maintenance. Also, it should be resistant to any environment/weather it could be used on.
  - Storage: Should facilitate its transport and storage. Should be able to compact itself to reduce its size (ex: rotating the bars) and no need of delicate protection of the components. Should be able to be carried lightweight, no need of big space for its storage and easy manipulation.
  - Ergonomics: Should be able to adapt to any user´s body, independently of their size and height. Should attach to the user´s body parts in an easy and quick way and should not create a discomfort on the user while wearing it.

> Others: The product should be able to attach and dis-attach the different components (sections) to facilitate its storage and commissioning, but not decompose into several ones because then it´s harder to store all of them and not lose them.

- Exoskeleton for holding an axe and using it for cutting
    - Functionality: Reduction of axes weight carried by the user´s arms while moving dynamically and cutting.
    - User: Firefighters.
    - Context: Situations in which the user has to move quickly while holding the axe.
    - Service life: Durability. Because of the price and complexity of these products, it´s necessary that they can perform their activity during a long period of time, without having to be replaced or have a constant maintenance.
    - Commissioning: Facility to put it on and off. Because the user must do the activity and respond quickly, the attachment of the product to the user should be as fast as possible. Easy and efficient attachment. Also, adaptability to any object that the user has to carry.
    - Maintenance and materials: Need of anticorrosion and resistant materials. Should function correctly at all times and no need of continuous maintenance. Also, it should be resistant to any environment/weather it could be used on.
    - Storage: Should facilitate its transport and storage. Should be able to compact itself to reduce its size and no need of delicate protection of the components. Should be able to be carried lightweight, no need of big space for its storage and easy manipulation.
    - Ergonomics: Should be able to adapt to any user´s body, independently of their size and height. Should attach to the user´s body parts in an easy and quick way and should not create a discomfort on the user while wearing it.

> Others: Should not need an external help to attach the product to the user. The product should have an easy and quick attachment to the user, without provoking loose of balance, being lightweight and not reducing the time the user has to react to the danger.

- Exoskeleton for continuously collecting debris after a building collapse
    > Functionality: Reduction of user´s effort when lifting debris from the ground.
    > User: Firefighters.
    > Context: Situations in which the user has to lift continuously debris from the ground in a quick and safe way.
    > Service life: Durability. Because of the price and complexity of these products, it´s necessary that they can perform their activity during a long period of time, without having to be replaced or have a constant maintenance.
    > Commissioning: Facility to put it on and off; instant attachment to the user´s body and ready for its use.
    > Maintenance and materials: Need of anticorrosion and resistant materials. Should function correctly at all times and no need of continuous maintenance. Also, it should be resistant to any environment/weather it could be used on.
    > Storage: Should facilitate its transport and storage. Should be able to compact itself to reduce its size and no need of delicate protection of the components. Should be able to be carried lightweight, no need of big space for its storage and easy manipulation.
    > Ergonomics: Should be able to adapt to any user´s body, independently of their size and height. Should attach to the user´s body parts in an easy and quick way and should not create a discomfort on the user while wearing it.
    > Others: Should not need an external help to attach the product to the user. The product should have an easy and quick attachment to the user, without provoking loose of balance, being lightweight and not occupying a big space once it´s being worn by the user.

5.3 DESIGN OF CONCEPT ALTERNATIVES

Down the line, before starting with the concept sketches, it was useful to do an analysis of other external products that could solve these problems or circumstances, think about analogies and this way start getting innovative ideas. For each one of the concepts, an Influence Panel has been elaborated which collects all these commented before and can be seen in section 2.2 Influence Panels in the Appendix on page 39.

Consequently, there was a bigger idea of how each of the concepts should look like, what characteristics they should have, and its creation was realized. The final three concepts that have been designed are explained in detail, with visualization of their formal and functional development in section 2.3 Design of concept alternatives in the Appendix on page 40.

The visual representations of the three concepts are the following.

- Exoskeleton for holding hose in case of fire [see Fig. 15 on page 26]

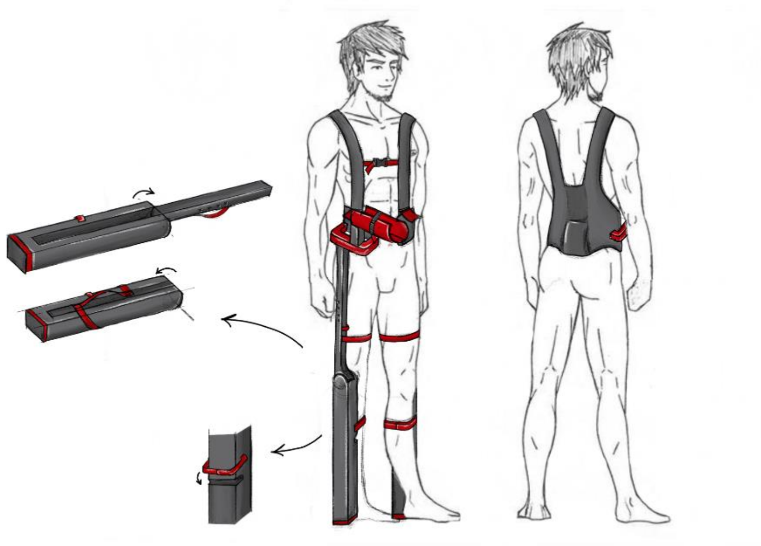

Fig. 15: Exoskeleton for holding hose in case of fire

- Exoskeleton for holding an axe and using it for cutting [see Fig. 16 on page 27]

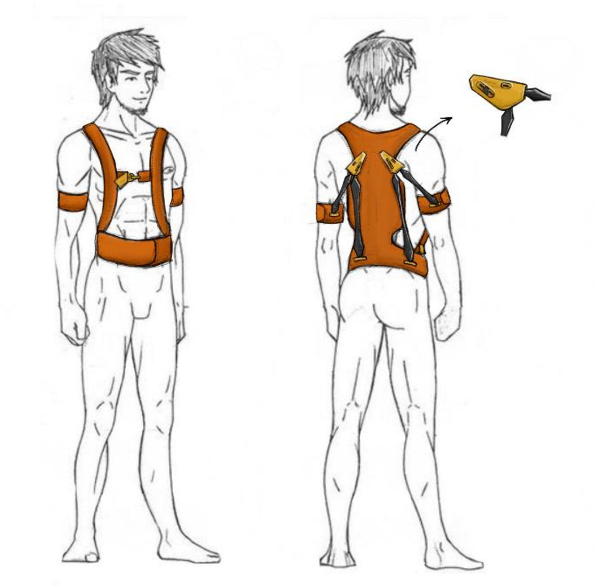

Fig. 16: Exoskeleton for holding an axe and using it for cutting

- Exoskeleton for continuously collecting debris after a building collapse [see Fig. 17 on page 27]

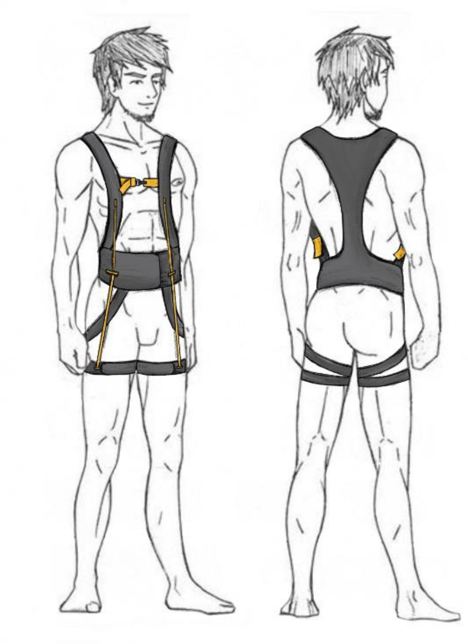

Fig. 17: Exoskeleton for continuously collecting debris after a building collapse

5.4 SELECTION OF FINAL CONCEPT

After generating each one of the concepts, to decide which one was going to be developed furthermore, an interview to a specialist on the sector was done. This person was Eduardo José Sánchez, Fire Chief of Zaragoza, and he was presented the three different concepts to study their efficiency and utility.

Further, he pointed out some interesting aspects that were taken into consideration. The first one, related to the Concept 1, was about the higher necessity of the product to withstand the environmental conditions and how there are some clothing requirements for these situations, than the actual functionality of the product. He thought it was interesting but due to the necessity of a high speed and regulations, an exoskeleton in these situations might not be the best solution.

In the other hand, he was really surprised and interested on the Concept 3. He liked the idea of being a mechanical strength enhancer, its lightweight, usability and no need of external power. He proposed the idea of being able to change its functionality depending on the need of the user. He also considered the possibility of designing a product that could enhance the user´s strength to increase the maximum weight a worker could hold, following the occupational risk prevention standards. Finally, he liked the idea of future expanding this product to other sectors like industry or medical assistance. Apart from presenting him the concepts, both supervisors of this thesis also took part into this decision and the final concept selected was Concept 3: “Exoskeleton for continuously collecting debris after a building collapse” but amplifying its usability to different situations and its adaptability to the user´s needs.

Therefore, the final concept has focused on an exoskeleton for reducing fatigue and injuries when lifting and holding different elements. Some examples of these could be the debris commented before, equipment or even victims. For each one of them, the firefighter requires a constant movement of bending down and lifting, apart from stretching and shrinking the arms. Some users might need an extra help to realize one type of these movements or the others, so then the product had to allow its adaptability to satisfy the user´s needs depending on the situation.

5.5 FINAL CONCEPT DEVELOPMENT

5.5.1 INITIAL ANALYSIS

Prior starting with the development of the concept, as we can observe in section 2.4 User case of final concept in the Appendix on page 49, an extra user case has been realized. This one consists of the study of the steps when lifting and holding victims, to study the different movements, interactions and needs that the user might have depending on the moment. Apart from it, a photo analysis has been done for each one of the steps to really understand the process and have an image of the actual situation and its environment.

Moreover, apart from the exoskeletons that have been analyzed in the earlier sections, there are many others that have been designed to achieve the same objective and are more focused on reducing the pressure or injury on the lower back when bending. The two main products that were analyzed in detail and served as an influence are Muscle Suit Every by Innophys, and Le HAPO by ErgoSanté.

In relation to the first product, there were a few characteristics that couldn´t be applied into the final concept. In one hand, the mechanism of the Pneumatic Artificial Muscles works correctly but it could be dangerous in situations of contact of the compressed air with the fire. In the other hand, the design that has been given to this product is lightweight but its size wouldn´t be adequate to the firefighters use. It occupies a big space, and doesn´t allow a completely free movement of the user. In relation to the second one, the concept of storing the energy when bending in a spring and enhancing the straightening of the trunk with it, was taken as influence for the final project. Also, interest has been given to the maintenance of the lumbar vertebrae in a correct position and the redirection of the weight and effort to other body parts.

Therefore, the final concept focuses on allowing perform the same movement and serve as an aid to the user, but in an indirect manner. In other words, keeping the correct back posture and redirecting the weight to other body parts, while enhancing these to realize the movement, can have an influence in all the body and increase the performance of the movement while minorizing the injuries and efforts.

5.5.2 MEDICAL STUDIES

To have a concrete proof about the relation between the body parts and how their movements are connected, an analysis of different medical studies has been developed.

This research had to be classified into two groups. The first one, the study of the relation between lower back, legs, and knees, and the second one; relation between the arms and lower back. All these, focused on the repetitive movement of bending down and lifting and carrying heavy loads.

In relation with the first one, “impairments in knee strength, stability, or flexibility can predispose the back to injury due to the chain reaction of forces” (Ehren Allen, 2021). There are several studies like: *“Effects of load mass and position on the dynamic loading on the knees, shoulders and lumbar spine during lifting: a musculoskeletal modelling approach”* (Sebastian Skals, 2021) that determined the “effects of load mass, asymmetry angle, horizontal location and deposit height on the dynamic loading of the knees, shoulders, and lumbar spine during lifting” (ibid). These can assure that “the forces on the knees are significantly affected by all the lifting factors” (ibid) and “the ability to execute exercises such as jumping or squatting can differ depending on the location of the trunk, vertical stiffness, and muscle activity” (Tae-Sik Lee, Min-Young Song and Yu-Jeong Kwon, 2016). Moreover, “the human trunk is associated with the transfer of energy and the connection of movements between the lower and upper body” (ibid).

In addition, “muscle tightness in a person´s hamstrings, which can cause knee pain, increases the risk of injury and pain in the lower back” (Carolyn Farnsworth, 2023) and “when your hamstrings are tight or weak, it can cause you to destabilize back and hip muscles. It puts pressure on your back and knees and can even change the way your spine curves” (Babylon Team, 2021).

Apart from this, there have been several medical studies in which they have analyzed the influence of exoskeletons on both back and legs like in: *“A passive exoskeleton reduces peak and mean EMG during symmetric and asymmetric lifting”* (Mohammad Mehdi Alemi, Jack Geissinger, Athulya A Simon, S Emily Chang and Alan T Asbeck, 2019). “The exoskeleton reduced back muscle activity the most during squat lifting, followed by freestyle and asymmetric lifting, and finally, during stoop lifting. Additionally, the activity of leg muscles reduced by 19.1% and 14.1% for peak, and mean, respectively, while wearing the exoskeleton” (ibid).

Another study: *“The effects of a passive exoskeleton on muscle activity, discomfort and endurance time in forward bending work”* (Tim Bosch, Jennifer van Eck, Karlijn Knitel and Michiel de Looze, 2016) confirmed that “the exoskeleton is intended to transfer forces from the lower back to the chest and leg pads. We observed similar reductions of back and leg muscle activity in the with-exoskeleton condition. As a result, the endurance time was found to be almost three times longer” (ibid).

Although, it is necessary to highlight that “the most important piece of advice for low back safety is to maintain a neutral spine when lifting. Your low back naturally has a slight forward curve, and you should do your best to keep it that way during lifting” (Barnes, 2021).

In conclusion, certain exercises that involve movement of the knees, such as squats, can place additional stress on the lower back, especially if performed incorrectly or with overload. Therefore, it is important to maintain good technique and progress. In summary, the knees and lower back are closely interconnected, and their problems are affected within each other. Therefore, promoting the movement in the knees when lifting a load will help reduce low back pain in some people, especially if the cause of low back pain is poor posture, incorrect lifting technique and lack of strength on the joints and muscles.

By encouraging the movement in the knees, you can help reduce the strain on the low back and transfer some of the stress to the legs. This can decrease the load on the spine and reduce the risk of low back injury, while enhancing the movement on the knees and reducing the injury in them too.

In the other hand, the relation between the arms and low back has also been studied.

In general, by increasing the movement in the arms, some of the stress can be transferred to the arm muscles and reduce the load on the spine and lower back, notwithstanding its relation is not as considerable as the one between the low back and legs.

Although, enhancing the movement in these extremities will help develop the movement while reducing their possible injury. It is important to note that reducing stress on the arms is only one of the factors that can help reduce low back pain. As it was explained before, it is also important to use a proper lifting technique, maintain good posture and use appropriate lifting equipment when necessary.

5.5.3 FUNCTIONAL DEVELOPMENT

5.5.3.1 ANALYSIS OF PRODUCTS

To achieve the final product, the functional and formal developments of the product were realized. The first one consisted of studying different approaches and techniques to satisfy the requirement of enhancing the movement by applying the help on the knees and arms.

Several products have been analyzed although those that were useful for the development of the product are: ROAM by Roam Robotics, AGAINER, SKI MOJO and Xnowers Levier. The conclusions that were obtained are the following.

- ROAM [see Fig. 18 on page 32]

From its design, the most interesting characteristic is the introduction of the technology and sensing the next user´s movement to be able to help immediately. Although, because of the requirements and use of the final concept, this type of technology can´t be included and should focus more on a mechanic design.

Fig. 18: ROAM

- AGAINER [see Fig. 19 on page 33]

Its functionality consists of a gas spring with a pump that allows each user to adjust the gas to have the desired support level. Although, having gas near fire could be a possible dangerous situation, and for that reason this type of mechanism was discarded. However, the concept of removing most of the extreme pressure on both knees and back follows the same objective as the final concept.

Fig. 19: AGAINER

- SKI MOJO [see Fig. 20 on page 33]

This product was more related to the final concept´s objective. Having a mechanical function, that can be both activated and disactivated by a simple movement and not requiring technology or complex mechanisms, made this product the most influential for the developing of the final concept. Although, as we can observe in the following analysis in section 5.5.3.2 Analysis of mechanisms on page 34 , the spring recoil technology is complex and not that available for common products. Therefore, the idea of how another type of compressing spring could enhance the movement of the leg and knee was used as a reference for the final concept.

Fig. 20: SKI MOJO

- Xnowers Levier [see Fig. 21 on page 33]

As a conclusion, its functionality is similar to the one commented before. It uses a series of springs to provide kinetic energy to assist the leg extension.

Fig. 21: Xnowers Levier

5.5.3.2 ANALYSIS OF MECHANISMS

Apart from analyzing several existing products, a knowledge of different useful mechanisms was also required to understand their functionality. Those that were analyzed in detail were the piston and the spring recoil.

- Piston

In this case, the movement of the piston is caused by applying pneumatic pressure thereby moving the piston upwards. When removing the pneumatic pressure, then the piston goes down. In addition, there exists two types: "Air to Close"; filling it with air for compressing and "Air to Open"; filling it with air for stretching.

- Spring recoil

The spring recoil is one of the types of springs that exist nowadays and is commonly used in guns. There are different ones which contain several springs on their inside, but they all have the same objective; straightening with high velocity and force against the object that is compressing them. The following video has served as help to understand the mechanism and its functionality: "*Worlds only progressive triple spring recoil reduction system*" (DPM Systems Technologies Ltd, 2013).

As it was explained before in section 5.5.3.1 Analysis of products, Ski Mojo on page 33, the spring recoil might be really powerful but not that much adaptable and available for common use. Therefore, the idea of using the spring compression and decompression for providing kinetic energy was used, but utilizing other types of springs that are explained further on, in section 6.2 Functional final concept on page 43.

5.5.4 FORMAL DEVELOPMENT

5.5.4.1 LEGISLATION

Subsequent to deciding the mechanism required for the correct functionality of the product, its formal development was followed. To start with, due to the application of this product on firefighters during their activity, it was necessary to analyze and follow the legislation on firefighters´ PPE.

There exists three different PPEs:

1. Protective clothing for firefighting (UNE-EN 469)
2. Protective clothing for forest fires (UNE-EN 15614)
3. Protective clothing for technical rescue (UNE-EN 16689)

To allow the product to be used in any of these cases and by any user that might need this external help, the product has followed these three regulations, which are explained in detail in section 2.5 Legislation in the Appendix on page 55.

5.5.4.2 INFLUENCES OF DESIGN

As influence for the design, two main products have been taken into consideration, apart from the other exoskeletons that have been analyzed on the earlier sections and their components.

The first one: the Self-Contained Breathing Apparatus that firefighters use to carry on the oxygen tank on their backs. This type of bag helped to study the way in which the elements were connected to each other, their adaptability, and the aesthetic. The second one: Lumbar and back braces. They were useful to study how they can correctly position the body´s trunk without complex mechanisms and how they adapt to the user´s body.

Apart from this, different ways of connecting two elements, adjustment to the user´s body parts, adaptability to user´s measurements, ergonomics and far more characteristics were evaluated to end up with the final product design. The final sketch of how the product should look like and how the different elements had to be connected can be seen in section 2.6 Influences of design in the Appendix on page 56.

5.5.4.3 ANTHROPOMETRIC MEASUREMENTS

Subsequently, before the final design of the product, and its 3D modeling, it was necessary to determine several measurements. These had to be adjusted to the anthropometric measurements for product design in order to base the product on actual measurements that would allow its use by any user. The sizes that were used for the product design are the following [see Tables 1, 2 and 3 on pages 36 and 37].

Table 1: Relation with the arm

[mm]	**P5**	**P50**	**P95**
Shoulder-elbow length	328	366	399
Maximum horizontal reach	632	720	796
Elbow-cuff length	312	347	380

Table 2: Relation with the lumbar and back

[mm]	**P5**	**P50**	**P95**
Shoulder height	1309	1414	1520
Elbow height	970	1049	1134
Iliac spine height	855	947	1040
Chest thickness	209	251	292
Abdominal thickness	184	240	301
Chest width	280	320	364
Hip width	310	344	383
Shoulder-elbow length	328	366	399
Shoulder width	318	386	436
Chest circumference	860	989	1130
Waist circumference	751	920	1075

Table 3: Relation with the leg

[mm]	**P5**	**P50**	**P95**
Elbow height	970	1049	1134
Height of the iliac spine	855	947	1040
Tibia height	409	461	520
Hip width	310	344	383
Hip width (sitting)	317	363	415
Leg length	388	428	468
Thigh thickness	113	147	146
Thigh height	516	568	619
Height of third metacarpal	680	746	813
Popliteal-rear length	451	497	545
Knee-rear length	550	598	650

6 DESIGN PHASE

6.1 FORMAL FINAL CONCEPT

The final concept consists of an exoskeleton which incorporates three elements of differentiated use which could be worn together or separately, depending on the user´s needs. Although, to reach the most efficient functionality and serve as the main aid for our user´s problem, the three should be used altogether. It reduces the musculoskeletal disorders and associated injuries that can arise from uncomfortable positions when repetitive strenuous lifting, resulting in a decrease of approximately 55% in the effort needed by the user to perform its movements, calculations in section 6.2.1 Open Modelica simulation on page 44.

The first assembly is the “Lumbar and Back Protector” [see Fig. 22 on page 38 and Fig. 25 on page 42]. This protector will help the user maintain the correct back posture for realizing the movement while not occupying a big space and providing user comfort. It consists of the Lumbar and Back Protector itself, and different types of buckles to connect them within each other to ensure that the product attaches to the user correctly. To adapt itself to the body measurements, these buckles are connected directly to Kevlar straps which could be adjusted.

Fig. 22: Lumbar and Back Protector

The Lumbar and Back Protector secures the entire lumbar area as well as the back. It consists of a lumbar belt connected to a back protector, which can be adjusted to the size of the user due to the arm straps. These are connected to the back protector in a superior area, comparatively with the school backpacks. Consequently, when these are tensed, they will go below the user´s armpits making the user´s back to stretch, sticking out gently the chest and maintaining a correct and stable posture.

It is necessary to highlight those certain areas like the lumbar belt, sections of the back and the arm straps which are extra cushioned with Polyurethane foam. These three body parts are the ones that most feel the action of the product and have a direct contact with it. Therefore, this additional material increases the comfort without hindering the movement.

Apart from these, on the lower back part of the Lumbar and Back Protector, there are two hanging straps. These should be connected to the Adjustment Measure Bar of the leg, see section 3.2 Blueprints, Leg Enhancer nº2 in the Appendix on page 70, and tensed so that the functionality of the product works at its best. Having this connection between the two assemblies, the enhanced movement realized on the knees will also be transferred into the hip and back helping the user to stand back again. However, when the user doesn´t use the two assemblies together and just wears the Lumbar and Back Protector itself to help maintain the good posture when working, to prevent them from falling and causing discomfort, they can be connected to the buckles on the sides of the pelvic belt.

In relation with the aesthetic of this assembly, it should be noted that all buckles and the cushioned areas are in yellow. This way, the user can find them in a quick way and attach the product to the body without taking a considerable time. In addition, in the lumbar belt, the straps that secure the adaptable straps are also in yellow to identify them quickly and avoid leaving them hanging instead of well secured.

The next assembly is the "Leg Enhancer" [see Fig. 23 on page 39 and Fig. 26 on page 42]. This product will enhance the movement of standing up by providing the user some driving torque that will assist him/her to stand up while lifting heavy loads. The explanation of the mechanism can be found in section 6.2 Functional final concept on page 43, apart from the calculations and element dimensions for its correct functionality.

Fig. 23: Leg Enhancer

In relation with its structure, it consists of the assembly of different components.

The main one is the “Leg Mechanism”, see section 3.2 Blueprints, Leg Mechanism nº2.3 in the Appendix on page 73 which contains the upper and lower mechanism bars, the BOA System, and the rotation axis. This last one allows the two bars rotate within each other, following the user´s knee movement without causing any discomfort or additional effort. The explanation of the BOA System can be found in section 6.2.2 Spring tensor on page 48.

This mechanism is surrounded by the Top and Low Hitch. These will in one hand protect the mechanism from possible shocks, in addition to providing heat resistance. In the other hand, they will attach to the user´s leg, allowing its adaptability to any measurements because of the use of Velcro and its possibility to adapt to any shape.

Apart from these, there are too several buckles to connect different components within each other. Especially the one on the Adjustment Measure Bar that will connect the Leg Enhancer with the Lumbar and Back Protector, as it was explained before. It should be mentioned that the way in which the Adjustment Measure Bar is attached to the user´s leg is slightly different to the Velcro Straps. To facilitate its attachment and decrease the user´s discomfort, the section that surrounds the front part of the thigh is made of Polyurethane foam covered by Nomex Nano Flex which are softer and have a more structured and defined shape. The rest of it consists of a Klevar strap that will attach to it by a buckle assembly and can be tensed to adapt itself to the user´s measures. To attract rapidly the attention of the user and not loose time finding the straps, the upper buckles, the Klevar strap and the edges of the Velcro straps are in yellow to contrast the dark color of the rest of the elements.

It should be noted that in each one of the user´s legs there will be a Leg Enhancer, therefore the aid is provided in both legs, providing sufficient driving torque to perform the movement.

Moreover, the third assembly consists of the "Arm Enhancer" [see Fig. 24 on page 41 and Fig. 27 on page 42]. As we can observe in the description of the mechanism and its calculations, the Arm Enhancer functions in a really similar way as the Leg Enhancer, but instead of providing a driving torque to extend, it helps shrink the arms when lifting heavy loads.

Fig. 24: Arm Enhancer

In relation with its structure, it consists of the assembly of a few components. The principle one, the "Arm Mechanism", see section 3.2 Blueprints, Arm Mechanism nº3.1 in the Appendix on page 79. This is composed of the upper and lower mechanism bars, the BOA System and the rotation axis. The BOA System´s functionality is the same as the one explained before in the Leg Enhancer. Also, following the same way as in the Leg Enhancer, the rotation axis allows the two bars to rotate within each other to facilitate the movement. This mechanism is surrounded by the Top Cover and Low Hitch, providing shock and thermal resistance, apart from attaching the product to the user´s arms. It is worth mentioning, that in comparison with the Leg Enhancer, because of its dimensions, the Arm Enhancer just needs two points of connection to the user´s body part instead of three.

The upper one which belongs to the Adjustment Measure Bar has a different design. The section that surrounds the biceps, has a more structured and constant form, due to the Polyurethane foam, to allow the user to place the product on top of his/her arm and move the Velcro strap around it to close the attachment. This way, it allows the placement of the product to be done by the user, without external help in a quick and easy way. On the contrary, the Low Hitch consists of Velcro straps that surround the user´s lower arm and adapt themselves to its measures. In the same way as in the Leg Enhancer, the edges of the straps are in yellow to be visualized quickly.

It should be noted, that in each one of the user´s arms there will be an Arm Enhancer, therefore the aid is provided in both arms, providing sufficient driving torque to perform the movement.

Furthermore, it is necessary to highlight that the color decision has been made following the firefighter´s equipment colors and the necessity to facilitate the user to find the attachment parts quickly and be able to highlight the main elements.

The cornerstone of the product´s appearance was to match the rest of the firefighter´s equipment as well as being a product that looks technical, functional, efficient and fits into the environment. It should be noted that instead of attracting the user´s attention at the time of purchase or differentiating itself from the competition because of its appearance, it was more important that the product stands out for its efficiency and purpose than for its design. Therefore, the design of the different components focused on: allowing the correct functionality, occupying the least possible space, being adaptable and easy to carry the same as to put on and off. In addition, other characteristics that were taken into consideration were the capability to wear it without external help, the possibility to be worn under the PPE, the resistance to its environment and the ease for its understanding and operation.

To obtain a further knowledge about the measurements and components of each one of the elements, see section 3.1 Renderings in the Appendix on page 58 and section 3.2 Blueprints in the Appendix on page 67.

Fig. 25: L&B Protector

Fig. 26: Leg Enhancer v.2

Fig. 27: Arm Enhancer v.2

6.2 FUNCTIONAL FINAL CONCEPT

As consequence to the earlier analyses, the mechanism that will help the user´s knees and arms to straighten the body when lifting the elements will be a combination of compression and traction springs that will enhance the movement.

In relation to the legs, when the user squats down to the floor, causing a rotation on its knees and moving forward the ground, the springs will be compressed due to the BOA System, see section 6.2.2 Spring tensor on page 48, and will store the mechanical energy. When these springs are subjected to a compression load, they compress, grow shorter and absorb a large amount of potential force. In addition, they will create a recovery force and driving torque that will push up the user´s leg with kinetic energy to straighten them and obtain the normal and comfortable position when standing up.

On the other hand, the development of the mechanism for the arms had to be determined too. Because the needed force to shrinking the arm when lifting up objects is much lower than the one on the knees for lifting the whole-body weight of the user, the required mechanism could be smaller and simpler.
After the analysis of the earlier mechanisms, applying a tension spring was the most accurate solution. When the user´s arm stretches, it will tense the spring by a traction force, and this will cause a recovery force and driving torque that will help the user to shrink back the arm while lifting the element. These work the same as the compression springs but in the other direction. Instead of being compressed, they are extended, storing the potential energy, and then releasing it as kinetic.

For realizing the calculations to know what type of springs should be chosen, the software Open Modelica has been used. With it, a digital simulation of the real behavior has been done to both visualize the movement of the user and obtain realistic results depending on the parameters introduced into the model, see section 6.2.1 Open Modelica simulation on page 44.

6.2.1 OPEN MODELICA SIMULATION

In one hand, the simulation consists of one leg that bends down and up showing the realistic movement of the user through the different angles that the movement requires [see Fig. 28 on page 44]. It contains the upper and lower leg, each one with their parameters like height, width, and density, following the anthropometric table measures, and the superior body. This last one simulates the lumbar area of the user, and it has been defined with the parameters representing the weight that would be put into one of the legs. The composition of the simulation's elements can be seen in Fig. 29 on page 44.

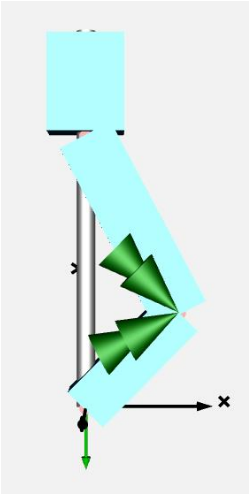

Fig. 28: Leg body simulation

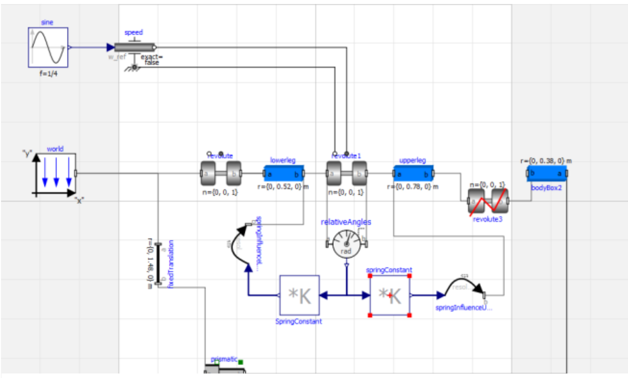

Fig. 29: Leg simulation components

Due to the average weight of firefighters from 70 to 100 kg, with an average of around 80 kg, a firefighter of 100 kg has been selected for the calculations. In addition, consequently of the average weight of an adult from 50 to 82 kg, with an average of around 62 kg, an adult of 80 kg has been selected for the calculations.

Therefore, the springs that had to be selected after the realization of the calculations, had to be able to enhance the performance in the maximum weight situation. For this reason, when the user squats down into the ground and lifts the victim, the total weight that would be pushing down the strings would be: 100 + 80 = 180 kg. Therefore, the weight put into one of the legs would be approximately 90 kg, and this value is the one that has been introduced into the simulation.

Secondly, once the model of the body was realized, the springs that would enhance the performance in the knee had to be added. It should be noted, that as consequence of the small space and lightweight of the product, two small springs are used in each leg for the mechanism. Due to the components that Open Modelica provides, a rotational spring has been added representing both linear springs. Therefore, its spring constant is the same as the spring constant of both springs combined. Due to the reason that the action of the spring interacts with both upper and lower legs, from the knee, it is connected to both in the simulation model [see Fig. 30 on page 45].

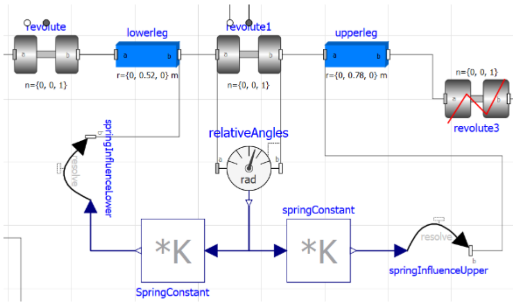

Fig. 30: Spring connection

Once the model was completed, the simulation result that was necessary for observing how the springs would interact with the leg and know the required parameters for these, is the Driving torque in direction of axis of rotation on the knee [N*m]. Visualizing the results of this variable with and without the spring, it can be confirmed that the inclusion of the springs will reduce the torque that needs to be done by the knee.

As we can observe in Fig. 31 on page 45, the total driving torque in the knee, without the springs, is 422.5 N*m. Due to the selected mechanism and its limits, the springs to be able to push back with such a moment would require big dimensions. Therefore, the springs will push back with a 55% of the driving torque, causing the knee to work with 45% of the total driving torque: 189 N*m, as we can observe in Fig. 32 on page 45.

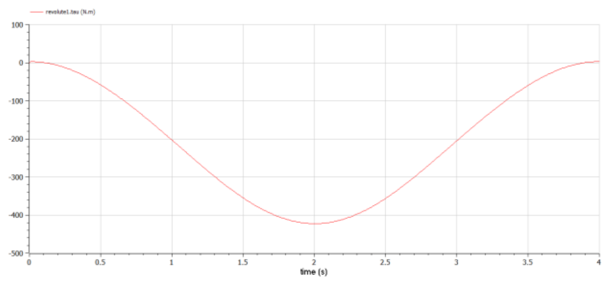

Fig. 31: Driving torque without spring

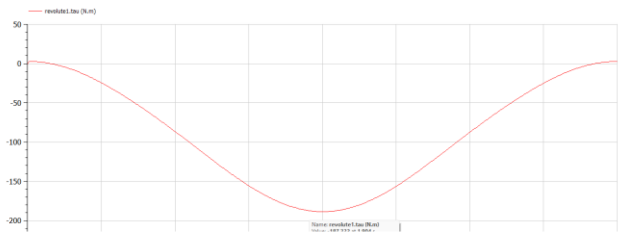

Fig. 32: Driving torque with spring

To do so, the rotational spring constant must be 180 $\frac{N}{m}$, so the spring constant of each one of the used springs in reality is approximately 90 $\frac{N}{m}$.

Not only the needed torque had to be calculated, but also the maximum distance the spring should compress to allow the whole movement of squatting. By taking as reference the distance difference from a specific point on the thigh of an adult with 1.90 m height to the floor, from being in a standing position to squatting, the difference of the height was 7 cm, therefore the compression spring should be able to compress 7 cm.

The calculations for obtaining the parameters of one spring are the following.

The spring constant, we can be calculated using the equation (1.1) on page 46.

$$k = \frac{G*d^4}{8*na*D^3} \quad \left(\frac{N}{m}\right) \tag{1.1}$$

Being: G = Shear modulus of material $\left(\frac{N}{m^2}\right)$; d = spring wire diameter (m); Na = number of active coils; D = average diameter of the spring (m)

After searching several springs, calculating their efficiency, and checking if they would be able to have the spring constant required, the final spring that has been selected is a carbon-filled rubber spring with the following dimensions and parameters:

Wire diameter = 0.7 mm; Spring outer diameter = 8 mm; Length: 100 mm; Number of active coils = ; Shear modulus = 50 GPa

Introducing these parameters into the spring constant force: [see equation (1.2) on page 46]

$$k = \frac{(5*10^{10})*0.0007^4}{8*43*0.0073^3} = 90\,\frac{N}{m} \tag{1.2}$$

In addition, it should be noted that carbon-filled rubber springs are widely used due to their high stiffness, enhanced durability, superior damping properties, flexibility, and weight reduction. Characteristics that are needed for the correct functionality of the mechanism.

Once the springs used on the knees were decided, the ones on the arm had to be determined too.

In this situation, the weight that the spring should support consists of just the victim's weight: 80 kg, 40 kg on each arm. Changing the parameters on the simulation [see Fig. 33 and 34 on page 47] to represent the arm and the victim´s weight, as a result, the driving torque in the elbow is 85.8 N*m without the spring [see Fig. 35 on page 47]. With the same reason as before, the spring will enhance the 55% of this driving torque: 47 N causing the elbow to work with 45% of the total driving torque: 38 N*m [see Fig. 36 on page 48].

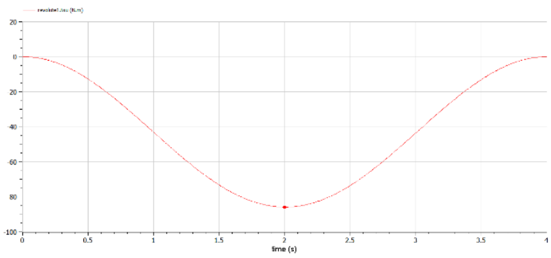

Fig. 35: Driving torque without spring

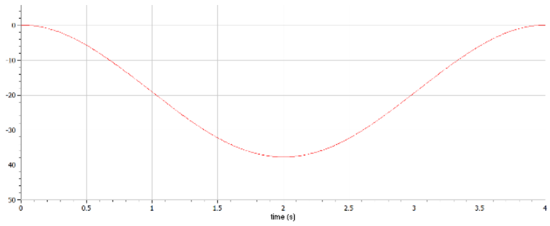

Fig. 36: Driving torque with spring

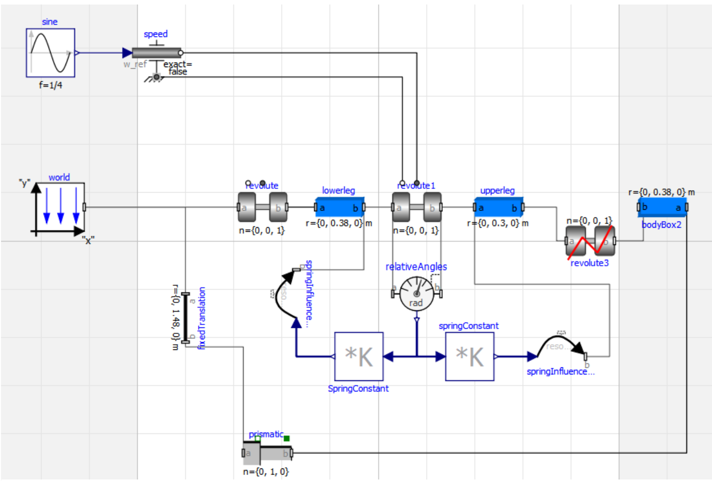

Fig. 33: Arm simulation components

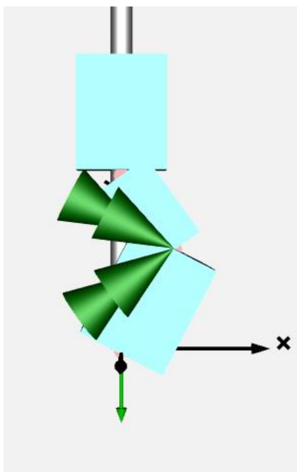

Fig. 34: Arm simulation

To do so, the rotational spring constant must be 37 $\frac{N}{m}$. Also, following the same process as before but now calculating the distance difference from the arm being stretched and shrinked, the distance the spring should enlarge is 4 cm.

The carbon-filled rubber spring selected, with lower shear modulus as the one before, has the following parameters:

Wire diameter = 1 mm; Spring outer diameter = 12 mm; Length: 50 mm; Number of active coils = 13; Shear modulus = 16 GPa

Introducing these parameters into the spring constant force: [see equation (1.3) on page 48].

$$k = \frac{(1.6*10^{10})*0.001^4}{8*40*0.011^3} = 37\frac{N}{m} \quad (1.3)$$

6.2.2 SPRING TENSOR

Moreover, the strings must be compressed or enlarged by a component that will follow the user´s movement. Consequently, the BOA System has been analyzed, and out of all their variety, the M4 has been selected for both knees and arms [see Fig. 37 on page 48].

The BOA System is an innovative and efficient product whose objective focuses on the quick, easy, and simple cable or cord collecting. The M-Series is *"*a powerful solution […]. With its fast-tightening system, the M-Series can withstand increased wire tension, longer and more powerful wires and gives the user great flexibility. The powerful dial combines durability and closing strength and resists external impact without sacrificing it*"* (Iron Steel, 2022).

Fig. 37: M4 BOA System

In specific, the M4 has a 29.5 mm diameter dial that allows the user to tighten, lock and loose the laces, altering the fit with precise click by click adjustment. Also, the lightweight laces are designed to withstand extreme tensions. They are made up of 49 nylon-wrapped stainless-steel wires that are designed to combine comfort and performance.

These wires will be connected in one of their extremes to the springs and in the other to the dial that will be situated on the bar that follows the extremity movement. Once the cable is tensed to its complete, whenever the user bends down or stretches the arms for lifting the object, the cables will create a traction force into the springs making them compress or enlarge, depending on the enhancer. Later on, the springs will create the responsive driving torque that will help the user stand up or shrink the arms.

In addition, the procedure for the activation and deactivation of the product is the following:

1. Press dial.
2. Rotate dial to tighten the wire.
3. If there is too much pressure, rotate dial in opposite direction to loosen the wire.
4. Use of product.
5. When quick deactivation, pull out the dial and the wire will loosen to its complete.

6.3 MATERIALS

Apart from complying the fire resistance regulations explained on section 5.5.4.1 Legislation on page 35, other characteristics like comfort, easy modelling and adaptability to the design were also taken into consideration when deciding the different materials.

The five main materials that are used in the final product are Nomex Nano Flex, Kevlar, PEEK, Polyurethane foam and Velcro. Each one of these materials are used for different components, depending on their requirements, and these appear on section 3.2 Blueprints in the Appendix on page 67.

- Nomex Nano Flex

“This material is thin, flexible, lightweight and an excellent particle barrier for protective clothing. It is a nonwoven material made of continuous submicron fibers and has intrinsic flame resistance” (DuPont, 2023). In addition, some of its features which were needed for the final product are its high level of heat insulation, low thermal conductivity and high filtering and blocking efficiency against particles.

The elements that are made with this material are those that cover the mechanism elements as a case or surround the Polyurethane foam. This way the product is completely resistant to really high temperatures and protects all the other components from possible deformations.

- Kevlar

“Kevlar is a synthetic para-aramid fiber with thermal resistance that has a molecular structure of many interchain bonds that make it incredibly strong. Some of its other main features are tensile strength, ballistic resistance, cut and puncture resistance and thermal resistance” (DuPont, 2023).

The elements that are made with this material are all the different straps that each one of the subassemblies have. This way, it allows the adaptability to the different users and the connection between components, while resisting to really high temperatures and having a high durability.

- PEEK

“PEEK polymer is a high-performance plastic material with an excellent balance of physical properties. It has one of the highest levels of heat resistance and mechanical strength available among plastics” (Ensigner, 2023).

Although the PTFE polymer was also proposed due to its similar characteristics and fulfillment of requirements, its heat resistance was lower than the PEEK, therefore this second one was chosen.

The elements that are made with this material are all the components needed for the mechanism of the product. These include the bars, the rotation axis, and the pushers. Apart from these, all the couplings attached to the Kevlar straps, male and female, are also made of PEEK.

- Velcro

“Many environments where there are extreme temperatures, such as firefighting, oil & gas and metallurgy, workers must rely on materials that can withstand the heat. In installations where high temperatures and flames are an everyday occurrence, VELCRO® Brand products include solutions that can withstand at least 800°F (426.6°C)” (Algarcia, 2022). In addition, Velcro has great strength, but one of its greatest advantages, apart from the ones commented before, is the ease of use.

Those elements that serve for the adaptability of the product to the user but don´t consist of straps and couplings, are made of Velcro. These are the top hitch of the leg and the low hitch for both legs and arms.

- Flexible polyurethane foam

“Flexible polyurethane foam is used as cushioning for a variety of consumer and commercial products […]. Flexible foam can be created in almost any variety of shapes and firmness. It is light, durable, supportive and comfortable” (American Chemistry Council, 2023).

The elements that are made of this material are those that have a direct contact with the user and are required to adapt him/her and give comfort. These are the lumbar and back protector and the adapting bars for both legs and arms. These are covered by Nomex Nano Flex to give protection and shock and temperature resistance.

6.4 PRODUCTION PROCESSES

In relation with the production processes required for the Nomex elements, due to the fact that Nomex Nano Flex is produced by DuPont and consists of a textile, the required process consists of the weaving process following the components dimensions. This material will cover the Polyurethane foam that gives the product its shape and comfort or other PEEK elements.

In relation with the polyurethane foam, once the shape has been designed in a CAD model, the next step consists of cutting it into the required shape and size using an automatic or manual cutting machine. Later, a special adhesive is applied to the surface of the polyurethane foam so that it adheres to the Nomex, and then this is finished by sewing the sides.

The Kevlar straps are already produced outsourced with standardized dimensions so these would be sewed into the different components depending on their position and requirement. To these, all the buckles will be connected to allow the adaptability of the product. In the other hand, the Velcro straps are easily produced. The steps consist of cutting it following the exact dimensions and attaching them to the different materials by sewing.

Finally, but not least, the PEEK components are produced differently. Due to the fact that the mechanism bars for the leg and arms assemblies are empty and have the mechanism on their inside, the main production process that they are going to follow is the Compression molding. In this process, PEEK is placed in a hot mold and pressure is applied to shape it. Later on, the part is cooled and removed from the mold. These will be produced cut in half; therefore, the mechanism could be inserted inside and finally the two components can be closed by means of Epoxy adhesives. They are a good choice for bonding PEEK due to their high resistance to temperature, chemicals and moisture. These adhesives form a strong, durable bond when properly cured. Ultimately, to make the necessary holes, a milling machine will be used: CNC: Computer Numerical Control, to allow precision in its processing.

7 IMPLEMENTATION PHASE

7.1 MODELING

To achieve the 3D CAD models of the different assemblies, the software SOLIDWORKS has been used. It provides powerful 3D modelling tools, allowing to create intricate designs and visualize them in three dimensions.

7.2 BLUEPRINTS

All the blueprints which include the dimensions and composition of the different assemblies, subassemblies and components can be seen in section 3.2 Blueprints in the Appendix on page 67. Although some examples to visualize the way in which the subassemblies and components have been represented can be seen in Fig. 38 and 39 on page 53.

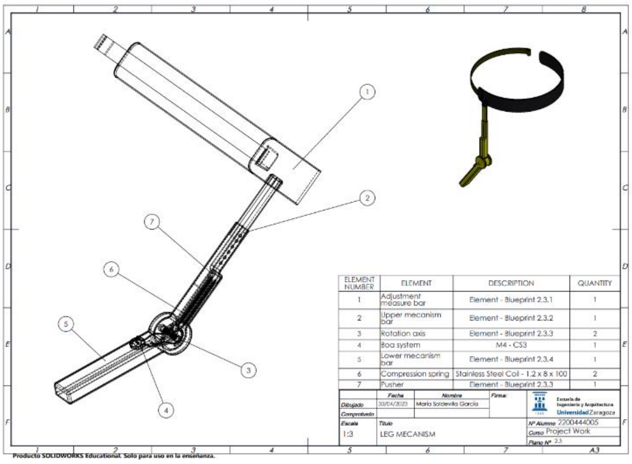

Fig. 38: Leg Mecanism Blueprint

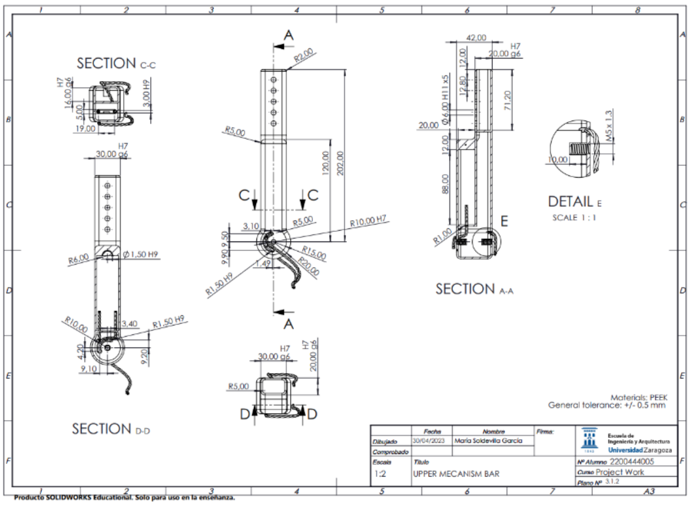

Fig. 39: Upper Mechanism Bar (Arm)

7.3 PROTOTYPE

Following the realization of the design, defining the whole mechanism, and confirming its functionality, a 3D printed prototype has been developed [see Fig. 40, 41 and 42 on page 54]. It consists of the leg mechanism: upper and lower bars, rotation axis and the internal mechanism with the springs and BOA System. It has been executed to check the adequate design of the single components and the decisions that were taken considering the placement of the cables for allowing its correct functionality.

Additionally, it allows the movement of one bar within the other and permits to have a clearer view of the inside of the mechanism to increase its understanding.

Fig. 40: Prototype v1

Fig. 41: Prototype v2

Fig. 42: Prototype v3

7.4 RENDERINGS

Brought the project to completion, several renderings [see Fig. 43-48 on page 55] have been realized for both visualizing the final product and showing the product on different contexts to have a better understanding and envisage the product operational.

The softwares that have been used are: SOLIDWORKS Visualize Professional, Make Human, Blender, and Sketchbook. All the renderings can be seen in section 3.1 Renderings in the Appendix on page 58.

Fig. 43: Situation carrying victim

Fig. 44: Situation carrying container

Fig. 45: Situation carrying the hose

Fig. 46: Back and Lumbar Protector

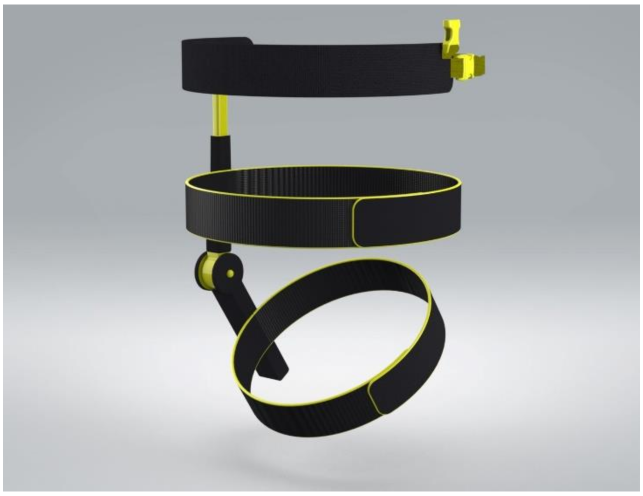

Fig. 47: Leg Enhancer

Fig. 48: Arm Enhancer

8 CONCLUSIONS

Firefighters are the epitome of unwavering courage and selflessness. They face unimaginable danger and chaos and with each call to duty, they willingly embrace the weight of responsibility to protect and serve their communities. They constantly push their physical and mental limits, overcoming fear and exhaustion. For that reason, as recipient of this assistance, decided to conduct a study to develop a product proposal for facilitating their performance.

Most of the products that are being developed nowadays for firefighters, focus on allowing them to develop their abilities and skills to precisely perform their actions. Therefore, this study focuses on the assistance from another point of view: minimizing the required physical exertion to perform while reducing the risk of possible injuries.

Out of all the analyzed statistical studies related to the subject, the study *"United States Firefighter Injuries in 2021"* (Richard Campbell and Shelby Hall, 2022) stands out by confirming that nearly 2 of 5 injuries on the fireground are due to overexertion or strain. In addition, the results from the carried user survey to a considerable group of firefighters, showed how most of the injuries they have had consist of low back pain and knee sprains. The reason for these were situations like lifting and carrying heavy objects, in which they would have willed to have an external help from some type of product.

Consequently, this project has focused on providing a solution for this exact situation. It recognizes health and safety issues at work and deals with them to minimize the degree of risk. In other words, it allows firefighters continue functioning on the same level they are required to, while minorizing or even eliminating the probability of harming themselves when realizing this type of movements.

Several medical studies have been analyzed and confirm that the knees and lower back are closely interconnected, and their problems are affected within each other.

In addition, promoting the movement in the knees when lifting a load will help reduce low back pain especially if the cause of it is poor posture, incorrect lifting technique and lack of strength on the joints and muscles. In relation to the arms, by increasing the movement in them, some of the stress can be transferred to the arm muscles and reduce the load on the spine and lower back. For that reason, enhancing the movement in these extremities while maintaining a correct back posture, will help develop the movement and reduce their possible injury. To do so, the final product consists of an exoskeleton that maintains a good technique and posture when bending down and lifting heavy objects while encouraging the movement in both legs and arms.

It consists of three elements of differentiated use which could be worn together or separately, depending on the user´s needs. Although, to reach the most efficient functionality and serve as the main aid for our user´s problem, the three should be used altogether.

The first component consists of the Lumbar and Back Protector. It protects the entire lumbar area as well as the back, slightly forcing the user to maintain a correct straight posture. Due to the combination of the materials, its adaptability to the user and the comfort provided, the firefighter will be able to perform any movement without any difficulty while decreasing the load on the spine and reducing the risk of low back injury. In the other hand, the user´s extremities are also protected and even receive assistance to carry out the movement.

The Leg Enhancer should be attached to the legs and connected to the Lumbar and Back Protector for the greatest efficiency. By its combination of springs, the mechanical mechanism enhances the driving torque on the knee when lifting the object, reducing the physical effort required from the user, and consequently, reducing its probability of injury.

Likewise, the Arm Enhancer should be attached to the arms and by a similar mechanism it will provide a driving torque on the arms that will help the user lift the object. Because of the execution of a series of simulations with the Open Modelica software, it has been confirmed that due to the use of the three elements, the user will require approximately a 55% less effort for performing its movement.

Additionally, based on the research carried out with the fire department and the functional, structural and usability analyses, a series of requirements have been detected and applied to the final product.

The design consists of a combination of materials which are resistant to the environment and at the same time suitable for the operation and interaction with the user. They allow its attachment and adaptation to the user´s body, as well as being easily carried due to its lightweight. Furthermore, it does not require an external help to be worn and due to its reduced size, it could be worn under or on top of the PPE. It should be noted that the various yellow details, which contrast with the rest of the materials, help the user to identify them quickly so as not to require an extensive time and allow the firefighter to operate immediately.

Different programs, such as Solid Works and Blender, have made it possible to obtain a realistic visualization of the product on its own as well as in context situations for a better understanding. In addition, a 3D printed prototype has been made to confirm that both the design and mechanism selected were the adequate ones.

As a final observation, due to the design of the independent exoskeleton components, its use could be diversified to different groups in the industry such as production or medical care. Overall, it may be said that this product could actually make a difference on the user´s health and performance and could be further developed in the future.

9 LIST OF FIGURES

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