

## **REALISTIC COMPUTER AIDED DESIGN MODEL OF AN EXOSKELETON**

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## Abstract

The musculoskeletal disorders have significant health care, social and economic consequences in the factories nowadays. One of the most promising possible solutions is the use of exoskeletons in the workstations. Exoskeletons are assistive wearable robotics connected to the body of a person, which aims to give mechanical power or mobility to the user (Wang, Ikuma, Hondzinski, & de Queiroz, 2017).

The objective of this project is to create a realistic CAD model of a passive exoskeleton which will be used in future research to analyse the behaviour of the workers in a virtual environment with and without the exoskeleton. This model will be a virtual representation of the exoskeleton EKSOVest which has been designed to support these workers who have to realize overhead tasks. This virtual representation will be carried out in PTC CREO and exported to IPS IMMA in order to check the viability of this model. To achieve a realistic model, the exoskeleton should have the same characteristics than the real exoskeleton. The objectives of this project will be defined for these characteristics, which are part creation, mechanisms, forces simulation, and parametrization. The parts and the mechanisms will be created and defined in PTC CREO with the same dimensions and behaviour as the real exoskeleton. Furthermore, this report will be focussed mainly in force simulation and the parametrization.

The forces of the EKSOVest are generated by two different spring and by a high-pressure spring. To simulate these forces, the equation of these springs will be obtained and introduced in PTC CREO. These equations will be obtained through the regression of a set of points, which will be obtained from the real exoskeleton using a dynamometer. The parametrization will be carried out with the objective to make the virtual model adaptable for every type of mannequins. This parametrization will modify the length of the exoskeleton's spine bar and the distance between the mechanical arms. These distances will be adapted according to the mannequin's measures which will be introduced by the user. The measures that have to be introduced by the user are shoulder height, liac spine height, and chest width.

In conclusion, it can be said that the regression of the springs obtained are an accurate result which can imitate quite well the forces of this exoskeleton. Furthermore, the results of the parametrization allow the exoskeleton adaptable to any type of dimensions that the mannequin could have. The final model obtained has been exported to IPS IMMA and implemented in a mannequin.

**Keywords:** EKSOVest, PTC CREO, Exoskeleton, Parametrization, High-pressure spring, Musculoskeletal disorder.

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Skövde, May 2019

David Hoyos Rodríguez

## Certificate of Authenticity

Submitted by David Hoyos Rodriguez to the University of Skövde as a master's degree Thesis at the School of Engineering Science.

I certify that all material in this Master Thesis Project which is not my own work has been properly referenced.

Signature.



Student Name

David Hoyos Rodriguez

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## Terminology

### C

CAD  
Computer Aided Design ..... i

### G

GBD  
Global Burden of Disease ..... i

### H

HTO  
Human-Technology-Organization ..... i

### M

MSDs  
Musculoskeletal disorders .....i

### V

VR  
Virtual Reality.....i

### W

WMSD  
Work related musculoskeletal disorder .....i

### Y

YLDs  
Years lived with disability.....i

# 1 Introduction

## 1.1 Background

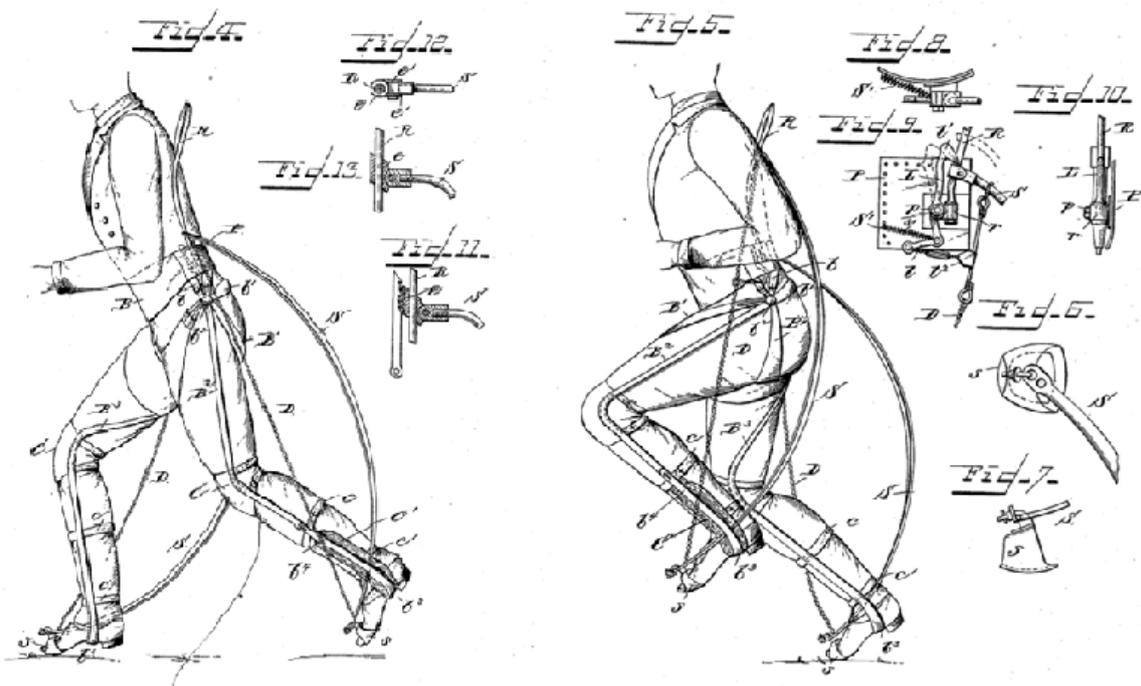
Companies have improved over the years, due to the changes in society and technologies. It is clear that the requirements to survive in the market for the companies are not the same as before. The beginning of the current industrialization that we know today goes back hundreds of years ago. In 1800 Eli Whitney was a pathfinder implementing the interchangeable parts to assemble muskets which allowed an easier, faster and cheaper repair of the broken parts (HISTORY, 2019).

In the 19th century, the industrial revolution took place, which introduced standardization and mass production (Bellgran & Säfsten, 2010). The inventor of the modern line systems was Henry Ford (Hellman & Liu, 2013). Ford implemented the assembly lines, dividing the process in a series of workstations, each of them with different work. The main objective of mass production was the cost reduction by increasing the number of finished products. These advances, mass production, and assembly line inserted the collaboration between automation and manual labour. During 1960, this collaboration created in the UK interest for work satisfaction (Waterson & Eason, 2009). Several studies have demonstrated that the productivity, occupational health, safety and satisfaction of the workers can become better with the application ergonomics or human factors (Shikdar & Sawaqed, 2003). The repetitiveness of tasks in the industry increased labour dissatisfaction, which fostered a bad work environment. From here, a new perspective in ergonomics emerged, which focuses on the relationships between people, technology and organizations. These relationships are described by the human-technology-organization (HTO) concept (Karlton, Karlton, Berglund, & Eklund, 2017).

One of the most important problems for the production industry is that workers have to take sick leave because they have to recover from a physical disability that affects them to move and handle loading. This is called work-related musculoskeletal disorder (Berlin and Adams, 2017). However, WMSD does not occur just for handle loading, it can be also a consequence of high task repetition and awkward postures during work tasks (da Costa & Vieira, 2009; Mohd Fazi, B Nik Mohamed, & Bin Basri, 2019). The automotive sector is one of the industries most affected by the incidence of MSD. Several solutions have been tried to solve this condition in the automotive sector. One of these solutions is the vehicle rotation angle, which could allow to getting a variety of car postures during the assembly process (Ferguson et al., 2011). But one of the most promising possible solutions is the use of exoskeletons, which are providing a realistic power enhancement for soldiers, firefighters, emergency

personnel, and industrial workers increasing their physical potential and helping them and lifting heavy loads (Dellon & Matsuoka, 2007).

Exoskeletons are assistive wearable robotics connected to the body of a person, which aims to give mechanical power or mobility to the user (Wang et al., 2017). The invention of the exoskeletons is credited to the Russian Nicholas Yagn (1890) who designed, what he called “Apparatus for facilitating walking, running and jumping”, whose main objective was to reduce user fatigue (United States Patent No. US420179A, 1890). This invention can be appreciated in Figure 1.



**Figure 1.-"Apparatus for walking, running and jumping". Image obtained from US420179A (1890)**

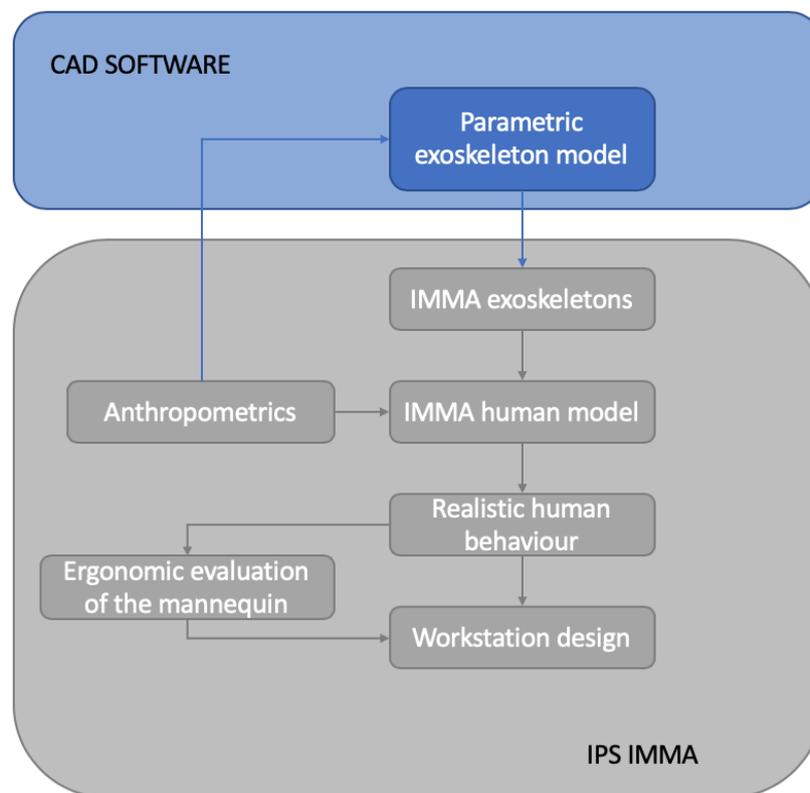
Exoskeletons are starting to be implemented now in industrial usage. Some of the automotive companies that are currently using exoskeletons in their assembly lines are Ford, Volkswagen or BMW.

## 1.2 Problem description and aims

The musculoskeletal disorders have significant health care, social and economic consequences in the factories nowadays, especially car manufacturing. They are due to work conditions. To avoid it, Volvo Cars is studying the possibility to implement an exoskeleton in these workstations where the workers have to work overhead. For this, Volvo Cars bought three different exoskeletons, which will be studied to know which exoskeleton is more beneficial for the workers. This research has been divided into

three different projects. The three of them will be focused on the analysis of the exoskeleton and their advantages and disadvantages for the workers. However, each study will be performed from different perspectives and with different objectives. While the other two studies will have as a target, the workers and their interactions with the exoskeletons, this project will be focussed in the creation of a virtual model of the exoskeleton, which will be used to evaluate the exoskeleton's effects in the virtual world.

In order to analyse the effects of the exoskeletons in the virtual world, it will be necessary to carry out the steps showed in Figure 2. This project will be mainly focussed in the CAD software, which will use anthropometrics aspects for the design of the exoskeleton. In addition, this CAD model will permit to bring the knowledge of the most important exoskeletons' aspects that should be taken into account for the ergonomics analysis in the virtual world.



**Figure 2.- Flowchart for ergonomics analysis of exoskeletons in IPS IMMA.**

This project is closely linked to the fourth industrial revolution, which is currently being developed, in this industrial revolution (Industry 4.0) the real and virtual worlds are growing together (Schluse, Priggemeyer, Atorf, & Rossmann, 2018). In the Industry 4.0 is when the term digital twins appear, and this will be the objective of this project and of those that will be carried out from it.

The aim of this project is to create a realistic parametrized Computer aided design (CAD) model of an exoskeleton. Once this model has been created, it will be used in a virtual mannequin to simulate the workers' task. This virtual model will have the objective to identify the benefits of the exoskeletons in the workers without its implementation in the real factory. In order to achieve this, the virtual exoskeleton model must have the same characteristics as the real one. These characteristics are related to the behaviour and physical restrictions of the real exoskeleton. According to this, it can be said that the objectives of this project are the simulation of the following characteristics:

- The exoskeleton's shape (measures and dimensions).
- Exoskeleton's mechanisms (fixings, joints, and springs), including the degree of freedom in each of them and the rotational angle of the joints.
- Forces created by the exoskeleton, which should be transmitted to the virtual mannequin as the real one does with a worker.
- Parametrization of the model, making it adaptable for different mannequin measurements.

Basically, the main objectives are to create a virtual model of a real artefact, which should have the same behaviour (mechanism and forces), this means to measure by doing experiments, the characteristics of the springs in the exoskeleton and represent them in virtual correspondence.

### 1.3 Research methodology

To realize the research of this project, the main research question will be presented from which other sub-questions will be raised in order to get a deeper knowledge of the field. The main question is:

How to create a realistic Computer aided design model of a passive exoskeleton?

Realistic will mean to imitate as much as possible the behaviour of the real exoskeleton. The important aspects for the simulation are the dimensions of the links, the grade of freedom and range of motion in each joint and the force created for the mechanisms. The solution to this main question will bring the knowledge to perform the project, but still, it is a broad question that can be divided into several sub-questions, in order to perform the research. These sub-questions are:

1.-How to create this model?

2.-How and what mechanisms are necessary to create this model?

3.-How to measure and simulate the forces of the exoskeleton?

4.-How to parametrize the exoskeleton's dimensions?

The first question is related to the program that will be used for the creation of this model. For the creation of this model, there are different programs that can be used for the creation of a CAD model. However, there are just two programs which permit both, direct modelling and parametric modelling in a single platform. These programs are PTC CREO and Siemens NX. Both programs are suitable for the realization of this project and both programs have their advantages and disadvantages. In order to choose one of them, the integrations will be compared. The integration is the most important characteristic for the realization of this project since the CAD model will be created with the objective to be exported to other software. Both programs allow a good integration, Siemens NX use file format translators to share the data and although it has an intuitive import and export menu function, it was decided to use PTC CREO, this is due PTC CREO permit to open files without any translations from several types of platforms reducing the time-consuming process of the file translation ("Siemens NX vs. Creo," 2018).

The second question is related to the behaviour of the exoskeleton and with PTC CREO. This is because the representation and creation of the mechanisms will depend on the program that is being used. The third question is related to the mechanisms and with PTC CREO because, before the forces are measured, it is necessary to know the characteristics that the program will need to represent it. Once the characteristics are known, the measuring process can be performed. The last question is related to the dimensions that can be modified in the model to adapt it for different mannequins.

## 2 Frame of Reference

### 2.1 Research strategy and data collection techniques

It can be affirmed that the best research methodology for this project is Design and creation since this strategy is focused on the creation of IT products or artefact. To perform this project, the creation of a CAD model (the artefact) will be necessary to simulate the behaviour of the real exoskeleton. Compared to other strategies, this is the one that fits best for this problem. While the other strategies focus on the study of different cases or nature to create knowledge, design and creation is a strategy where the IT artefact or model is itself the principal knowledge contribution.

For this project, the artefact or virtual correspondence of a real exoskeleton will itself be a contribution of knowledge, since this model could be used in future researches. These researches could implement the virtual exoskeleton to a mannequin and simulate the behaviour of a worker with and without the exoskeleton in a virtual environment. These results could be implemented in the real world, later on, saving money in comparison with the direct implementation of the exoskeletons in a real factory.

The data collection techniques chosen for this project are documents, interviews, and observation. Documents data collection technique will be the main technique used to perform this project, the documentation technique will be realized through papers, books and manuals. The most useful information from these documents will be used to learn the method that should be implemented and to learn how to use the different programs required for this task.

Interviews will give information to problems with the program that could not be solved with the manuals. The principal interviewer will be my supervisor Aitor Iriondo, who has been working with this program before. In this case, the information will be obtained from experts, which will give faster and more precise information than the previous technique.

Observation and experiments will be used for the method, once the process of the project has been defined with the previous techniques, observation and experiments will be used to collect the different measures and forces created for the real exoskeleton. These measures will be introduced in the virtual model later on. These are the most important techniques for this project since the data has to be as accurate as possible.

## 2.2 Ergonomics

According to Shikdar & Sawaqed (2003) “Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance.”

Ergonomics is a broad term and can signify anything from the requirements of the work and the physical activities, how the mind of the persons comprehend the instructions and interfaces, to how different factors as teamwork, motivation or how the organizations have repercussions in the human’s welfare and efficiency. In addition, it may include aging or working in an extreme environment. Basically, anything related to human activity can be approached from an ergonomic point of view (Berlin and Adams, 2017).

An engineer educated and trained to identify the aspect of the humans' welfare and system performance in cohesion with his work can make a workspace which is more efficient, social and economical. In other words, the engineers with knowledge in ergonomics can have a very positive impact on companies in the long term, since this knowledge will result in changes in the system that avoid risks in the safety of workers ( Berlin and Adams, 2017).

There are different domains within ergonomics that have different competencies depending on specific human attributes or human interaction (IEA, 2000). These domains are the following:

- Physical ergonomics: It is related to the anatomical, anthropometric, physiological and biomechanical characteristics of the human being with regard to physical activity.
- Cognitive ergonomics: It is related to mental processes (memory, perception, reasoning...) since they affect the interaction between humans and other elements.
- Organizational ergonomic: It is related to the development of sociotechnical systems including structures, policies, and processes.

## 2.3 Musculoskeletal disorders

Musculoskeletal disorders (MSDs) are injuries and disorders that associate with nerves, tendons, muscles, and structures that support the body (U.S. Department of Health and Human Services, 1997). The appearance of MSDs is due to the influence of risk factors, which begin to fatigue the worker’s body. Once the fatigue exceeds the capacity of the body’s recovery, musculoskeletal imbalances begin

to appear. With time, a musculoskeletal imbalance develops into MSD (The Definition and Causes of Musculoskeletal Disorders, 2015). There are three workplace ergonomic risk factors:

- High task repetition: Often many jobs are defined by production goals per hour, day and work processes which make them repetitive. High repetition of work together with other factors (force or posture) can create MSDs. If a work cycle is 30 seconds or less, it is considered highly repetitive.
- Forceful exertions: The excess of force load in some work tasks increases the muscle effort which causes fatigue, leading to MSDs.
- Uncomfortable repetitive or sustained postures: The uncomfortable posture applies an excessive force on the joints and overburdens the muscles and tendons around these joints. The joints work more efficiently if they operate near to the mid-range motion of the joints. The risk of MSDs increases when the joints work out of this mid-range in a repetitive way and without enough recovery time.

The MSDs implied a reduction of a worker's ability to perform their job or any activities due to pains, dexterity, restrictions in mobility, and reduction in functional capacity. The most frequent MSDs are lesions, systemic inflammatory conditions, back, and neck pain and fractures related to bone fragility (World Health Organization, 2019).

According to a study performed by the Global Burden of Disease (GBD), the main causes of MSDs are the low back pain and neck pain. In this study (Vos et al., 2016), the MSDs were the second largest contributor to global disability. Since it was first measured in 1990, low back pain continues being the main cause of disability.

## 2.4 Digital Twins

According to Schluse, Priggemeyer, Atorf, & Rossmann (2018) "Digital twins represent real objects or subjects with their data, functions, and communication capabilities in the digital world." Digital twins can be used for the visualization and verification of results in a virtual environment (Qi & Tao, 2018). In addition, digital twins are also considered the future for the optimization and simulation since it lets one examine different situations that could be presented in the lifecycle of a product without the cost of the real tests (Rosen, von Wichert, Lo, & Bettenhausen, 2015).

## 2.5 Exoskeletons

According to Looze et al. (2016) exoskeleton can be defined as “wearable, external mechanical structure “ whose objective is to reinforce or restore the physical performance of the person. The exoskeletons are placed on the user’s body and can be classified into two categories:

- **Passive:** This kind of exoskeleton does not use any type of electrical power source. On the other hand, these are constituted with mechanisms as springs, dampers or high-pressure springs. It can be used for weight re-distribution or energy capture to support the users with the posture or motion.
- **Active:** unlike passive exoskeletons, active exoskeletons do use some type of actuator which increases human power. This actuator can be an electric motor, pneumatic muscles or hydraulic power (Gopura & Kiguchi, 2009).

Depending on what body part are the exoskeletons supporting, de Looze et al. (2016) and Wang et al. (2017) classify it in three different categories, lower body exoskeletons which give power or support the lower extremities (legs), upper body exoskeletons which give power or support the upper extremities (back, arms or shoulders) and full-body exoskeletons which give power or support both lower and upper extremities.

In addition, depending on the exoskeletons’ purpose they can be classified into three main fields which are rehabilitation, military and industry. The rehabilitation field is one of the oldest fields in exoskeleton development, the exoskeletons for this field can be defined as wearable robotics used to assist the patient in the rehabilitation. The objective of these exoskeletons is to make the recovery of movement easier and faster. The principal objectives of the military exoskeletons are to be comfortable to wear for hours and adapt to the current military’s standards and equipment. The military exoskeletons should help the soldiers by decreasing fatigue and the possibility to suffer MSDs during their tasks. The industrial exoskeletons are the fastest evolving field of exoskeletons. The principal benefits of these exoskeletons are the reduction of injuries at the workplace, saving money to the companies, and an increase in work quality and productivity. The objective of the industrial exoskeletons is to help and support the workers in their tasks by reducing worker fatigue and correcting their posture (Lorenza, 2018).

## 2.6 Computer Aided Design

Computer Aided Design (CAD) is a computer tool to design a product and to record the design process. This tool facilitates the work process and is used to create two-dimensional or three-dimensional diagrams that can be rotated to be viewed from different perspectives. CAD is used to create engineering designs of physical components, assemblies, manufacturing dynamic analyses and to create environmental effect reports.

Kimura, Kawabe, Sata, & Hosaka (1984) pointed out that a CAD model should represent all the information about the product, which will be used for the manufacturing process. This information has to be organized and represented in the CAD software.

Farjana & Han (2018), defined CAD as “parametric and history-based feature modelling systems which uses a parametric model definition of the CAD object with a boundary representation (b-rep) model of the final shape”. The part models are made in the feature-based design. The feature-based parametric modelling normally creates models by a history of modelling steps. These steps store the parameters and process. It preserves the measures and the object designed.

The models can be translated from one CAD system to another CAD system. According to Farjana & Han (2018), there are two types of CAD model translation, direct translation, and translation based on XML format. The direct translation can lose some information such as the product creation or history of modifications. While the translation based on the XML format (Macro-parametric) permits to share the information comprising of the product creation and modification history.

## 3 Literature review

A literature review was carried out in order to get the necessary knowledge for the realization of this project. First of all, the literature review will be focussed in the MSDs and its influence on the workers (especially the automobile sector). Afterward, the literature review will be focused on exoskeletons and how they could be beneficial for the workers. And finally, the last search object will be CAD and simulations, and how the CAD software can be used with other software.

### 3.1 Musculoskeletal disorders

The industry sector is evolving more and more over the years and with it, the awareness and implementation of ergonomics in the workplace. But still, the prevalence of MSD has not decreased (Lotz, Agnew, Godwin, & Stevenson, 2009). According to Vos et al. (2016), pain in the lower back, major depressive disorder, migraine, anaemia, and hearing loss are the main causes of years lived with disability (YLDs) worldwide. The study performed for Eurofound (Paoli, 2012) showed that the principal health problems related to work in the European Union are back pain, stress and muscular pains in arms or legs. As it can be appreciated in Figure 3, 30% of the workers declare to suffer backache and 17% suffer muscular pains.

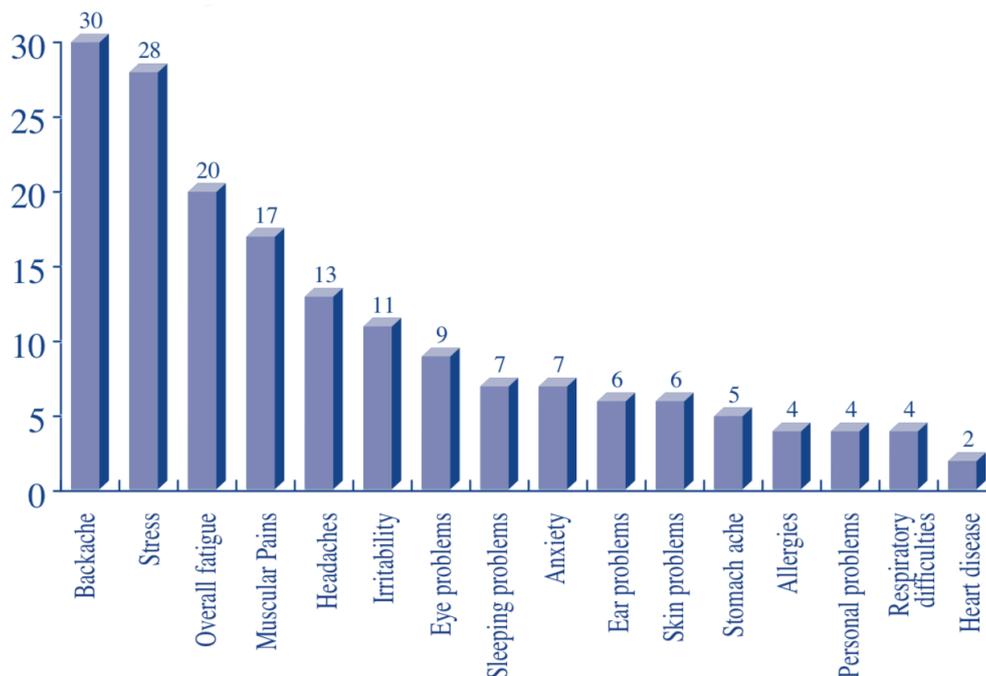


Figure 3.- Percentage of problems related to work in European Union. Image obtained from Eurofound (Paoli,2012)

The total cost of back pain in Netherland to Dutch society was €3.5 billion in 2007 (Lambeek et al., 2011). It is clear that MSDs have an important impact on the cost of society, especially low back pain. The main sectors that influence the development of a country are the manufacturing sectors. The automobile manufacturing industry is a global industry with high competitiveness, that contributes a large amount of income to the country (Mohd Fazi et al., 2019). The physical load in an assembly line has an important impact in the economy of automobile factory as it was demonstrated by Falck, Örtengren, & Högberg (2010), who proved that a high and medium physical load assembly have 8.7 times and 8.2 times higher cost respectively than a low physical load assembly.

### 3.1.1 Work related musculoskeletal disorders

The most common identified risks factor that can produce work related musculoskeletal disorders (WMSDs) are high task repetition, forceful exertions and awkward postures (da Costa & Vieira, 2009; Mohd Fazi et al., 2019).

The study performed by Aziz, Ghazalli, Mohamed & Isfar (2017) identified a serious WMSDs correlated with the team members of an automotive production assembly. This study demonstrated that the workers of this assembly plant had a very high risk of WMSD in the worker's neck, in the back and in the shoulder/worker's arm. The overhead workers are very likely to suffer MSDs since, in the long term, these postures cause tension and fatigue in the shoulder muscles (Shin, Yoo, & Kim, 2012).

The study carried out by Anita, Yazdani, Hayati, & Adon (2014) wanted to find a correlation between the MSDs and the tasks performed in an automotive assembly line in Malaysia. The results showed that 78.4% of the workers suffer MSD. The different MSDs suffered by these workers is shown in Table 1.

**Table 1.- MSDs according to the body region.**

Lower Back	Shoulder	Wrist/Hand	Neck	Upper back	knee	Ankle/Feet	Hip/Thigh	Elbow
50.9%	37.9%	34.1%	32.2%	31%	25.4%	24.1%	16.4%	9.1%

To solve the problem of the MSDs, Rashedi, Kim, Nussbaum, & Agnew (2014) tested a wearable assistive device for overhead work. The study showed that the device reduces physical demands for upper arms and shoulders.

## 3.2 Exoskeletons

Koopman, Kingma, Faber, de Looze, & van Dieën (2019) wanted to test a passive exoskeleton as a possible solution to reduce the risk of low back pain. For this task, five different heights of hands in a static bending were performed. The research found important reductions in back muscle activity using an exoskeleton.

In order to test the exoskeletons as a solution to reduce the risk of suffering low back pain in stressful jobs, Bosch, van Eck, Knitel, & de Looze (2016) studied the presence of a passive exoskeleton on muscle activity, persistence time and discomfort in work that required a forward bending. The results showed that the exoskeleton tested (Laevo) made a reduction in the internal muscular forces and spinal forces for the lumbar region. A similar study was performed for Huysamen et al. (2018), who focused on static overhead tasks instead of forwarding bending. This research found a significant reduction on arms muscle activity lifting up 2kg, but no significant improved were found on trunk or leg muscle activity.

The functional behaviour of the exoskeletons in different tasks related to work was tested by Baltrusch, van Dieën, van Bennekom, & Houdijk (2018). In this study, 12 tasks were carried out for 18 healthy men wearing a passive trunk exoskeleton. The results showed that the exoskeleton decreased the back pain and the dorsal side of the upper legs for static tasks. Otherwise, the discomfort increased for these tasks that require dynamic movements such as walking or hip flexion.

With the objective to test the effect of a passive exoskeleton in a workplace, Dahmen & Hefferle (2018) simulated a workplace and compared the effects with and without exoskeleton with different ergonomic assessment methods. The results showed improvements with the exoskeleton in all the ergonomic assessment methods.

In order to check the possible implementation of the exoskeletons in the automotive industry, the ABLE exoskeleton (Sylla, Bonnet, Colledani, & Fraisse. 2014) and Levitate exoskeleton (Spada, Ghibaud, Gilotta, Gastaldi, & Cavatorta. 2017) were tested. The results obtained in both researches show an improvement in the performance in the workers and a lesser perception of fatigue.

### 3.2.1 EKS0 Vest

EKS0 Vest is a passive upper body exoskeleton designed for those tasks that require an arm lift. The exoskeleton is attached to the lower back, the chest and the upper arm with the objective to transfer

the load from the arms to the frame on the back (Wesslén, 2018). The EKSO Vest exoskeleton is shown in Figure 4.



**Figure 4.- Exoskeleton EKSO Vest. Image obtained from “EksoVest - Upper Body Exoskeleton Supports Endurance,” (2019)**

Kim et al. (2018) studied the influence of EKSO Vest during simulated repetitive drilling overhead, concluding the lack of discomfort between the participant and perceiving a reduction in shoulder muscle activity. Otherwise, a second study was performed by Kim, et al. (2018) in order to find some unexpected worker safety challenges. In this study, a reduction in the maximum shoulder abduction range of motion has been found, however, it concluded that the use of this exoskeleton can be beneficial for this type of tasks.

### **3.3 Simulation of Exoskeletons**

Copilusi, Ceccarelli, Dumitru, & Carbone (2014) and Şahin et al. (2014) performed the design and simulation of two different lower active exoskeletons. To carry out this task, they created a CAD model

of the exoskeleton and a kinematic study of the exoskeleton, after which Şahin et al. (2014) executed the design of the electro-hydraulic system, while Copilusi, Ceccarelli, Dumitru, & Carbone (2014) simulated it into MSC.ADAMS environment. According to their conclusion, both achieved the result desired.

Karvouniari, Michalos, Dimitropoulos, & Makris (2018) proposed a set of method for the implementation of exoskeletons in the production lines through the utilization of Virtual reality (VR). The adjustment and validation of the exoskeleton are done through the visualization of the prototypes. The implementation of the exoskeletons in virtual reality will allow its testing in multiple scenarios which cannot be provided without the same.

Singh, Singla, & Virk (n.d.) proposed a passive exoskeleton for rehabilitation constituted by four bars. The simulation of this exoskeleton was performed designing the different parts of the mechanisms in CAD software (PTC CREO) and controlling it through SimMechanics toolbox in Matlab environment. The parts created in PTC CREO had to be exported to an XML file with the objective to introduce these parts into SimMechanics. The result showed a dynamic analysis of this passive exoskeleton, where the final objective was to obtain the velocity of each joint.

## 4 Method

The method for this project will have the objective to collect all the information needed for the creation of the exoskeleton CAD model, with the objective to use all this information in future research for ergonomics analysis in IPS IMMA. By doing experiments, all the necessary data (input requirements) to import the exoskeleton into IPS IMMA will be collected. Nonetheless, it will be impossible to import the exoskeleton model into IPS IMMA without the data lost. To make it possible, it is necessary to have an interface between PTC CREO and IPS IMMA, which is being developed right now.

Springs in CAD are not innovative, however, understanding how exoskeletons deliver forces is necessary to build an interface between CAD software and IPS IMMA, since IMMA exoskeleton models are built based on anthropometric formulas and force functions. Same interfacing is necessary for sizes, that is why parametrization is applied as a formula related to human sizes for the use of ergonomists.

This leads to a creation of an artefact by the means of Design and Creation methodology, which consists on a method for design based on anthropometrics and an instantiation of a parametrized CAD exoskeleton model.

The experiments performed for the data collection will be constituted for all the steps used for the creation of this CAD model. Those steps are parts creation, assembly and mechanisms, forces simulation and parametrization. These steps are represented in Figure 5. This report will be focused mainly on the simulation of the forces and the parametrization since these steps can be considered the most important for obtaining a realistic model. All these steps should be realized in order since if one of them is not performed properly, the rest of them should be carried out again.



**Figure 5.- Steps performed in the method.**

The method and the experiments that should be carried out for the collection data will depend on the exoskeleton that is going to be modelled. These experiments and data collected will depend on the dimensions and mechanisms of each exoskeleton.

## 4.1 Parts creation

All the parts created for this model are shown in the first column of Table 2. The dimensions of the parts were obtained measuring the exoskeleton EKSO Vest through the utilization of tape measure and a measuring calliper. Once all the measures were obtained, the creation of the parts was performed using the PTC CREO.

**Table 2.-Parts, sub-assemblies and mechanisms performed in the model.**

Part Name	Sub-Assembly	Mechanism (Sub-Assembly)	Mechanism
Back_Plane	Parametrized_Back_Plate	Rigid	Default
Spine_Plane_Joint	Parametrized_Back_Plate	Rigid	
Axis_Slide_Back_Plane	Parametrized_Back_Plate	Rigid	
Lateral_Slide_Back_Plane_1	Parametrized_Back_Plate	Rigid	
Lateral_Slide_Back_Plane_2	Parametrized_Back_Plate	Rigid	
Right_Arm_Joint	Parametrized_Back_Plate	Rigid	
Left_Arm_Joint	Parametrized_Back_Plate	Rigid	
Right_Lower_Back_Bar	Right_Lower_Bar_Assembly	Rigid	Rotational
Right_Lower_Back_Joint	Right_Lower_Bar_Assembly	Rigid	Rotational
Left_Lower_Back_Bar	Left_Lower_Bar_Assembly	Rigid	
Left_Lower_Back_Joint	Left_Lower_Bar_Assembly	Rigid	Rotational
Right_Upper_Back_Bar			Rotational
Left_Upper_Back_Bar			Rotational
Shoulder_Link			Rotational
Shoulder_Link_Left			Rotational
Right_High_Pressure_Spring	Right_High_Pressure_Spring_Assem	Rigid	Rotational
Right_Arm_Plane_Support	Right_High_Pressure_Spring_Assem	Rigid	
Left_High_Pressure_Spring	Left_High_Pressure_Spring_Assem	Rigid	Rotational
Left__Arm_Plane_Support	Left_High_Pressure_Spring_Assem	Rigid	
Bar_Spine_Relations			Rigid
Pelvis_Plane	Pelvis_Assembly	Rigid	Rigid
Pelvis_Joint	Pelvis_Assembly	Rigid	

## 4.2 Assembly and mechanisms

In order to get the assembly in a structured way, it has been carried out through the utilization of sub-assemblies. The second column of Table 2 represents the names of the sub-assemblies associated with the parts which constitute it. The sub-assemblies cannot have any moving part since this could give problems in the final assembly. For this reason, all of these parts will have a rigid connection, as observed in the third column of Table 2. The last column of Table 2 describes the mechanism chosen for the connection of the parts and sub-assemblies to the main assembly. The sub-assembly Parametrized\_Back\_Plate will be described as the Default mechanism to attach the rest of the elements to it.

The rotational mechanism will permit the movement around a predetermined axis. These mechanisms have been used for the movement in the joints of the arms. In addition, these rotations have been limited with an angle. In order to create this model as similar as possible to the real exoskeleton, the angles used are the same as that of the ranges of motion in each of the joints.

## 4.3 Forces Simulation

The exoskeleton generates forces in three joints of the mechanic arm. The joints are represented in Figure 6. These forces are created by springs. There are two types of springs in this exoskeleton, torsion springs, and high-pressure spring. The behaviour of the torsion springs is represented for Equation 1. In order to represent these springs, it is necessary to find the variables of this equation for each of the springs.

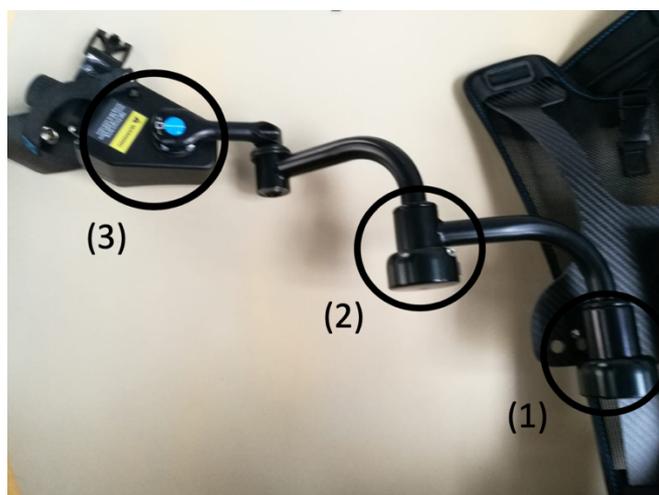


Figure 6.- EKS0 Vest arm mechanism. (1) Lower spring, (2) Upper spring and (3) High pressure spring.

$$F \cdot r = k \cdot \theta \quad [1]$$

The torque, the force ( $F$ ) multiplied by the radius ( $r$ ) will be equal to a constant of elasticity ( $k$ ) multiplied by the angle ( $\theta$ ). The objective will be to find the constant of elasticity for each spring which is the torsion stiffness that should be represented in the model.

In order to find this constant, the forces of each spring will be measured with a dynamometer. These forces will be calculated by always measuring the same distance (radius) and using different angles, which will be measured with a goniometer. The set of points obtained for the lower and upper spring are represented in Table 3.

**Table 3.- Set of points for lower and upper spring.**

Lower Spring			Upper Spring		
F (N)	r (m)	$\theta$ (deg)	F (N)	r (m)	$\theta$ (deg)
3,8	0,11	1	2,7	0,115	1
4	0,11	15	2,9	0,115	28
4,2	0,11	52	3	0,115	49
4,4	0,11	95	3,1	0,115	94
4,5	0,11	109	3,2	0,115	119
4,7	0,11	154	3,4	0,115	182
4,8	0,11	165	3,5	0,115	201

PTC Creo provides a user interface for the user to input the data for different types of springs. The type of spring that has to be introduced for this exoskeleton are torsion springs (lower and upper spring). The variables that have to be introduced to create the lower and upper spring in PTC CREO are position, orientation, spring property (torsion stiffness) and additional rotation. The position will be the joints shown in Figure 6. The orientation will be the axis of these joints. To obtain the property of the spring, it is necessary to make a linear regression with the points showed in Table 3. This regression will give the equation of a line whose slope will be the torsion stiffness of the spring. This regression has been carried out in Matlab for each of the springs with the code showed in Appendix A. The additional rotation is the initial angle in which the spring starts to make force.

To check how close the data is to the fitted regression line, the R-Squared will be calculated. This R-Squared should be higher or equal to 95% in order to get an accurate regression line.

The process for the representation of the high-pressure spring will be similar but with the difference that it will not follow a linear equation. Since the behaviour of this spring will not follow a linear equation, the spring property will be introduced as a graph. In order to achieve this, a set of point with the different position will be obtained using a dynamometer and a goniometer. These points are represented in Table 4. Once the points have been obtained, a polynomial regression will be performed with the objective to find the equation that suits better for these sets of points with the lower polynomial degree.

**Table 4.- Set of points for high pressure spring.**

F (N)	R(m)	M(N·m)	$\theta$ (deg)	$\theta$ (rad)
13	0,16	2,08	1	0,017
15	0,16	2,4	21	0,366
22	0,16	3,52	32	0,558
28	0,16	4,48	38	0,663
39	0,16	6,24	46	0,803
49	0,16	7,84	58	1,012
56	0,16	8,96	73	1,274
57	0,16	9,12	81	1,414

PTC CREO has the option to introduce advanced springs, creating a graph with a set of points. Once the equation of the high-pressure spring has been obtained, this equation will be used to get a set of points, which will be introduced in PTC CREO to create the graph with the behaviour of the high-pressure spring.

## 4.4 Parametrization

The parametrization will be the most important part of this project since this parametrization can be used later on for the interface that is being developed between PTC CREO and IPS IMMA. In order to create this parametrization, some key parameters will be used as inputs; this is due to the parametrized mannequins cannot be used as a reference for the parametrized exoskeleton 3D models.

In order to make this model adaptable for all types of mannequins with different dimensions, the key parameters have to be chosen. These key parameters will be the dimensions which will permit to adapt

the exoskeleton. These dimensions will be the length of the bar that joins the top and bottom part of EKSO Vest (Bar\_Spine\_Relations) and the distances between the two mechanical arms. The Bar\_Spine\_Relations has been chosen because this length will permit to adjust the exoskeleton to the different lengths of the back that the mannequin may have. Furthermore, the distances between the mechanical arms will permit to adapt the exoskeleton to the multiple back widths.

The parametrization of spine bar has been performed to be adjusted in the same way that the real exoskeleton does. The real exoskeleton has six number with a distance of 20 mm between them, each number can be changed, modifying the length of this bar. This bar has also two letters A and B, which can increase or decrease the length in 100 mm as shown in Figure 7. According to these dimensions, two variables have been defined. Number, which will represent the numbers in Figure 7, and A, a string variable that will have the value “Yes” or “No”. These variables will be the result and they will be shown as an output.



**Figure 7.- Extendable back bar.**

The input for the parametrization of this bar will be introduced by the user and it will be the shoulder length and the liac spine height of the mannequin. Once these dimensions have been introduced, the length of the back can be found. The length of the other elements of the exoskeleton will be subtracted from the length of the back obtained with the input data, the result obtained from this subtraction will give the dimension that the spine bar should have for this mannequin. The different solutions that this

bar can assume will be divided into several ranges, which will be a combination between the numbers (1 to 6) and the letters (A or B). The dimension that the spine bar should have will be placed between one of these ranges. Once the range has been found, the spine bar will adopt the length designed for this range and PTC CREO will show as a solution a number from 1 to 6 and a “Yes” or “No” described for this range.

The parametrization for the distance of the mechanical arms has been performed in the same way. But this time the input data will be the chest breadth. This parametrization will have three ranges, and the distance between the mechanical arms will increase or decrease 40 mm in each range. The ranges have been determined according to the percentiles of the Swedish population for the chest breadth measurement. If the chest breadth is lower than the percentile 4 % for woman, the program will show as input the first position, if the chest breadth introduced is higher than the percentile 96 % for men, the program will show the position number 3 and if it is between these percentiles, the program will show the position number 2.

## 5 Results

The results obtained for this project will be divided into three sections. The springs results, which will show the results of the regressions and the equation of each spring, the parametrization results, and the final CAD model, which will show the results of the parts creation and assembly.

### 5.1 Spring results

The results of the springs will be the graphs of the linear regression and the equation obtained for each of the springs with their respective R-Squared since it will show the reliability of the regressions obtained. The result for the high-pressure spring will be the graph of two possible solutions with their respective equation and R-Squared.

Figure 8 shows the linear regression for the lower spring with the set of points presented in Table 3. Equation 2 is the result of this linear regression, which has an R-Squared of 98.6 %. The slope of this graph is 0.035, which will be the torsion stiffness for the lower spring.

$$M = 0.035 \cdot \theta + 0.425$$

[2]

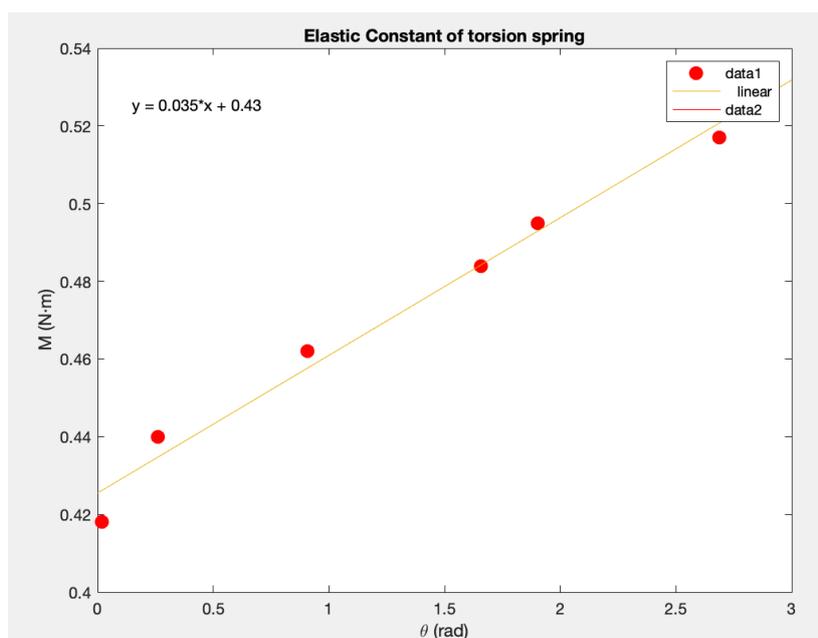


Figure 8.- Linear regression for the lower spring.

Figure 9 shows the linear regression for the upper spring with the set of points presented in Table 3. Equation 3 is the result of this linear regression, which has an R-Squared of 99.5 %. The slope of this graph is 0.022, which will be the torsion stiffness for the upper spring.

$$M = 0.022 \cdot \theta + 0.323$$

[3]

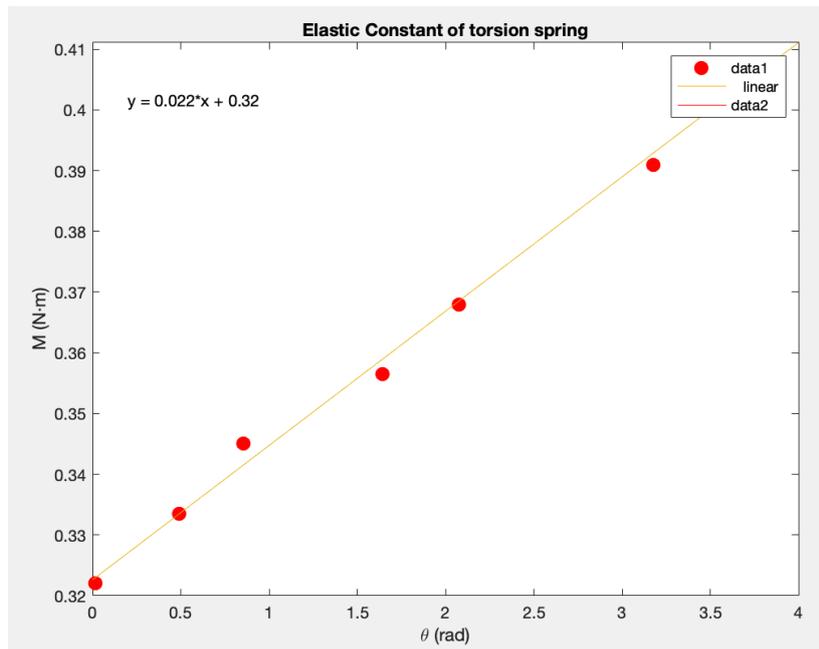
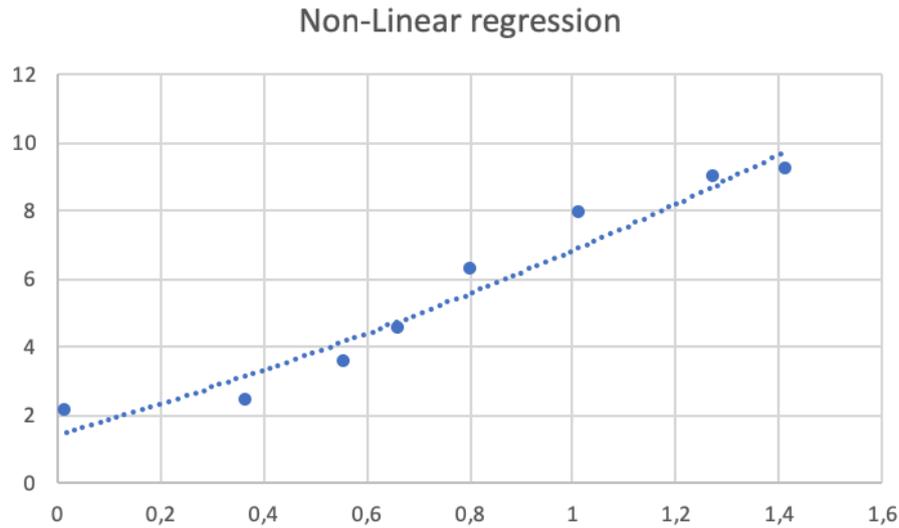


Figure 9.-Linear regression for the upper spring.

Figure 10 shows the second-grade polynomial regression for the high-pressure spring with the set of points presented in Table 4. Equation 4 is the result of this regression, which has an R-Squared of 94.6 %. In Figure 9 the axis X will represent the torque (Mm) and the axis Y will represent angle (rad).

$$M = 1.187 \cdot \theta^2 + 4.199 \cdot \theta + 1.456$$

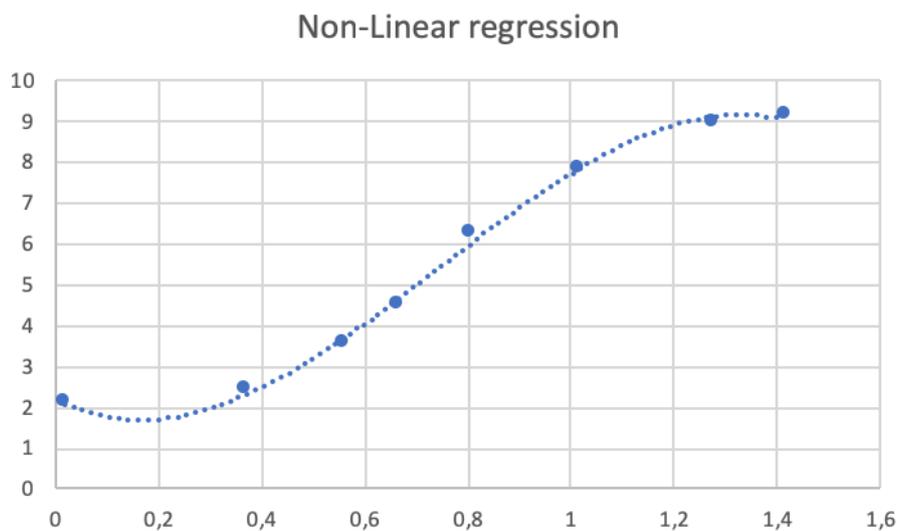
[4]



**Figure 10.- Non-linear regression for High Pressure Spring. Second grade equation.**

Figure 11 shows the third-grade polynomial regression for the high-pressure spring with the set of points presented in Table 4. Equation 5 is the result of this regression, which has an R-Squared of 99.7 %. In Figure 9 the axis X will represent the torque (Mm) and the axis Y will represent angle (rad).

$$M = -9.517 \cdot \theta^3 + 21.308 \cdot \theta^2 - 6.262 \cdot \theta + 2.191 \quad [5]$$



**Figure 11.-Non-linear regression for High Pressure Spring. Third grade equation.**

## 5.2 Parametrization

The final result of the parametrization is a dialogue box that will appear. This dialogue box will ask the user if the model is going to be parametrized. If the user introduces “y”, PTC CREO will ask for the key parameters previously mentioned in Section 4.4 and the model will be adapted automatically to these dimensions. If the user introduces “n”, the model will not do anything.

To make possible this parametrization a series of relations have been created to adapt the exoskeleton. These relations are shown in Appendix B and Appendix C. Figure 12 and Figure 13 shown different positions that the exoskeleton can perform through the parametrization.



Figure 12.- Exoskeleton CAD model. Spine bar: number 6, A Yes. Mechanical arms: Position 3.

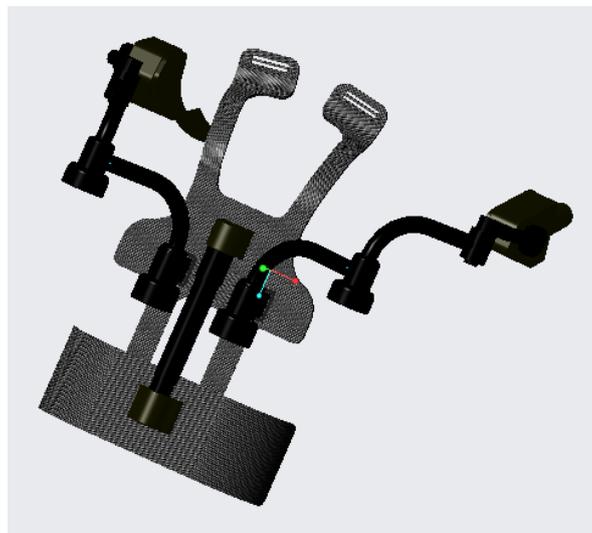


Figure 13.- Exoskeleton CAD model. Spine bar: number 1, A No. Mechanical arms: position 1.

### 5.3 Final CAD model

The result of the final CAD model is shown in Figure 14. In addition, this model has been exported to IPS IMMA. Figure 15 shows the exoskeleton implemented in a female mannequin from different perspectives. Figure 16 shows the exoskeleton implemented in a male mannequin from different perspectives.

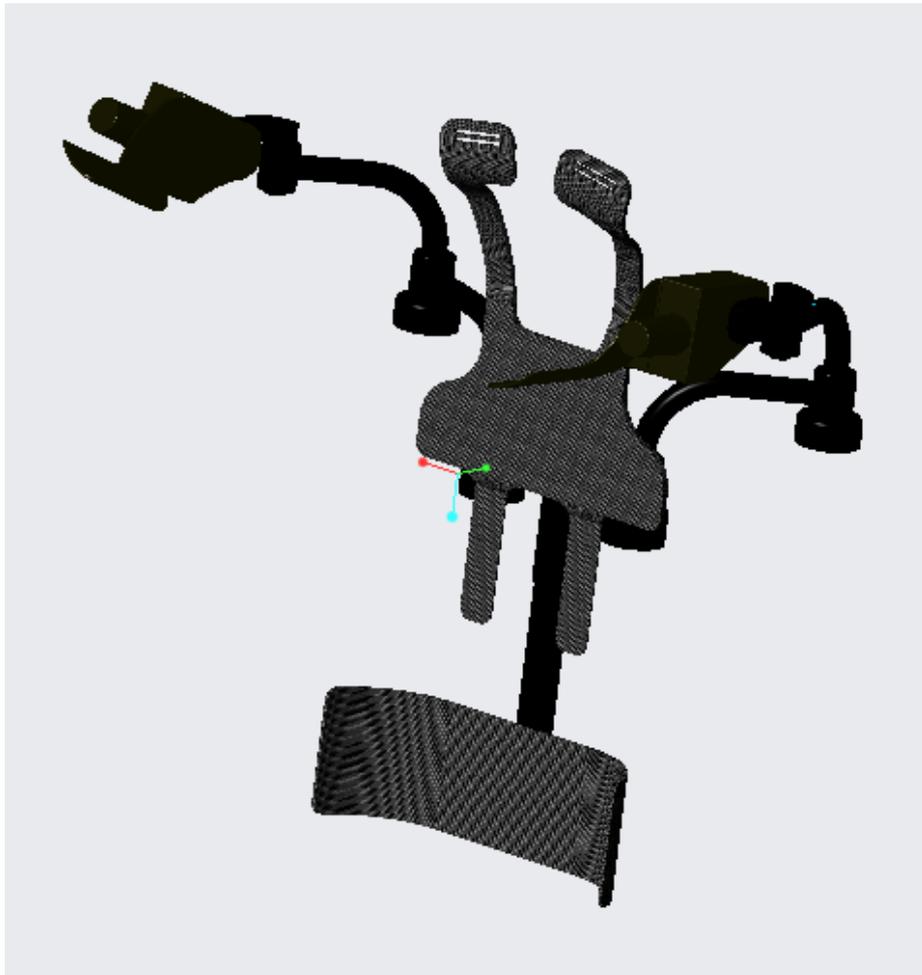


Figure 14.- Final Exoskeleton model.



Figure 15.- Exoskeleton CAD model implemented in a virtual female mannequin.

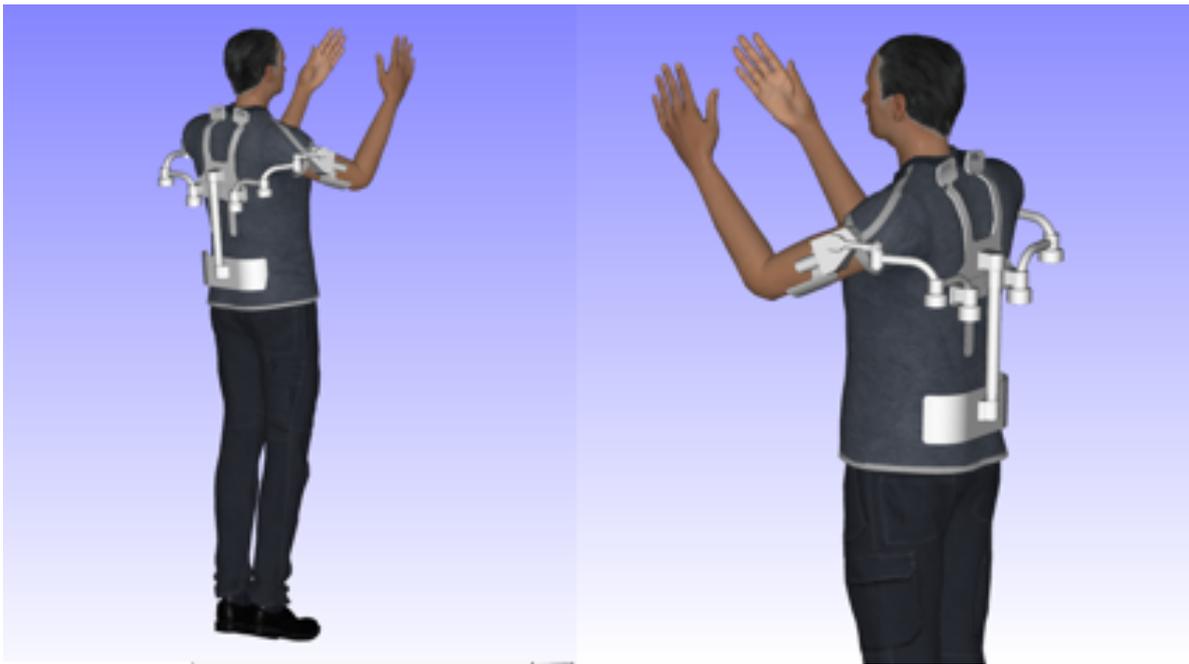


Figure 16.- Exoskeleton CAD model implemented in a virtual male mannequin.

## 6 Discussion

### 6.1 Springs

The regression performed for the lower and upper springs gave an accurate result as it can be observed in Figure 7 and Figure 8, the R-Squared obtained for these regressions are 98.6 % and 99.5%. These high percentages can prove the reliability of the equation introduced in PTC CREO. Otherwise, it has to be said that the set of points obtained to make this regression could have some errors since the sample of points contains only seven positions of these springs. In order to get a more accurate solution for the regression, a larger sample of points should be measured.

The second-grade polynomial regression performed for the high-pressure spring gave an R-Squared of 94.6%, which is close to the 95% mentioned in section 4.3, but as it can be seen in Figure 10, the equation obtained does not fit very well to the set of points obtained for the high-pressure spring. In order to get a better result a third-grade polynomial regression was performed; this regression gave a more accurate result that fit better with the set of points presented in Table 4. Equation 5, which was obtained from the third-grade regression was used to find a set of points which were used to create the behaviour of the high-pressure spring as a graph in PTC CREO. In conclusion, it can be said that this spring can simulate the behaviour of the high-pressure spring quite well since this graph was very similar to the graph showed in Figure 11.

At first instance, the Equation 5 was introduced in PTC CREO as a servo motor in order to simulate the forces of the high-pressure spring, but later on, it was changed and introduced as an advanced spring. This is due to the servo motor can reproduce the forces of the graph as shown in Figure 11, but it is according to the time instead of the angle. The springs do not move according to the time, they move according to the reaction of a force which was previously applied.

PTC CREO can represent the spring physically, but in this case, the springs are represented as a spiral line because the springs are placed in holes inside the bars. This does not, however, affect the simulation of the springs' behaviour.

### 6.2 Parametrization

There are several ways to perform the parametrization of this model, one of these ways is adapting the dimensions of each part to the dimensions of the mannequin. Otherwise, it was decided to change just

the dimensions of the spine bar and the distance between the mechanical arms. This type of parametrization has been chosen with the objective to make the CAD model as similar as possible to the real exoskeleton, without changing the dimensions of EKSOVest. Different parametrizations were performed until the final solution (Appendix B and Appendix C) was found. The previous version used the variables number and A (Mentioned in Section 4.4) as input. In this case, the user will introduce the value of the number (1 to 6) and A (Yes or No) and the model will adapt to these parameters. The main disadvantage of this parametrization is that the user will not know if the parameters introduced will be adapted properly to the mannequin.

Initially, the objective was to adapt the dimensions of the spine bar and the distance between the mechanical arms automatically to the mannequin that was imported. To make it possible, these dimensions should be related to the measurements of the mannequin. This is not possible since each time a mannequin is imported to PTC CREO, the program assigns a different name for the mannequin's measures. It is impossible to create a relation with an unknown variable. For this reason, it was decided to use different ranges, where the user will introduce the desired dimensions of the mannequin, and the exoskeleton model will adapt according to the dimensions introduced.

It can be said that the result obtained for the parametrization is quite good. It would have been better if the exoskeleton would be adapted automatically to the mannequins, but it was not possible. Otherwise, the result obtained will permit to adapt the exoskeleton to any mannequin's measure giving as output, the real number and letter that can be used for the real one.

### **6.3 Implementation of the exoskeleton model**

First of all, the exoskeleton was exported to Jack in order to test the exoskeleton in a mannequin. Different problems were found since the model lost a lot of information during this process. The first problem found is that the exoskeleton did not conserve the dimensions predefined, to solve this, the scale of the exoskeleton had to be changed in Jack. The second problem was that the exoskeleton lost all the mechanisms, which permit the movements of it. The exoskeleton model was completely rigid, which did not even make the assembly with the mannequin possible.

Subsequently, the exoskeleton was exported to IPS IMMA. Once the exoskeleton model was exported to IPS IMMA, it completely restricted the movement of the exoskeleton as well. To make the movement possible, the exoskeleton was exported part by part, with the aim to perform the assembly

again inside IPS IMMA. The resulting model of this new assembly is shown in Figure 15 and Figure 16.

The loss of information could be avoided once the interface between PTC CREO and IPS IMMA has been developed. This interface could permit to equip the exoskeleton in a mannequin into IPS IMMA, which could be used to make ergonomics analysis with exoskeletons in the virtual world.

## 7 Conclusion

In conclusion, it can be said that the final model of the exoskeleton is a good result since it can simulate the forces of the springs and it can be adapted for different mannequin's measures. Otherwise, it should be taken into consideration the loss of information in exporting the model to different programs. To correct all this loss of information, the lost details should be introduced again in the new program. The information that has to be introduced again for the exoskeleton EKSOVest can be obtained from this project. Furthermore, once the interface between IPS IMMA and PTC CREO has been developed, this information will be collected directly from PTC CREO without the loss of information.

Furthermore, the implementation of this model in mannequins simulating a real workstation could be really useful since it could help to analyse the benefits and disadvantages of the exoskeletons in the factories. The simulations of these workstations will permit to get results which could be used to improve the real factory. The implementations of the results obtained from the simulations will make companies save money in comparison with the costs associated with real implementation in the factories.

In addition, this model could be also implemented in IPS IMMA to analyse the ergonomic aspects of the exoskeletons. One example of this analysis could be the study of muscle activity in mannequins. This could be useful to test the difference between the same type of tasks with and without the exoskeleton.

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## Appendix A: Matlab code for linear regression

### Lower spring

```
x=[1 15 52 95 109 154 165]*pi/180;  
y=[3.8 4 4.2 4.4 4.5 4.7 4.8]*0.11;  
plot(x,y,'ro','markersize',8,'markerfacecolor','r')  
xlabel('\theta (rad)')  
ylabel('M (N·m)')  
title('Elastic Constant of torsion spring')  
hl=lsline;  
B1 = [ones(size(hl.XData(:))), hl.XData(:)]\hl.YData(:);  
Slope1 = B1(2)  
Intercept1 = B1(1)  
mdl=fitlm(x,y)
```

### Upper spring

```
x=[1 28 49 94 119 182 201]*pi/180;  
y=[2.8 2.9 3 3.1 3.2 3.4 3.5]*0.115;  
plot(x,y,'ro','markersize',8,'markerfacecolor','r')  
xlabel('\theta (rad)')  
ylabel('M (N·m)')  
title('Elastic Constant of torsion spring')  
hl=lsline;  
B = [ones(size(hl.XData(:))), hl.XData(:)]\hl.YData(:);  
Slope = B(2)  
Intercept = B(1)  
md=fitlm(x,y)
```

## Appendix B: Spine bar relations

```
back_lenght=shoulder_height-liac_spine_height
total_bar_dist=back_lenght-179
holes_distance=20
IF total_bar_dist<=220
  d6:28=1*holes_distance
  d12:28=1
A="No"
ENDIF
IF total_bar_dist>220 & total_bar_dist<=240
  d6:28=2*holes_distance
  d12:28=1
A="No"
ENDIF
IF total_bar_dist>240 & total_bar_dist<=260
  d6:28=3*holes_distance
  d12:28=1
A="No"
ENDIF
IF total_bar_dist>260 & total_bar_dist<=280
  d6:28=4*holes_distance
  d12:28=1
A="No"
ENDIF
IF total_bar_dist>280 & total_bar_dist<=300
  d6:28=5*holes_distance
  d12:28=1
A="No"
ENDIF
IF total_bar_dist>300 & total_bar_dist<=320
  d6:28=6*holes_distance
  d12:28=1
A="No"
ENDIF
IF total_bar_dist>320 & total_bar_dist<=340
  d6:28=2*holes_distance
  d12:28=101
A="Yes"
ENDIF
IF total_bar_dist>340 & total_bar_dist<=360
  d6:28=3*holes_distance
  d12:28=101
A="Yes"
ENDIF
IF total_bar_dist>360 & total_bar_dist<=380
  d6:28=4*holes_distance
  d12:28=101
A="Yes"
```



```
ENDIF
IF total_bar_dist>380 & total_bar_dist<=400
  d6:28=5*holes_distance
  d12:28=101
A="Yes"
ENDIF
IF total_bar_dist>400
  d6:28=6*holes_distance
  d12:28=101
A="Yes"
ENDIF
number=d6:28/holes_distance
```

## Appendix C: Mechanical arms relations

```
IF chest_breadth<178.70
back_dist=1
d3:6=1
ENDIF
IF chest_breadth>=178.70 & chest_breadth<=381.67
back_dist=2
d3:6=20
ENDIF
IF chest_breadth>381.67
back_dist=3
d3:6=40
ENDIF
```