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Experimental Design for Small-Scale Trials of Upper Limb Exoskeletons in Automotive Assembly Workstations

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Abstract

This thesis deals with the design of small-scale experimental tests for the ergonomic analysis of upper limb exoskeletons in automotive assembly workstations. The study was carried out at the Stellantis plant in Mirafiori, Turin, in collaboration with Homberger SpA and SuitX by Ottobock. The device used for the experimental tests was Ottobock's IX Shoulder Air, designed to support the upper limbs during overhead tasks.
The study began with research into the needs that led to the introduction of exoskeletons, a general overview of the current characteristics of exoskeletons on the market, and a general description of the regulatory landscape in use. After describing the device used in detail, the study moved on to an in-depth risk analysis divided into risks due to the design of the exoskeleton, risks related to the working environment, with a particular focus on the specific characteristics of the production line, and risks arising from the implementation of the exoskeleton.
After discussing the risk assessment methods adopted, the application of the Ocra Checklist in the case in question was addressed. This is followed by a detailed description of the exoskeleton implementation procedure and the evaluation methods used to interpret the results obtained, divided into subjective feedback from operators and objective parameters obtained through laboratory tests with a the Xsens Awinda system and reprocessing using Scalefit.
The results obtained from this experiment show that the device has a clearly positive and beneficial impact on the operator. The laboratory measurements, supported by the calculation of average support values and the comparison of behavior curves as a function of time of the torque acting on the scapulohumeral joint, show a decrease in the torque values acting on the scapulohumeral joint and an improvement in working conditions. However, subjective data suggest that this is not enough, as the emotional sphere, the working environment, the predisposition to change, and the choices of

working comfort of each individual operator also influence the user's relationship with the device.
This study therefore highlights, above all else, the need for adequate and meticulous personalized training for each individual operator, in order to consider every aspect of the person's physical and mental well-being.

Introduction

This study reports on my master's thesis experience, in which I worked on the design of small-scale experimental tests for the ergonomic analysis of upper limb exoskeletons in automotive assembly workstations. The study was carried out at the Stellantis plant in Mirafiori, Turin, in collaboration with Homberger SpA and SuitX by Ottobock. The device used for the experimental tests was Ottobock's IX Shoulder Air, designed to support the upper limbs during overhead tasks.
In studying the current regulatory landscape, it was concluded that there is currently no unified and binding legislation to follow either at global or European level, but rather that each country has its own guidelines, which are often voluntary. With this situation in mind, the preliminary phase consisted of a study of the regulations of various European and non-European countries in order to obtain as comprehensive an overview as possible.
The next step was my inclusion in the working group chosen by Stellantis for the experimental implementation of the device. Thanks to this opportunity, I was able to follow all the various stages of the project in collaboration with my contact person, the process ergonomists, the plant safety managers, the occupational physician, and the representative of the company supplying the device.
In addition, I had the opportunity to visit, with the guidance of an expert, the production line on which we would later introduce the exoskeleton. The assembly line chosen was the recently built Fiat 500 assembly line, which boasts a modern and cutting-edge vision of the assembly line concept itself, with its swivel hooks that can transport cars at various heights and angles in order to minimize underbody workstations as much as possible, which are problematic from a biomechanical and load-bearing point of view for operators. Thanks to the swivel hooks, there were only two stations where it was necessary to design a hypothetical exoskeleton insertion.
During my collaboration with the working group, in addition to supporting

the various members throughout the entire process, I was tasked with interacting directly with the representative from Homberger, the device supplier, who described and illustrated the characteristics of the exoskeleton to me in detail, so that I could then explain them to the other members of the group. At that point, with all the information at our disposal and the data from past experiments, we moved on to studying the implementation of the device. Thanks to the ergonomists and safety managers, we were able to draw up a comprehensive and exhaustive risk analysis together with professionals in the field, including risks related to the design of the exoskeleton, risks related to the working environment, and risks arising from the implementation of the exoskeleton itself.
Once I had decided on the various steps of the implementation procedure, we moved on to training the line personnel involved and conducting actual tests on the production line. It was particularly significant that, despite the fact that testing with the exoskeleton involved time for putting on, adjusting, and then removing the device, the line was never slowed down or, worse still, stopped due to the unusual situation we were creating, maintaining an average production of 180 cars per shift. In addition to the tests on the production line, tests were carried out in the plant's ErgoLab laboratory, with the aid of Xsens Awinda sensors and subsequent data processing using ScaleFit Industrial Athlete, in order to obtain as complete a picture as possible of the interactions of the exoskeleton.
Two types of assessment methods were used to deduce the results: subjective, through questionnaires completed by each operator involved both on the line and in the laboratory, and objective, i.e., by evaluating and analyzing the parameters collected during the ErgoLab tests with sensors. The results obtained from this experiment show that the device has a clearly positive and beneficial impact on the operator, with a consequent improvement in working conditions. This is supported by the parameters collected, such as the decrease in the torque acting on the scapulohumeral joint and the drastic increase in the time needed to reach the maximum daily cumulative dose when using the exoskeleton. On the other hand, subjective results show that the emotional sphere, the working environment, the predisposition to change, and the choices of working comfort of each individual operator can also influence the user's relationship with the device.
This thesis experience has shaped me greatly from every point of view, both academically and professionally, allowing me to participate in an innovative project in a professional working environment at the forefront of

research into ergonomic and technological solutions for improving working conditions. From this, I understood that, as a biomedical engineer, I will always have to put the person who will be affected by the device at the center of the project, so as to consider every aspect of their physical and mental well-being.

Chapter 1

State of the Art

1.1 Background

Work-related musculoskeletal disorders (WMSDs) constitute a leading cause of long-term absenteeism in industrialized nations. These disorders, that affect muscles, tendons, nerves, and joints, are frequently associated with physically repetitive tasks, sustained awkward postures, and manual handling of heavy loads. If not properly prevented, WMSDs may progress into chronic conditions, compromise workers' functional capacity, and in severe cases, lead to permanent disability [11].
A precise characterization of improper postures and movements required during work activities helps identify potential locations of WMSDs. These hazardous movements and postures can exhibit three defining characteristics: they involve joint positions that surpass 50% of the maximum range of motion, they consist of repetitive identical technical actions or action clusters performed during more than half of the work cycle duration and/or they include sustained static positions held continuously for over 50% of the cycle time [6]. When implementing these assessment parameters in practice, evaluators should use specific evaluation criteria [10]:

- Arm: Determine how long the arm is abducted at an angle greater than 45°, flexed at an angle greater than 80° or extended at an angle greater than 20°.

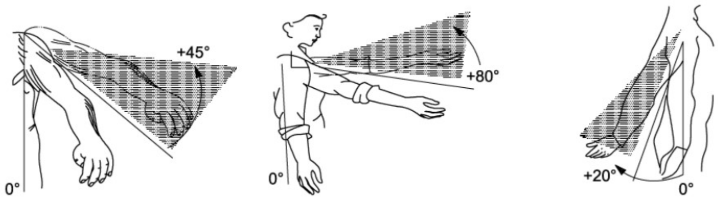


Figure 1.1. Angle Awkward Position Shoulder [10]

- Elbow: Identify whether flexion-extension or pronation-supination movements are performed at angular amplitudes exceeding 60°. The evaluation of the elbow represents an exception, as it is the movement itself, rather than the static posture, that is considered biomechanically awkward.

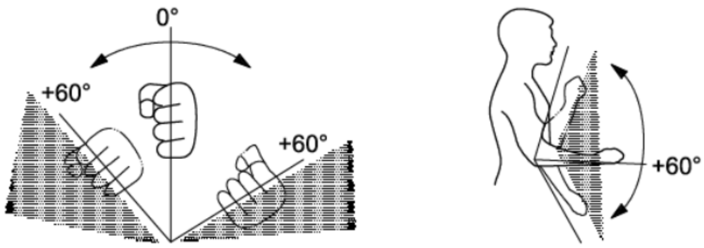


Figure 1.2. Angle Awkward Position Elbow [10]

- Wrist: Quantify the duration of non-neutral wrist postures defined as flexion or extension exceeding 45°, radial deviation greater than 15° or ulnar deviation greater than 20°.

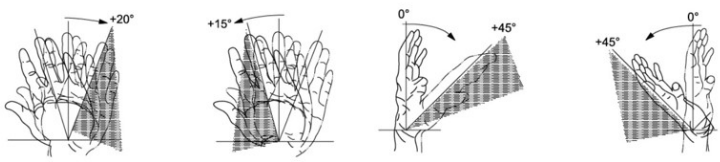


Figure 1.3. Angle Awkward Position Wrist [10]

- Hand: Determine whether a suboptimal grip type is employed, specifically: pinch grip, palmar grip or hook grip

The literature also emphasizes the importance of an ergonomic approach in eliminating or mitigating the risks associated with repetitive material handling. Ergonomics focuses on the design of work and its adaptability to human needs, as well as to physical and cognitive capabilities. An ergonomic approach considers repetitive handling tasks in their entirety, taking into account a range of relevant factors, including the nature of the task, object characteristics, the required physical effort, the working environment, and individual limitations and capabilities [8]. Regarding the object's characteristics, the load may be excessively heavy, bulky, or difficult to grasp, unstable in terms of balance, or its contents may be prone to shifting. It may also be positioned in such a way that it must be held or handled in an awkward posture or it may pose a risk of injury to the worker, particularly in the event of impact due to its external structure and/or consistency. Considering the required physical effort, it may be excessive or require a trunk-twisting motion only; it may involve a sudden movement of the load or be performed while the body is in an unstable posture. In terms of the working environment, the available space, particularly the vertical clearance, may be insufficient to carry out the required task; the floor may be uneven, unstable, or sloped, thus posing tripping hazards or being slippery. The workstation or working environment may not allow the worker to perform manual handling of loads at a safe height or in an ergonomically favorable position. Finally, temperature, humidity, or ventilation conditions may be inadequate. With respect to individual limitations,the worker may lack the physical capability to perform the task; clothing, footwear, or other personal items worn by the worker may be inappropriate, there may also be insufficient or inadequate knowledge, training, or instruction. To conclude regarding the nature of the task, there may be physical efforts that place particular strain on the spinal column, performed too frequently or for excessively prolonged periods; insufficient breaks or recovery time; excessive lifting, lowering, or carrying distances; or a work rate dictated by a process that cannot be adjusted by the worker.
In the effort to prevent injuries related to repetitive handling, it is essential to first assess whether such activities can be eliminated altogether. Designers of machinery, systems, or work processes should evaluate the feasibility of

implementing mechanical or automated handling systems in place of manual operations. However, it is important to note that the introduction of automation or mechanization may introduce new risks. All equipment must therefore be properly maintained, compatible with the overall work system, effective, appropriately designed, and easy to operate. Moreover, workers must receive adequate training to use such equipment safely and effectively. Finally, all devices should be clearly labeled with operating instructions and safety warnings.
To date, no long-term controlled studies have been conducted to systematically assess the incidence of WMSDs associated with exoskeleton use. The majority of the reviewed studies have focused on short-term evaluations, with usage periods ranging from a few hours to several days or weeks. Only a limited number of publications, derived from the same research project, have investigated prolonged usage over several months [14] [15]. The scarcity of long-term studies can be attributed to the inherent methodological challenges and significant resource requirements associated with longitudinal research in this field.
Beyond individual consequences, WMSDs entail substantial social and economic costs, including increased healthcare expenditures, reduced productivity, and a higher incidence of occupational injury claims. In response to these challenges, technological innovation has focused on preventive solutions, among which wearable exoskeletons have gained increasing attention. Furthermore, the adoption of exoskeletons in industrial settings remains a relatively recent development, constrained in part by user skepticism and preconceived biases regarding their efficacy and usability

1.2 Exoskeletons

These devices are engineered to support, augment or assist human movement with the goal of reducing biomechanical loads on the musculoskeletal system. In industrial and logistics environments, exoskeletons are proposed as potential tools to mitigate risk factors associated with repetitive strain and overexertion, particularly in tasks involving the upper and lower limbs. However, the integration of such technologies into the workplace must be supported by rigorous task-specific risk assessments and ergonomic evaluations.
In this context, the application of technical standards, validated assessment

methodologies, and longitudinal studies is essential to ensure that the implementation of exoskeletons is effective and safe from an engineering and occupational health perspective.
Currently, exoskeletons can be categorized based on two criteria: the actuation method and the kinematic structure. Based on the type of actuation, exoskeletons can be classified as follows:

- Active exoskeletons: equipped with actuators (electric, pneumatic, or hydraulic) to support movements.
- Semi-active exoskeletons: combine elastic elements with low-power servomotors.
- Passive exoskeletons: utilize elastic elements to store and release energy.

Figure 1.4. Exoskeleton Categorization by Actuation Type [11]

Instead, based on the type of kinematic structure, exoskeletons can be classified as follows:

- Exoskeletons with rigid kinematic structure
- Anthropomorphic exoskeleton: at least one rotational axis of the device structure is designed to correspond with a rotational axis of the human joint.
- Non-anthropomorphic exoskeleton: none of the device's rotational axes are designed to align with a joint's rotational axis.
- Soft exoskeletons (also known as Exosuits): made of flexible materials without a rigid frame. Through cable-driven systems or fabric-based

solutions, they apply tensile forces in parallel with the action of the musculo-tendinous complexes.

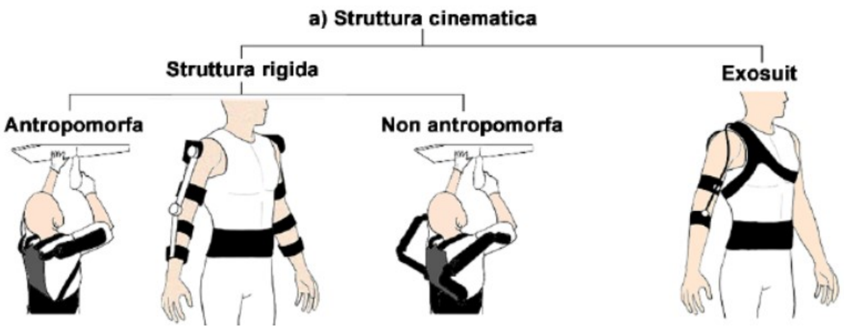


Figure 1.5. Exoskeleton Categorization by Kinematic Structure [11]

Regarding the characteristics of the individual exoskeleton, the manufacturer is required to include in the instruction manual accompanying the device important information like intended purpose, technical characteristics and Scientific evidence regarding the device's effectiveness.
The intended purpose is the use for which a device is designed, according to the manufacturer's specifications. The main intended uses identified for occupational exoskeletons is the support of work activities characterized by manual handling of loads, repetitive movements of the upper limb and static postures
The technical characteristics are referring to the general features of the device that define its functions such as weight, bulk, actuation mode, autonomy, characteristics of the assistive force, rigid and soft kinematic structures, degrees of freedom, sizes, materials, and applicable regulations.
In the end, scientific evidence regarding the device's effectiveness represents one of the most important elements for its evaluation, especially considering that, to date, there are no shared specific methodologies for the assessment of biomechanical overload risk that refer to technical standards, good practices, or guidelines.
Moreover, it is essential to design products that are easy to use, intuitive, and understandable in their management. The user thus becomes a fundamental element of the design process. It is therefore evident how a design focused solely on safety aspects or on the technological requirements of the device may hinder the actual implementation of wearable systems. The design

must consider all aspects of human interaction with the wearable device, in terms of physical, cognitive, and organizational characteristics.
A fundamental aspect in the design of an exoskeleton is the attention dedicated to the physical interfaces, these areas of the device are in direct contact with the user and are directly related to the alignment of the exoskeleton with the human anatomy.Only through a careful study of the interfaces and the design of the device's components can good comfort and effective force transmission be achieved. In fact, if the interfaces and overall design are not properly developed, the efficiency of assistance may be reduced by up to 50 % due to misalignment of the exoskeleton on the body [18].
In general, it is essential that exoskeletons, whether rigid with anthropomorphic or non-anthropomorphic kinematic chains, or even soft—are worn correctly (according to the manufacturer's instructions) so that the forces applied to the human body follow the intended direction for which the device was designed. Improper donning or any potential migration of the device on the user's body (for example, after extended use, if not adequately secured, it may "slide down" due to gravity) can lead to the application of undesired forces, resulting in discomfort that may eventually cause pain or skin irritation.
Some exoskeletons are equipped with self-aligning mechanisms or kinematic systems designed to absorb mechanical misalignment, thereby reducing unwanted effects. The way in which the exoskeleton and the wearer move and interact with each other is referred to as dynamic adaptation.
If a physical support device, such as an exoskeleton, is to be acquired, it is essential to precisely define in advance the company's needs, the specific characteristics of the task, the risk factors associated with its use, and the local complications it may introduce. Exoskeletons provide highly specific support and cannot be universally applied to all workstations job and associated tasks.
For each task involving high physical demands, for which no primary prevention solution has been identified, is used a dedicated task analysis form [16]. The selected exoskeleton should be as well-matched as possible to the working environment. The choice may fall on a robotic or non-robotic exoskeleton, a commercially available device, a modification of an existing solution, or the design of a customized mechanism.
Moreover, the use of exoskeletons in real working environments raises several issues related to occupational risk prevention. It is necessary to evaluate the new limitations introduced by exoskeletons, such as mechanical risks.

Like most work equipment, exoskeletons, due to their bulky dimensions and structural design, may pose collision hazards with other individuals or surrounding elements. There are also risks related to mental workload. Certain tasks performed with the aid of exoskeletons require increased attention due to changes in work practices and operator strategies, which may lead to heightened stress levels. These and other types of risks will be analyzed in detail in the following chapters.

The literature emphasizes that the use of exoskeletons must be carefully assessed in light of the specific risks of the workplace [19]. It is essential to implement appropriate preventive measures, provide worker training, and monitor the impact of the exoskeleton on operators' health and safety. To account for individual differences, the evaluation process should be repeated with multiple volunteers. At a minimum, all operators who will ultimately be involved in the deployment of the exoskeleton must participate [16].

In conclusion, exoskeletons are not universal solutions and must be selected based on the specific requirements of both tasks and workers. Potential risks associated with exoskeleton use must be acknowledged, and operator training along with continuous internal communication within the company are critical to successful integration.

Regarding the assessment of the effects of exoskeleton use on muscle activity during occupational tasks, the literature shows significant discrepancies among studies, which limits comparability and makes it difficult to draw practical conclusions. There is evidence that some muscles may exhibit reduced activation when wearing an exoskeleton, potentially offering protection against fatigue and reducing joint loading. However, as the opposite effect has been reported for antagonistic muscles, this aspect requires further investigation through future studies focusing on specific workplace tasks [17].

In terms of the impact of exoskeleton use on occupational health and safety, one of the main challenges is the evaluation of long-term effects on human biomechanics and physiology. In working practice, this is complex, as it requires accounting for the type of exoskeleton, the nature of the work tasks, and the duration of use. Furthermore, research on the health-related effects—both physiological and biomechanical—is still in its early stages. Nonetheless, it is essential to develop new methodologies to assess the effectiveness of exoskeletons and to more accurately estimate the benefits and drawbacks of this technology [9]. While there is currently a lack of historical data demonstrating the actual long-term effects of industrial exoskeleton use, laboratory and simulated workplace studies provide encouraging results regarding their performance. Several studies on the application of exoskeletons in industrial settings have reported reductions in biomechanical overload and perceived fatigue [2].

Despite the promising outcomes observed in experimental studies, the long-term effects of daily exoskeleton use during real work activities remain unknown. The current data lacks historical depth. This absence of longitudinal data makes it risky to implement exoskeletons for daily use, particularly in populations with low exposure to musculoskeletal risk. Without evidence of medium- and long-term effects, deploying such technologies in a generalized manner may be premature. In this context, until exoskeletons are widely implemented in real-world settings, it will be impossible to obtain realistic long-term data. As often happens with innovative technologies, there is a risk of falling into a closed loop: without sufficient data, widespread implementation does not occur, and without implementation, the necessary data cannot be collected.

Recent review studies [11] have described over 30 occupational exoskeletons applied across various work sectors, including automotive, manufacturing, shipbuilding, logistics, construction, food processing, agriculture, industrial cleaning services, and healthcare. Additionally, specific work activities such as patient lifting and transfer, agricultural tasks, construction work, and elevated carpentry have been identified as relevant applications. In the automotive sector, many evaluation studies of occupational exoskeletons have been conducted. The automotive industry includes manual operations that require physical support for workers, such as overhead work beneath the chassis. In recent years, several automotive manufacturers have evaluated and tested exoskeletons within their production plants, in some cases developing custom devices tailored to their specific operational requirements. It is reasonable to assume that these sectors are among the most promising for the future adoption of such devices, particularly in light of the aging workforce, a factor that the occupational safety community must begin to address seriously.

1.3 Regulations

In relation to the regulatory framework, standards typically provide essential information to address and resolve many issues related to the interaction between humans and technological devices, as well as the environments in which they operate, with particular emphasis on those concerning the user interface. However, at present, no international technical standards specifically dedicated to the professional use of exoskeletons have been established. Still, the current regulatory landscape offers several ergonomics-related standards that provide useful information to address many of the various issues previously introduced.
This thesis therefore required extensive and in-depth research into the global regulatory landscape in order to identify the main guidelines currently in place, consolidate them, and derive a common guideline so that the integration could then be designed in accordance with standards validated by multiple sources. We principally analyzed the regulatory frameworks of Italy, France, Germany and European Standards, in addition to the guidelines issued by the ASTM and the international ISO standards:
With regard to the italian regulatory landscape, the analysis mostly considered the Ente Italiano di Normazione (UNI) and the italian legislative decree 81/08 with regard to occupational health and safety, as for the analytical risk assessment, reference was made to the revised OCRA Checklist method and the ISO standards.
Regarding the French material, the main source was the Institut national de recherche et de sécurité (INRS), which has focused particularly on occupational risk prevention and on providing a practical three-step approach to ensure the proper adoption and integration of exoskeletons in workplace environments.
Concerning the German regulatory landscape, reference was made to the Arbeitsschutzgesetz (ArbSchG), the national Occupational Health and Safety Act. This law implements the European Framework Directive 89/391/EEC and defines the employer's obligations in terms of risk assessment, the implementation of protective measures, and worker training. The ArbSchG plays a central role in shaping preventive strategies and ensuring safe working conditions across various sectors in Germany. Additionally , to adopt a risk assessment model related to the use of exoskeletons in the workplace, we referred to the documentation provided by the Institut für Arbeitsschutz

der Deutschen Gesetzlichen Unfallversicherung (IFA), which is the Institute for Occupational Safety and Health of the German Social Accident Insurance. The material includes a checklist and a risk determination matrix designed to identify and mitigate potential hazards associated with exoskeletons, which has also been adopted by ASTM.
Moreover, we referred to European standards concerning both short-term and long-term feedback. In reference to evaluation of risk factors associated with the implementation of exoskeletons in specific work contexts and guidelines for training individuals to use exoskeletons, we relied on ASTM.
Once the bibliographic research on the ergonomic and biomechanical context, the framework of work-related musculoskeletal disorders, the ergonomic background, the reasons for introducing the exoskeleton, the state of the art of exoskeletons, and the current regulatory landscape had been completed, the work continued with the analysis of the device and the risk assessment.

Chapter 2

Risk Assessment

2.1 The IX SHOULDER AIR

The exoskeletal device used in the present study is the Ottobock IX Shoulder Air, its dimensions are 850mm in length, 700mm in width, and 150mm in height, with a total weight of 2.4kg. [20] This device is already available on the market, leading its category and among the most advanced and competitive thanks to its low weight. This exoskeleton is specifically designed to provide upper limb support during overhead tasks. According to the device's user manual, with daily use of 8 hours and following the prescribed guidelines for proper use and maintenance, its operational lifespan is approximately 5 years. [20]

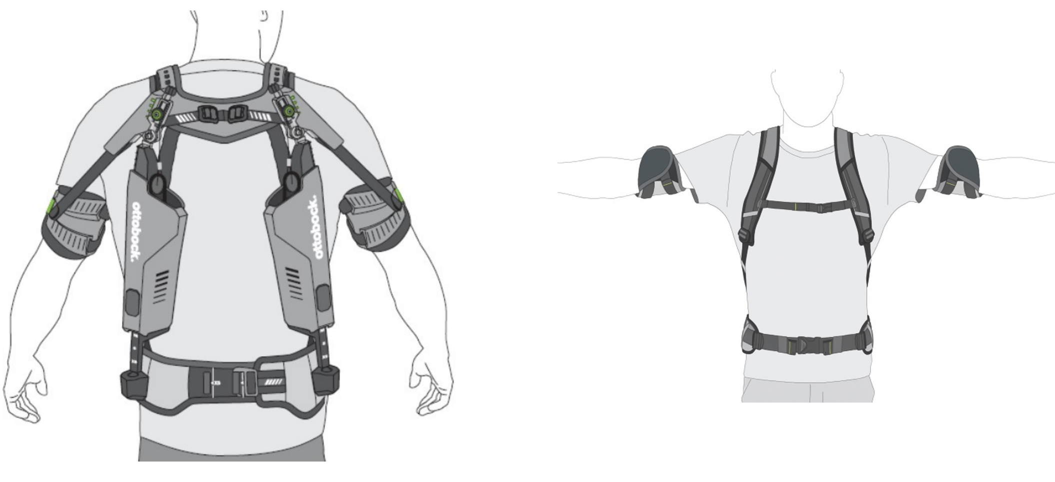


Figure 2.1. Ottobock IX Shoulder Air [20]

The front section of the device consists of:

- A pelvic belt with a buckle, snap closure and belt keeper.
- Adjustable thoracic belt.
- Shoulder straps with adjustable belts and resting positions with featuring magnetic closures for the arm support belts.
- Padded arm supports with adjustable belts and magnetic closures.

The posterior section, instead, consists of:

- A pelvic width adjustment range on the lumbar belt with a measurement indicator from XS to XXL and two housings for the end spheres of the height adjustment rods.
- The tension spring that are included in a plastic material covering, the height adjustment rods and an adjustment button.
- Adjustable elastic belt and strap for the back.
- Headrest support and carrying loop.
- The connection areas between the tension spring and the padded arm supports consist of a support adjustment knob, to which the tension spring is directly attached within the joint unit covered by a plastic casing, featuring an engraving indicating the support capacity. This assembly concludes with a connecting rod for the arm.

The configurations of the IX Shoulder Air are performed through five methods in a specific sequence:

1. Pelvic width configuration
2. Back height configuration (both sides)
3. Back strap configuration (both sides)
4. Elastic strap configuration (both sides)
5. Support capacity configuration using knob (both sides)

The device has a storage temperature between -10°C and +60°C and an operating temperature between -10°C and +45°C. [20]
After carrying out the necessary adjustments and verifying that both the chest belt and the pelvic belt are open, the device can be easily equip in the same way as a backpack. The pelvic belt should subsequently secured, followed by the chest belt. The next step involves the more complex stage, which requires more operator training—specifically, the positioning of the arm supports. With great care to prevent the tensioned rod from slipping, the loop of the arm support must be pulled downward, positioning the arm in front of the body above the closure point. Then, the arm should be placed centrally within the support, open the padding , extend the strap over it and secure the magnetic closure with the loop in the locked position on the arm support. Verify and adjust, if necessary, the configurations of the various straps once the device is worn.

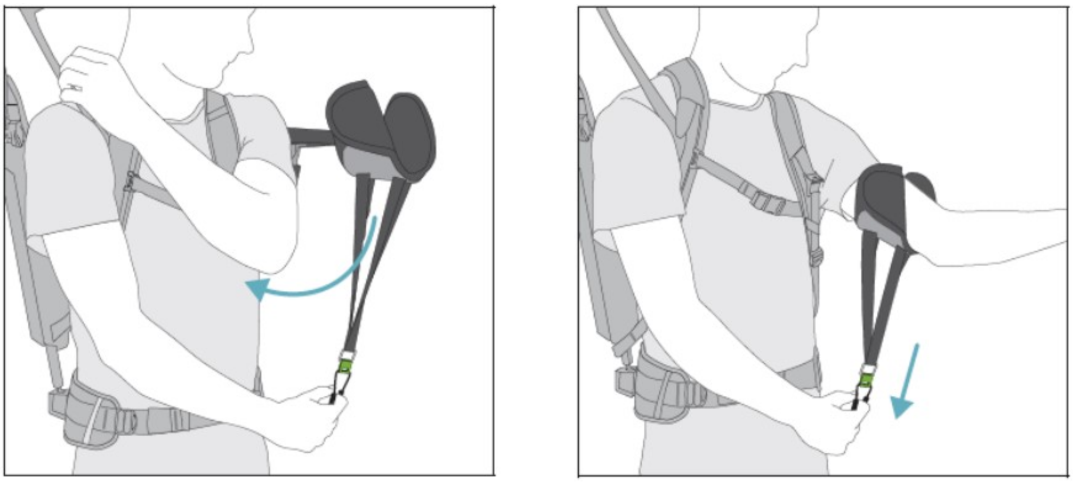


Figure 2.2. Arm Attachment Ottobock IX Shoulder Air [20]

Regarding the removal of the exoskeleton, the procedure must be carried out in reverse: first, release the magnetic closure loop from the arm support catch, then lower the elastic strap while keeping the belt tight, withdraw the arm from its support and bring it in front of the body. Next, slowly slide the arm support upwards and fully secure the magnetic closure in the resting position on the shoulder strap. Only after this you can open the chest belt and the pelvic bel, and you can remove the device as if it is a backpack.

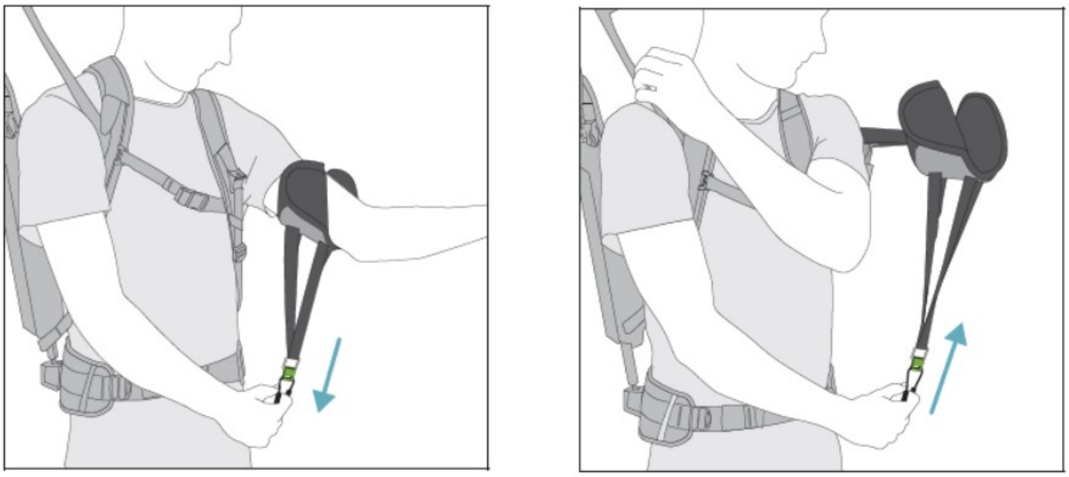


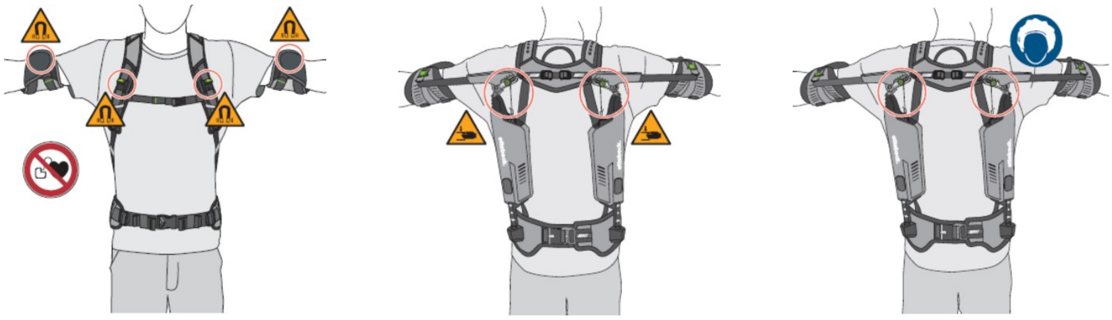
Figure 2.3. Arm Detachment Ottobock IX Shoulder Air [20]

In general, this exoskeleton offers a wide and customizable range of configurations thanks to numerous adjustable belts and straps. This allows it to adapt to a large variety of operator physiques while maintaining moderate simplicity and good wearability. The only drawbacks are the textile components that during long work cycles increase the operator's sweating and the non-immediate positioning on the arms. The latter one requires appropriate operator training to ensure production line timing without delays, stoppages, injuries, or malfunctions. However, if proper training is followed, after a couple of cycles of putting on and taking off, operators acquire sufficient skill to perform the task safely and in minimal time.

2.2 Risk Analysis

2.2.1 Risks Related to Exoskeleton Design

The first aspects considered in the risk analysis were the dangers deriving from the manufacturing characteristics of the exoskeleton. Every mechanical device, by its very nature, entails risks associated with its use due to its structural design and manufacturing process. These aspects are fundamental to assess, as they may determine whether the device is appropriate or inappropriate for integration into a specific work environment. The user manual of the IX Shoulder Air identifies three main hazard zones: the magnetic field zone, the crushing zone, and the hair entanglement zone. [20]



a) *b)* *c)*

Figure 2.4. Danger Areas: a) Magnetic fields, b) Crushing, c) Hair Entanglement. [20]

Concerning the first area, the shoulder and arm support closures incorporate magnets that generate a magnetic field which may interfere with pacemakers or other active implantable devices. The manufacturer did not assess interactions with external magnetic fields. During workplace implementation, this issue was resolved through consultations with occupational health specialist, confirming that none of the operators involved carried active implantable devices.

In zone 2, during support-capacity adjustments, there is a potential risk of fingers being caught in the joint unit or the extender, leading to crushing. This risk was mitigated through a appropriate training program for all personnel involved in the device's application, use, and removal. No incidents of crushing or other injuries were reported.

Regarding zone 3, there is a potential risk of hair entanglement in the joint unit or the extender when the device is used by operators with long hair. To prevent this issue during our trials, operators and specialized technical staff were provided with appropriate instructions and training, and it was recommended that long hair be tied back or contained in a hair net or cap. No incidents of entanglement or other injuries were reported.

An additional critical risk associated with the exoskeleton's design is the potential uncontrolled recoil of the tensioned arm strut. When disengaging the magnetic locking mechanism, the operator must maintain finger contact with the loop handle until the lock has fully and securely returned to its resting position. Failure to follow this procedure may cause the uncontrolled

release of the connecting strut between the arm and extensor mechanism, potentially striking the operator. Furthermore, inadequate cleaning protocols may increase the risk of dermatological issues, including skin irritation, eczema, or microbial infections due to contamination. [20]
Both of these risks were effectively mitigated through comprehensive instructions and training provided to both end-users and specialized technical personnel. No incidents of injury or other related adverse events were reported.

2.2.2 Risks Related to the Work Environment

During the implementation of a device in a work environment, the risk analysis of the workstation before implementation is a fundamental phase to identify pre-existing risks. Moreover, it is essential to assess the risks to which operators are typically exposed, in order to introduce and utilize the device safely. Our aim is to improve the working conditions of operators by eliminating or reducing pre-existing risks, or, at least, by maintaining the same level of risk while mitigating muscular load relief.
During our implementation process, after analyzing and selecting the device to be introduced, we collected the necessary information through a meeting with process ergonomists and the safety managers of the production line on-site. From this meeting, we were able to clearly define the pre-existing main issues of each workstations under consideration as well as the measures already implemented to address them. Then, the data collected were summarized into thematic tables in dual language (English/Italian).
The distinctive feature of the environment in which the tests were carried out was the presence of swivel hooks instead of standard pantographs for transporting the cars under construction along the entire line. The use of pantographs means that cars remain at human height along the line for longer, with many more workstations forced to work under the chassis in static positions that are unfavorable for the shoulder joint and cervical joint complex. In the case of the Stellantis production line at the Mirafiori site, however, the use of swivel hooks significantly improves the work of operators, as the hook can be transported at various heights thanks to an elevated track and, at the same time, can rotate clockwise or counterclockwise, bringing the underbody parallel to the operator. In this way, it is possible to carry out underbody assembly in natural physiological positions in many more cases. The only two stations where, due to the layout of the line,

operators are forced to work under the underbody are precisely those being considered for the introduction of the exoskeleton.
The risk assessment study, which analyzed the risks associated with workstations and the implementation of exoskeletons, is based on a study by the Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA). [19], characterized by two metrics: frequency of the hazardous event and severity of the damage. Using these two factors, a table can be created with columns representing the severity of the damage, divided into five categories: no damage to health, minor injuries (no lost work days), moderate consequences (absence from work, but no permanent damage), serious consequences (irreversible injuries), and fatal consequences. The rows show the frequency with which the hazardous event may occur: unlikely (less than once a year), conceivable (once a year), possible (once a month), probable (once a week), and very probable (once a day). The table is used by cross-referencing the frequency of the event with the severity of the damage in order to obtain a risk classification (Low, Medium, High). The result helps employers and safety managers decide which preventive measures to take, since if, for example, a risk is assessed as high, immediate measures must be implemented to reduce it. Frequency is based on probabilistic estimates derived from observation of working conditions and analysis of similar situations, while the severity of the damage depends on the effects that a dangerous event could have on the worker's health. It is estimated through biomechanical analysis of the impact on joints and the body, consideration of possible resulting injuries, and review of scientific studies and data on workplace accidents.

Frequency	Severity of harm				
	No hazard to health	Minor injuries (no reportable lost working time)	Moderately severe consequences (lost working time, no permanent harm)	Severe consequences (non-reversible injuries)	Fatal consequences
Not probable (<1 per year)	Low	Low	Low	Medium	High
Conceivable (once per year)	Low	Low	Medium	High	High
Possible (once per month)	Low	Medium	High	High	High
Probable (once per week)	Medium	High	High	High	High
Very probable (once per day)	High	High	High	High	High

Figure 2.5. Means of determining risk table [19]

Tables such as this are generally based on existing regulations and standards. [1] [10] [8], risk assessment models already in use [12] [13], scientific articles and studies on the safety of exoskeletons [2], practical experience and feedback from work environments.

During our study, this table was slightly modified to adapt it to the case in question and to correct some details. Although the frequency classification is necessarily probabilistic and reported with acceptable intervals, the severity classification lacks precision because, although it is based on two parameters, namely consequences for the patient's health and loss of working hours, these two parameters do not always increase in tandem in the various distinctions, leading to a disproportion between the increase in severity and the increase in its own parameters. It can be noted that between the 'Moderate' and 'Severe' ranges, there is no distinction in terms of the parameter of hours lost, whereas there is a distinction in terms of the severity of injuries (non-permanent damage for 'moderate', permanent for 'severe'). I would therefore opt for a generic change to the two definitions and the inclusion of a third classification to eliminate the sudden increase in severity in the last columns:

- Moderate: non-permanent damage and lost working hours less than a given period (two months was chosen)
- Serious: non-permanent damage but hours of work lost >2 months
- Very Serious: permanent damage

These would then be accompanied by the other definitions of "Fatal" and "Minor injuries."

As regards the first category, i.e., "No health hazard," it should be noted that a "Very Probable" probability is considered a "High" risk, without further information. which seems to be a contradiction given that the wording states that there is no danger. This category has therefore been renamed "No danger to health but damage to products, devices, or equipment" in order to justify the fact that, if this were to happen every day, action would still need to be taken. Based on these changes, the medium risk category has been expanded to ensure consistency across the entire structure. In conclusion, the following table has been used:

frequency	Severity of harm					
	No Hazard to health but damage	Minor injuries	Moderate	Severe	Very Severe	Fatal
Not probable (<1 per year)	Low	Low	Low	Medium	Medium	High
Conceivable (once per year)	Low	Low	Medium	Medium	High	High
Possible (once per month)	Low	Medium	Medium	High	High	High
Probable (once per week)	Medium	Medium	High	High	High	High
Very Probable (once per day)	Medium	High	High	High	High	High

Figure 2.6. Means of determining risk adjusted table

However, the real weakness of this type of table remains the definition of low, medium, and high risk, which is not objective but established by those who compile the table based on experience and research reviews of those currently in use. The definitions can therefore be variable and modified if supported by adequate reasons [12]. In this case, for example, the definition of "medium" has been adopted for the final boxes in the first column because there is no real danger to the health of the worker, which is the key principle of this study and the drafting of this type of table, but rather mainly a risk of damage to the device, which is nevertheless important in a business context but not central to the drafting of this table. [1] [3]

As can be seen from tables 5.1 and 5.2, the working environment prior to the introduction of the exoskeleton is characterized by risks that are fairly standard in any automotive production line. In fact, there are protruding moving parts that could strike, grab, and drag workers, parts with dangerous surfaces at human height such as the underbody, possible falling parts or equipment, and unfavorable positions when picking up parts from a trolley on the side of the line at hip height. It is important to note that the trolley follows the car being assembled, so it is always close by and easy for the operator to reach.

Table 5.3 shows the preventive measures taken for the above risks. To solve the problem of protruding moving parts, the production line runs very slowly at a constant speed, which makes the movement of the hooks predictable and, in the event of a grab, simplifies immediate rescue. In addition, the protruding parts of the hooks have been covered with foam rubber protection

so as not to cause damage in the event of impact.
With regard to dangerous surfaces at human height, the use of protective headgear has been recommended. Finally, with regard to the possible fall of parts or equipment, personal protective equipment (PPE), such as safety shoes, helmets, and protective gloves against mechanical risks, has been made mandatory, in accordance with directive [8]. In addition to this, adequate training was provided to the personnel involved regarding all risks and also regarding the movements necessary for picking up parts in order to avoid accidents.
Analyzing the two workstations in more detail, starting with workstation 140, which is responsible for fixing the connecting rod to the frame, as summarized in table 5.4, this workstation is characterized by a main mechanical load on the upper limbs, in particular the scapulohumeral joint, by the manual handling of loads (in this case, 3.5 kg pins) on both the right and left sides of the car, and by the use of 2 kg screwdrivers on the reaction arm for fastening the connecting rods.
Going into more detail about workstation 147, which is responsible for assembling the front wheel 5.5, we can see that it differs only slightly from workstation 140, as in this case there is no manual handling of loads and the tools used consist of a 2kg screwdriver, a mallet, and a punch.
Both stations are equipped with the aforementioned mobile trolley that follows the operator for the collection of particulates, spacious work environments with workers who do not operate close to each other, the entire job is carried out in both cases on a fixed platform whose characteristics do not involve additional risks, operators wear the same PPE and shift management is the same, i.e. from 06:00 to 14:00 with three 10-minute breaks during the shift at 08:00, 10:00, and 12:00 and a lunch break at the end of the shift at 13:30.
Instead, the method used for risk assessment and prevention management of WMSDs, used to understand the possible benefits of the introduction of the exoskeleton, was the OCRA method (Operative Conditions Repeated Actions), which can be considered a system, where the term "system" is interpreted as a set of tools that allow different levels of risk assessment based on specificity, variability, and desired objectives. [6]
Risk assessment using the OCRA method is based on six main factors [6]:

- The duration of exposure, i.e., the actual time spent performing repetitive tasks during the shift.

- The frequency of movements, i.e., the number of technical actions repeated per minute.
- The force applied, assessed using the Borg CR-10 scale.
- Awkward and unfavorable postures for the shoulder, elbow, wrist, and hand.
- Various additional factors such as vibrations, use of inadequate gloves, working in cold environments, sudden movements.
- Recovery time defined as any time in which the upper limb is primarily physically inactive.

The final score on the Revised OCRA Checklist is calculated by adding the partial scores for each risk factor (frequency, force, posture, and additional factors), calculated separately for the right and left upper limbs, and multiplied by the recovery factor and duration factor values.

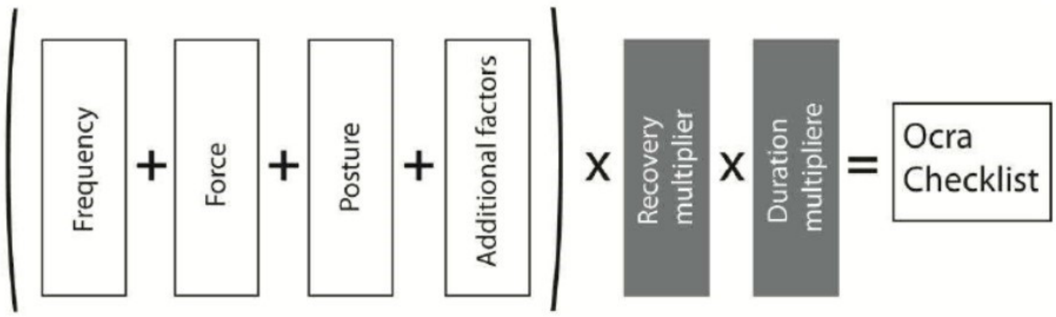


Figure 2.7. OCRA Checklist score calculation formula [6]

As demonstrated in [5], a medium- to long-term prediction model based on known OCRA Index values can be used to estimate the possible onset of work-related WMSDs. For each risk level of the OCRA Checklist, it is possible to associate a range of OCRA Index values, as shown in the image below. In the other columns, the table also shows the corresponding risk level with a color legend and an adjective, and finally a prediction of the percentage of staff who could be affected by WMSDs according to the predictions of previous studies [5].

OCRA CHECKLIST	OCRA INDEX	LEVEL	RISK	Predicted worker population with WMSDs (%)
< 7.5	<2.2	Green	Acceptable risk	< 5.3
7.6 – 11.0	2.3 – 3.5	Yellow	Very low risk	5.3 - 8.4
11.1 – 14.0	3.6 - 4.5	Light red	Medium-low risk	8.5- 10.7
14.1 – 22.5	4.6 – 9.0	Dark red	Medium risk	10.8- 21.5
≥ 22.6	≥ 9.1	Purple	High risk	>21.5

Figure 2.8. OCRA Final Score Table [6]

However, the exposure index calculated in this way is not indicative of the risk for workers who also perform other tasks. In this case, the value is determined in a second phase of the analysis, once all work activities involving repetitive work have been mapped. A different multitasking exposure index will therefore be calculated in the case of hourly rotations or different tasks, each lasting more than one consecutive hour. The cases under consideration for the introduction of the chosen device do not fall within the scope of multitasking exposure, so we will not go into further detail.
If we want to take a closer look at the Borg CR-10 scale, we can say that it is a scale for assessing the perception of physical exertion, developed by Swedish physiologist Gunnar Borg in 1982. It is applied in various contexts, such as monitoring fatigue during sports training, in rehabilitation, and also in assessing the perception of exertion in work activities. It should be remembered, however, that this scale is a subjective assessment system, allowing the sensation of exertion experienced during physical activity to be measured on a scale of 0 to 10, but only from the point of view of the person performing the activity. Each value represents a different level of perceived exertion, with 0 indicating ‘no exertion’ and 10 indicating ‘maximum exertion’. Nevertheless, it is a useful resource, as it provides a way to correlate subjective perception of fatigue with physiological parameters, without the need for complex instrumentation.

By applying the steps described above and following the guidelines and conversion tables of the OCRA method, it is possible to calculate the various factors of the OCRA checklist coefficient for the workstations of interest. [6]:

- Duration Multiplier:
  The duration multiplier value is unique for both workstations and was calculated as the net duration of repetitive work, i.e., the total time of the work shift minus the time dedicated to various breaks during the shift and the lunch break [6].

  $$\text{Net Duration Repetitive Work} = 420\,\text{min}$$

  From conversion table 5.9, the result is:

  $$\text{Duration Multiplier} = 0.95$$

- Recovery Multiplier:
  The recovery multiplier is also unique for both stations. It was calculated considering only guaranteed rest periods of at least 8-10 minutes as breaks, with the first 60 minutes of the shift and the 60 minutes prior to the lunch break counted as hours with adequate recovery time. In addition, any 60-minute period that includes a break, regardless of when it occurs within the period, will be counted as 1 hour with adequate recovery time, while any 60-minute period that does not include a break will be counted as 1 hour without adequate recovery time. Finally, work periods of less than 20 minutes are counted as periods with adequate recovery time, work periods of 20 minutes or more and less than or equal to 40 minutes are counted as 0.5 hours without adequate recovery time, and work periods of more than 40 minutes but less than 80 minutes are counted as 1 hour without adequate recovery time. At the end of this phase, all hours without adequate recovery time in the shift were added up [6].

  $$\text{Total Time Without Recovery} = 3\,\text{h}$$

  From conversion table 5.10, the result is:

  $$\text{Recovery Multiplier} = 1.2$$

- Frequency:
  The frequency factor was calculated by visually analyzing the videos on the production line, counting the number of actions performed in one minute, and then calculating the ratio. Its value varies depending on the workstation, as each one is characterized by different tasks. The column without the possibility of short breaks was then considered, as the tasks at both workstations had to be performed at line speed [6].

$$\text{Frequency of technical actions} = \frac{\text{Number of technical actions}}{\text{Minute}}$$

  The analyses conducted for station 140 gave the following results:

$$\text{Frequency}_{\text{ws140}} = 35\,\text{actions/min}$$

  While for workstation 147:

$$\text{Frequency}_{\text{ws147}} = 40\,\text{actions/min}$$

  From conversion table 5.11, the result is:

$$\text{Frequency Factor}_{\text{ws140}} = 2\,;\ \text{Frequency Factor}_{\text{ws147}} = 4$$

- Force:
  The force factor is deduced using an individual questionnaire based on Borg's CR-10 scale, which is associated with the percentages of time during the entire test in which the various levels of effort are applied [6]. The final value is given by the sum of all the values obtained using the conversion table 5.12 In this case, for both stations, the values on the Borg scale coincided with the 3-4 range, and the final multiplier score was the same:

$$\text{Force Factor} = 8$$

- Posture:
  The posture factor is assessed by separately identifying uncomfortable postures and movements for the scapulohumeral joint, elbow, wrist, and hand, for both the left and right sides. If the joint has to work at an uncomfortable angle, the duration of this work in relation to the complete cycle time must be estimated using the values 1/3 (between 25% and 50%), 2/3 (more than 50% and up to 80%), and 3/3 (more than

80%); the overall score for the posture factor will then be the highest value calculated for a joint segment. [6] The postural conditions used for the assessment of each joint are those already described in Figures 1.1, 1.2, and 1.3. The timing of uncomfortable joint postures, although slightly different in percentage terms at the two workstations, fall within the same conversion intervals for the associated factor score, so the two workstations will have the same posture factor. The analyses conducted found that the shoulder was in an uncomfortable posture 71% of the time for workstation 147 and 51.5% of the time for workstation 140, while the wrist was in an uncomfortable posture less than 25% of the time in both cases, the elbow 27% of the time, and the hand 26% of the time. From the conversion table 5.13, we therefore have:

$$\text{Posture Factors}_{\text{shoulder}} = 12\,;\ \text{Posture Factors}_{\text{wrist}} = 0$$

$$\text{Posture Factors}_{\text{elbow}} = 2\,;\ \text{Posture Factors}_{\text{hand}} = 2$$

From this, it can be stated that:

$$\text{Posture Factors} = 12$$

- Additional Factors:
  With regard to additional factors, document [6] provides an explanatory table from which to select the additional factors relevant to each situation. From table 5.14, in our cases only the second case in block B socio-organizational factors can be selected, namely “The work rate is entirely determined by the machine”:

$$\text{Additional Factors} = 2$$

Now that we have all the factors necessary for calculating the ochre checklist coefficient for both locations:

$$C_{\text{OCRA}} = (F_f + F_o + P + A) \times R_m \times D_m \tag{2.1}$$

where:

- C_{OCRA} is the OCRA Checklist coefficient;

- F_f is the *frequency factor*;
- F_o is the *force factor* ;
- P is the *posture factor* ;
- A is the *additional factors*;
- R_m is the *recovery multiplier* ;
- D_m is the *duration multiplier*.

The results are:

$$C_{\mathrm{OCRA}_{140}} = 27.36\,;\; C_{\mathrm{OCRA}_{147}} = 29.64 \tag{2.2}$$

By checking the above values in table 2.8, we can confirm that both workstations are high risk, which justifies the decision to introduce an upper limb exoskeleton in order to reduce the risk of WMSDs for operators.

2.2.3 Risks Related to the Exoskeleton's Implementation

When introducing an exoskeleton into the workplace, it is essential to also consider the possible risks introduced by the exoskeleton itself [2] [9] [12] [13] [16]. The introduction of any device should aim to improve productivity and working conditions, but when it instead adds further risks, which may be serious or unresolvable, then the intended use and effectiveness of the device are lost, and the conditions for its introduction no longer exist. Consequently, the risk analysis phase related to the implementation of the exoskeleton is a fundamental step in the introduction of the device. In this study, the risk analysis phase related to the exoskeleton was conducted in collaboration with process ergonomists, plant safety managers, and occupational physicians at the plant, simultaneously with the general risk assessment. As shown in the table 5.1 e 5.2 all risks associated with the introduction of the exoskeleton are low, with the risk related to magnetic fields being particularly significant, as it could cause serious damage to wearers of active implantable devices. However, thanks to the timely intervention of the occupational physician and the appropriate selection of personnel for testing, this risk has been completely eliminated. As for the other risks identified, thanks to the measures taken previously or initiated

after the meeting, they have all been minimized. A small number of the possible risks associated with the introduction of the exoskeleton required further verification during testing to understand their presence or absence and, if necessary, their severity.
The summary of the post-test risk analysis is shown in the tables 5.6 and 5.7. As can be seen, all risks fell within the low level thanks to the measures adopted, and most of the risks that required further verification during the testing phase proved to be non-existent, with the exception of three. The first risk identified concerns mental factors, in particular social isolation. Although station managers were instructed to train operators not to isolate or tease colleagues who were testing the device, this still happened. Sometimes the jokes were taken positively with irony, other times not, depending on the individual. Although this aspect does not affect the purely physical aspect of those wearing the exoskeleton, it does affect the mental aspect, creating an uncomfortable working environment for everyone and discouraging them from continuing to use the device. Therefore, in the event of full implementation of the device, more impactful training for staff and greater rigidity in reporting these events on the production line are needed.
The other two risks identified were increased physical strain and reduced mobility perceived due to the exoskeleton at particular moments during work. These symptoms were reported during testing, especially by one operator, who was overweight, but they improved with more appropriate customization of the exoskeleton measurements. The same symptoms, but reported as less severe, were reported by another operator of normal weight while performing tasks at workstation 147, in the line lowering area, which forced him to arch his back backwards, an action not provided for by the exoskeleton support and therefore not covered by its intended use.
Although there are some additional risks, thanks to the measures taken, these have been minimized, thus planning and authorizing the safe implementation of the exoskeleton for the operator.

Chapter 3

Methods for Implementation and Evaluation of the Exoskeleton

3.1 Exoskeleton's Implementation Procedure

The procedure followed for the implementation of the exoskeleton is based on the method reported in the study by the French National Research and Safety Institute (INRS) [16]. The implementation method is based on the creation of a working group that brings together stakeholders within the plants involved in the possible use of the exoskeleton. In our case, the group consisted of process ergonomists, safety managers, the occupational physician, integration managers, and the operators involved. Furthermore, it is important to regularly inform operators and managers, which is essential to ensure that everyone correctly understands and adopts the integration process. The method described is structured in three phases:

- Supporting the company in its decision to adopt exoskeletons.

- Assess the benefits and limitations of interaction between operators and exoskeletons.

- Creating optimal conditions for the integration of exoskeletons in work environments.

We therefore began by identifying all types of risks, both those related to the working environment and those arising from the exoskeleton and its introduction into the workplace. With the help of the aforementioned staff and the reports they had collected over the years, we summarized everything in tables 5.1 e 5.2. This was followed by an in-depth analysis of physical load, considering all factors that can cause physical difficulties and calculating the OCRA Checklist Index score. Based on this analysis, prevention solutions aimed at transforming work situations are identified (table 5.3), they must be consistent with the specific characteristics of the company and take into account its organizational, technical, and human dimensions. We have always sought to eliminate or reduce as much as possible the danger or exposure to danger, assess the extent of the risk in order to prioritize the preventive actions to be taken, integrate prevention as early as possible, take into account differences between people, avoid the use of dangerous processes or products when the same result could be achieved by a less risky method, and provide adequate training and information to employees. [16]. Once we had examined all possible preventive solutions for eliminating risk factors linked to excessive physical loads, we identified the tasks that require more specific physical support, in our case workstations 140 and 147, and drew up specific worksheets in tables 5.4 e 5.5. The final step in the first phase is to choose the device. Based on the considerations made in this phase, a ready-to-use device available on the market may be an option, as may be the adaptation of an existing device or the design of a custom-made mechanism. In our case, we chose a device already available on the market, the leader in its category: the Ottobock IX Shoulder Air passive exoskeleton.
Phase 2 consists of evaluating human/exoskeleton interaction. There are two types of evaluation tools: “objective” ones (which measure physiological or physical parameters) and “subjective” ones (which investigate human perception). It is always advantageous to combine both types of tools, as they are complementary [16]. In our case, subjective parameters were collected using a questionnaire, while objective parameters were collected using sensors on the subject’s body and reprocessed using simulation programs and data output. In both cases, we collected data on whether or not the exoskeleton was used. The exoskeleton was tested by each workstation

involved in the production line, first for a preliminary 20-minute trial to obtain initial feedback, then for a 1 hour and 30 minute trial by all operators involved in those workstations.
Finally, the third phase deals with short-, medium-, and long-term evaluation, which is essential as it allows for analysis of the benefits of the system in relation to changes in the work situation. The evaluation is based on a comparison between the initial situation and the situations under review. To be effective, the evaluation must be based on a good understanding of the initial situation and define clear objectives that are shared by all those involved [16]. This assessment should promote a culture of health in the workplace. At this point, the assessment will then be integrated into the company's normal occupational risk management process.

3.2 Evaluation Methods

As outlined in the previous sections, two types of evaluation methods were employed during the design of the experimental campaign aimed at introducing the IX Shoulder Air into the production line at the Stellantis Mirafiori plant: subjective and objective. This dual evaluation approach was selected because, as highlighted in the literature [16], the two methods are complementary, making their combination advantageous.

3.2.1 Worker-Reported Evaluation Methods

Looking more closely at evaluation methods based on operator feedback, we can say that these are subjective methods that provide feedback on parameters that would otherwise only be assessable using advanced instruments and methods that are difficult to apply directly on the production line [16]. An example of this concept is the muscle fatigue perceived by the operator. The most appropriate test to measure this is electromyography (EMG), which is performed using electrodes placed on the skin or, in some specific clinical cases, using needle electrodes directly anchored to the muscle fibers for greater signal accuracy. It is therefore clear that this type of testing is incompatible with a production line test where there is equipment to manage, parts to pick up and assemble, and, above all, deadlines to meet in order to avoid delays or even stoppages on the assembly line. Another illustrative example is the presence of misalignments between the operator and

the exoskeleton or parasitic forces. For adequate objective measurement, advanced sensors would be required on both the device and the operator. It is clear that such a setup could cause mobility and safety problems in an assembly line workstation. Thanks to the subjective feedback collected through detailed questionnaires during and after the test, we were able to evaluate even these aspects, which are difficult to measure.
The total number of operators who participated in the workstation tests was three, their average age was 48.6 years, the average height of the operators was 175 cm, and the average weight was 83.6 kg. The feedback requested from operators ranged from questions devised during the preliminary analysis phase by the working group to questions belonging to methods already validated by literature studies, such as the Borg scale [6] [5]. Most of the questions focused on operator-exoskeleton interaction, asking whether users experienced mechanical discomfort such as rubbing, biological discomfort such as excessive sweating, discomfort due to weight, size, or shape, mental factors, perceived effort, whether they perceived ergonomic problems, and whether they would agree to permanent implementation.
Feedback was collected during the tests, halfway through the 20-minute preliminary tests and every 30 minutes during the 1 hour and 30 minute tests and at the end of the tests, all operators involved in those workstations tried the exoskeleton.
In addition, feedback was also requested before the test regarding work without the exoskeleton, in order to be able to compare the two cases, even subjectively.

3.2.2 Objective Evaluation Methods

As regards objective assessment methods, we opted for laboratory measurements, as these are free from the limitations, risks, and interference typical of an assembly line workstation. The tests carried out in the laboratory sought to faithfully reproduce the conditions of the workstation and were conducted in the ErgoLab laboratory at the Stellantis plant in Mirafiori. The physical characteristics of the subject who performed the tests are: age 27, height 175 cm, weight 85 kg. The laboratory tests consisted of two 1-minute work cycles, first without and then with the exoskeleton.
The tests were carried out using XSens Awinda brand Movella sensors, an inertial motion capture system consisting of 17 wireless sensors attached to the body using adjustable straps that can be worn over clothing, or using a

tight-fitting Lycra shirt for easier application of the sensors to the shoulder joints and chest. With wireless transmission up to 50m, it can be used in a wide variety of applications including ergonomics, rehabilitation, injury prevention, and biomechanical analysis. First, the subject had to be calibrated, initially statically in the classic "T-pose" test for all humanoid 3D models, then dynamically with a simple walk and a final static physiological position. The data collected by the sensors was transmitted to the program attached to the XSens system, MVN Analyse, and reproduced on a 3D mannequin that faithfully animated every movement of the subject.
The output was then used by Scalefit's Industrial Athlete system, a cutting-edge digital platform for real-time ergonomic analysis that combines motion capture technology (Xsens), advanced biomechanics, and regulatory assessment to support healthy, efficient work environments and prevent musculoskeletal disorders. ScaleFit was used to represent the torque acting on the scapulohumeral joint during all upper limb movements.
The ScaleFit interface is a detailed but intuitive screen, divided mainly into a central area, where the 3D model reproduces the movements captured by the sensor system, and two side areas, where various windows displaying a range of acquisition data are arranged.

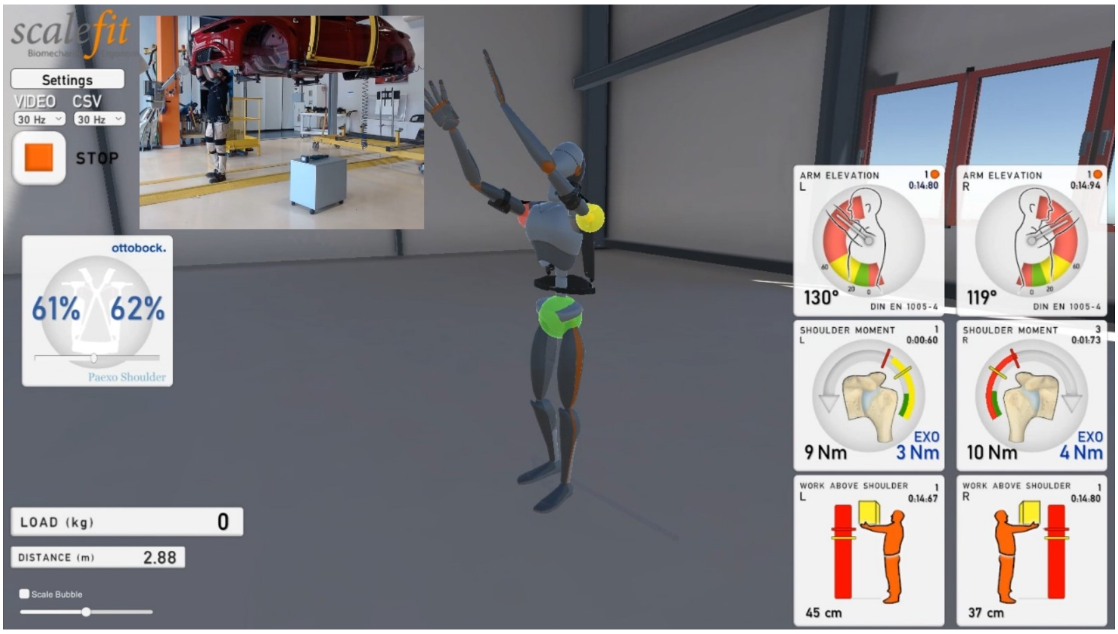


Figure 3.1. Scalefit interface

ScaleFit included a model of the exoskeleton's behavior implemented directly by the device manufacturer, capable of representing the torque value on the joint during use of the device, thus quantifying and visualizing the actual intervention of the exoskeleton on the load, a very useful feature for comparing tasks with and without the exoskeleton. All the data collected was then reprocessed to draw final conclusions.
Starting from the left column, at the top we have the program logo and various simulation playback settings. Next to it, a video filmed directly in the laboratory during testing has been added to provide a real-time correspondence with the simulation. Moving on to the central left-hand area, there is a window dedicated to the exoskeleton support. The two percentages correspond to the percentage support of the device at that moment on the individual limb, i.e., the percentage of load that the device relieves from each limb at that moment in time. Immediately below, there is a horizontal bar indicating the amount of support set on the exoskeleton during adjustment. The force exerted by the device on each arm of the exoskeleton can be adjusted using a special wheel, see figure 2.1 and user manual [20]. At the bottom of the left column, we finally find the boxes showing the possible load lifted, the distance from the spatial reference point, and an adjustment bar for the proximity of the view.
As mentioned above, the center of the interface is dedicated to the 3D model, with the exoskeleton implemented, which faithfully reproduces the movements captured by the sensor system during acquisition. Moving to the right side of the interface, we find two columns of windows, one for the right limb (marked with an R for right under the size name) and one for the left limb (marked with an L for left in the same position). All assessments of posture intervals, represented by a color legend in the windows, comply with the UNI EN 1005-4:2009 standard [7]. Starting from the top, we find two boxes showing the angle of flexion of the upper limbs in degrees (°) and a graphic representation of the position of the limb in relation to the body at that moment, together with a color legend below illustrating the various ranges according to the rules mentioned above [7]. The two central boxes, on the other hand, show the torque values acting on the scapulo-humeral joint at each moment in time on a double circular bar, where the outer bar represents the torque without the support of the device, while the inner bar represents the torque acting with the support of the exoskeleton. Immediately below are the values in Newton per meter (Nm), with the value in blue representing the case with exoskeleton support, while the value in

black represents the case without support. Finally, the last pair of boxes at the bottom shows the height above the shoulder at which the task is being performed, with the corresponding numerical value in centimeters (cm). With a clear and complete overview of the program adopted, we can now move on to the results obtained.

Chapter 4

Results

This chapter presents the results of the analysis and simulation of the introduction of the IX Shoulder Air exoskeleton for the upper limbs on the assembly line at the Stellantis plant in Mirafiori. The main objective was to evaluate the effectiveness of the device in reducing the biomechanical load on operators, while improving the ergonomic conditions for workers without compromising production efficiency. The results are organized into two sections: the first illustrates the data emerging from the subjective assessments of the operators involved in the tests, while the second presents the results obtained from the objective assessments derived from the sensory analyses of the laboratory tests. Both sections then compare the scenarios with and without the exoskeleton, highlighting the benefits, limitations, and possible implications for the large-scale integration of the device.

4.1 Worker-Reported Feedback

This first section is dedicated to the results derived from the subjective feedback of the operators involved in the production line tests. A total of three operators were involved in the tests, namely all the personnel assigned to the workstations concerned (two workers at workstation 147 and one worker at workstation 140). The preliminary questionnaire on personal observations regarding work without an exoskeleton showed that all operators felt safe once at their workstations, protected in their work thanks to the safety measures previously adopted and without any mental or emotional stress due to the task to be performed. However, all three subjects complained of soreness and slight pain in their upper limbs at the end of their shift, although

not enough to report it to the plant manager. The Borg scale assessment of the three subjects' perception of exertion always coincided with a level 4.
During the preliminary test, the operator at station 140 complained of restricted movement and excessive tightness of the exoskeleton. In this case, the customisable measurements were promptly adjusted. After the adjustment, the discomfort caused by the tightness was reduced, but the feeling of restricted movement remained. In this case, the operator refused to continue with the full test. It is important to note that this specific operator had physical characteristics that were slightly unfavourable to the use of the device. He was clearly overweight, which could have affected the feel of the exoskeleton even though it was adjusted to its maximum width. In addition, his tall height brought him very close to the underbody of the passageway. Wearing the device in such an environment may have affected his perception of bulkiness. In further support of this, the same worker contradictorily stated that he found it easier to move his upper limbs. Another aspect to note is that this operator was the most targeted by ironic jokes from his colleagues during use. This may have caused him to reject the trial experience in order to avoid being the target of the other operators' irony.
Moving on to station 147, two operators were involved, referred to as the left operator (working on the corridor side) and the right operator (working on the other side). Starting with the left-hand operator, from the preliminary test onwards, he reported the benefits of the exoskeleton, communicating much greater ease of movement in his upper limbs. To quote the person concerned, "every time I raise my arms, they seem to fly, I don't feel any weight". In this case, the preliminary test did not reveal any ergonomic discomfort or hindrance to movement except when lowering the line, where the subject was forced to arch his back. The subject was also well disposed towards the device and enthusiastic about the next test. The latter, lasting 1 hour and 30 minutes, confirmed the positive feedback from the preliminary test. The exoskeleton required less effort for postural adjustment and greatly relieved the work on the subject's upper limbs. Even when using a 3.5 kg screwdriver, he only felt a slight additional load. The ergonomics of the device were rated as excellent, with the weight of the device on the shoulders and lumbar region described as very light and felt mainly during the lowering phase, even at the end of the test, even if slightly accentuated. The subject did not report any previous tendonitis, but rather soreness and slight pain in the upper limbs at the end of the pre-application shift. During the break at the end of the trial with the exoskeleton, he immediately noticed

less perceived fatigue in his upper limbs. The only negative aspects reported by the operator were slightly increased sweating, the need for specific training on how to put on the device independently and quickly, and slight discomfort with the ergonomics of the device in the line lowering work area when his back was arched backwards.

With the test of the operator on the right of station 147, similar results were expected. However, right from the preliminary test, it was noted that this operator, despite having the same tasks as his colleague on the left, worked much more in the line lowering area for reasons of comfort. which meant that his back was arched backwards or bent forwards almost all the time and his arms were almost always bent at an angle of less than 80°. Due to these conditions, the support that the exoskeleton should have provided was almost null, and ergonomics were also affected, as the sporadic situation in which the left-hand operator found himself had become the norm for the right-hand operator. In this case, it would therefore be necessary to reorganise this operator's work individually to bring it into line with that of his colleague at the workstation and thereby benefit from the support of the device. Due to these conditions, the operator did not want to continue beyond the preliminary test, complaining of restricted movement, a feeling that the device was slipping down and weight on the lower back. However, the same operator gave a positive assessment of the device's support for the upper limbs, adding that his work needed to be reorganised in order to take full advantage of the device without discomfort. Although this latest test on the production line did not produce the desired result, it did highlight the effectiveness of the device, subject to appropriate adjustments to the operator's work. However, changing working habits is a critical issue, as it must be well justified and well received by the worker, who must understand the reason for the change and accept it so that it is not seen as a criticism of their work.

Finally, the feedback from the operator involved in the laboratory tests is illustrated. He is a fourth operator who agreed to participate in this study, but who does not normally work at stations 140 and 147. As already mentioned in the previous paragraphs, his feedback refers to a simulation of working conditions and tasks carried out in the ErgoLab ergonomics laboratory. The test conditions, which were free from the stress of production line timings, and the fact that the operator in the laboratory wore the Xsens 17-sensor system in addition to the device, may have influenced the personal

considerations reported at the end. The operator did not report any ergonomic problems or other mechanical or other discomforts, except for a slight weight in the lumbar area when picking up the screwdriver from the trolley by bending his back forward and increased sweating in the lumbar area and shoulder straps. He rated the device's upper limb support very positively, as it almost completely eliminated the perceived effort even when using the screwdriver. He also praised the device's excellent dynamic adaptation during movement and the greater ease in maintaining correct posture. In conclusion, he agreed to its long-term use, subject to training on how to wear and remove it quickly in the production line working environment and subject to the decision on guidelines for managing the hygiene of the device due to increased sweating.
All four operators reported less perceived effort in their upper limbs thanks to the use of the exoskeleton. Their Borg scale assessment always ranged between levels 1/2, i.e. very light/light effort, except for the operator at station 140, who rated it as level 3, i.e. moderate, which was still an improvement compared to working without the exoskeleton.

4.2 Technical Results

This section is dedicated to the objective technical results obtained following tests in the ergonomics laboratory. The data collected using the 17-sensor Xsens system was exported in .mvn format and analyzed using ScaleFit's Industrial Athlete Software. ScaleFit produced an Excel table showing all the values collected, a video with real-time visual representations, and a report in .pdf format. Due to the large amount of data collected, it was deemed necessary to reprocess it using Matlab to calculate the parameters. The parameters chosen for analysis were:

- Percentage of time, relative to total time, during which the exoskeleton actually supports the operator's load
- Average discharge value of the device during the entire test
- Range of values of the torque acting on the scapulohumeral joint in the two cases
- Time required to reach the maximum permitted cumulative daily dose

- Time-dependent trend of the values of the torque acting on the joint in the two cases

4.2.1 Duration Percentage of Support

The percentage duration of support was calculated by observing the output videos of the test with the reproductions of the movements. Based on the percentage relief values in the center-left representation of the interface, the time was measured in which the exoskeleton, for a given interval, provided average support between the two limbs greater than 20% (times shown in the table 5.8).
At that point, all the activity intervals of the exoskeleton were added up:

$$T_{\text{supp}} = \sum \Delta t_i = 48.33\,\text{s} \tag{4.1}$$

Therefore, using:

$$T_{\text{tot}} = 60.00\,\text{s},\ T_{\text{supp}} = 48.33\,\text{s} \tag{4.2}$$

The percentage duration of the support was calculated:

$$\text{Tsupp\%} = \left(\frac{\text{Tsupp}}{\text{Ttot}}\right) \times 100 = 80.55\% \tag{4.3}$$

Thanks to this value, we have demonstrated how the exoskeleton to be implemented for this task provides effective support that is not negligible for a sufficiently long period of time to bring benefits to the user.

4.2.2 Statistical Values

In order to obtain a general overview of the orders of magnitude involved in the analysis of the agent couple on the scapulohumeral joint, it was considered useful to calculate some first-order statistical parameters.

Average Value of Support

The first statistical parameter considered was the average support value. This was calculated by taking the average of the values between the right and left shoulders for each case at each moment in time, then the difference between the values in the two cases (Cs = average torque acting without exoskeleton, Cc = average torque acting with exoskeleton) and finally the

average of the differences for all instances. Given the amount of data collected, the calculations were performed using Matlab through the script 5.1 in the appendix.
For example, for t= 0 s:

$$Cs(0) = \frac{Cs_{\text{left}} + Cs_{\text{right}}}{2} \tag{4.4}$$

$$Cc(0) = \frac{Cc_{\text{left}} + Cc_{\text{right}}}{2} \tag{4.5}$$

Then, the difference between the two cases:

$$\Delta C(t = 0\,\text{s}) = C_s(0) - C_c(0) \tag{4.6}$$

And so on for all time values.
The definition of media was then applied:

$$VM_{supp} = \frac{1}{n}\sum_{i=1}^{n} \Delta C_i = 4.63\,\text{Nm} \tag{4.7}$$

From this average value of the support, when compared to the orders of magnitude under consideration, it can be seen that the use of the exoskeleton has a significant impact on the actual final load on the shoulder joint, resulting in a considerable reduction in relation to the orders of magnitude obtained from the experimental data.

Torque Value Range

The second statistical parameter considered was the range of values assumed by the agent pair on the scapulohumeral joint. This was obtained by taking the average between the right and left values using equations 4.4 and 4.5, and calculating the difference between the maximum and minimum values:

$$Range = C_{\max} - C_{\min} \tag{4.8}$$

This step was repeated for both cases under analysis using the MATLAB script 5.1:

$$Range_s = 13.73\,\text{Nm} \tag{4.9}$$

$$Range_c = 9.83\,\text{Nm} \tag{4.10}$$

As can be deduced from the comparison between the two values, the use of the device allowed for a narrower range of values, with the upper limit shifted towards lower values compared to the case without the exoskeleton. In fact, it was found that:

$$Cs_{\max} = 14.81\,\text{Nm} \tag{4.11}$$

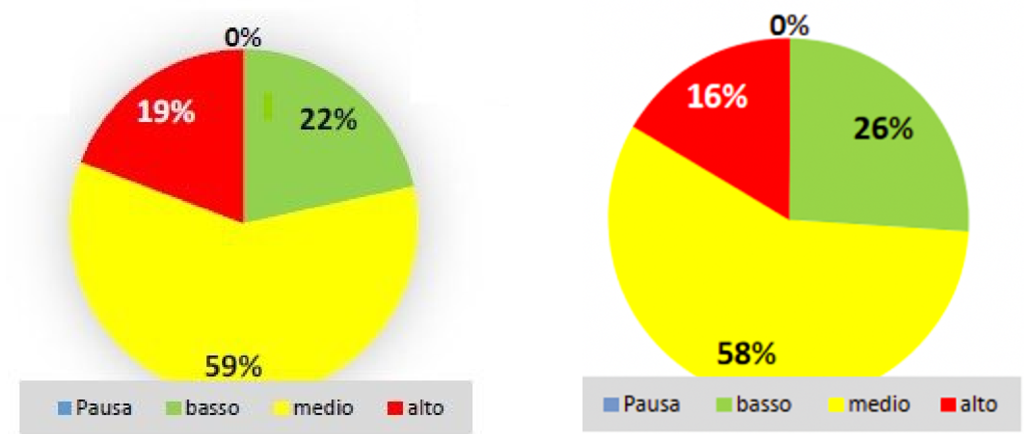
$$Cc_{\max} = 9.83\,\text{Nm} \tag{4.12}$$

This can be considered a positive aspect, as it is further confirmation that there has been a reduction in the peak values assumed by the joint and, with a narrower range of values, the joint is less subject to sudden stresses that are much higher than the average stress of the task.

4.2.3 Maximum Cumulative Dose

The cumulative dose represents the overall measure of the mechanical load to which a body part (e.g., upper limbs, spine, or specific joints) is subjected during a prolonged period of work activity. In practice, this parameter evaluates not only the intensity of a single movement, but also how long and how many times this movement is repeated. Consequently, the maximum cumulative dose represents how long the mechanical load can continue, without breaks, before causing damage to the subject subjected to it. It therefore serves to quantify the biomechanical risk associated with repeated exposure over time (daily, weekly, or throughout an entire working career) and is used, for example, in studies on wMSDs, where the accumulation of microtraumas can lead to chronic conditions. In the study of the maximum cumulative dose, moderate loads are also considered, which, if applied for long periods of time and with high repetitiveness, can become risky. It was possible to calculate this parameter thanks to the Mainz-Dortmund Dose Model integrated directly into ScaleFit, which provided the results of this calculation directly in the .pdf report file.
Considering that the exoskeleton supports 50% of its possible strength (the same amount used by operators on the production line) and wanting to analyze the two upper limbs separately, starting with the left, the report shows that, without the device, the maximum cumulative dose would be reached in 03:05:51 hours without breaks, while with the use of the exoskeleton, this

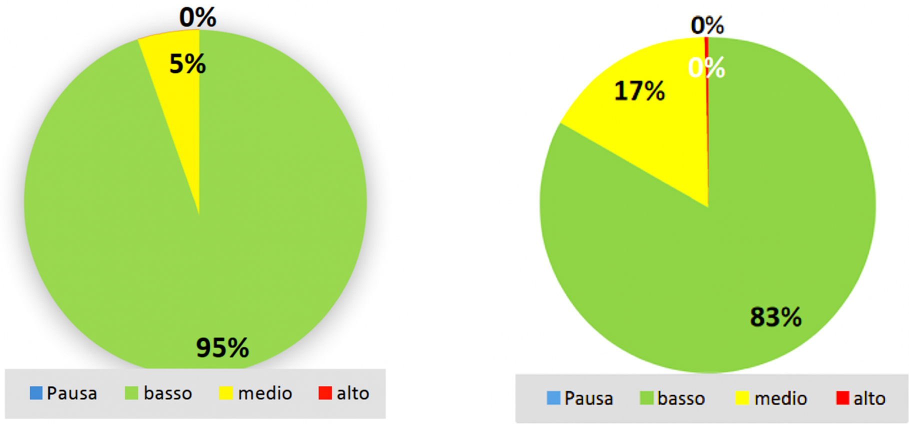
time becomes 06:40:33 under the same conditions. As expected, the same behavior is seen in the time it takes to reach the maximum cumulative dose for the right upper limb, which goes from 02:53:53 hours to 06:45:18 hours. This result is also supported by the variation in the division of time throughout the entire test between intervals with low, medium, or high effort. Low effort refers to a torque acting on the scapulohumeral joint of less than 7 Nm not including the extreme (green color), medium refers to a value between 7 Nm and 9 Nm including the extremes (yellow color), and high effort refers to a torque value greater than 9 Nm.
The pie charts below, taken from the report, show that, in the case of tasks performed without the aid of the device, there is a significant percentage of time during which the subject works at high effort, more than half of the test time is characterized by medium effort and the percentage of time that the operator works with low effort is only slightly higher than that with high effort.



Right Upper Limb *Left Upper Limb*

Figure 4.1. Percentage intervals of effort types without Exoskeleton

However, analyzing the graphs for device usage, it can be seen that most of the test duration is now characterized by low effort for almost all tests, a total elimination of time intervals corresponding to high effort, and very short periods of medium effort in relation to the total test time. The laboratory tests were carried out under the same conditions as the line tests, i.e., with 50% support from the device.



Right Upper Limb *Left Upper Limb*

Figure 4.2. Percentage intervals of effort types with Exoskeleton

These characteristics are further accentuated if a higher percentage of support from the exoskeleton is set in ScaleFit. In order to further investigate aspects relating to the cumulative dose, an additional simulation was carried out during the reprocessing phase with 75% support, resulting in a report file. The additional simulation showed consistency with the results previously obtained. In fact, there was a drastic increase in the time needed to reach the maximum cumulative dose, which increased by +219% in the case of the left limb and +280% in the case of the right limb, between the case without the use of the exoskeleton and the case with the application of the device. Analyzing the times corresponding to the various intensities of effort, in the case of 75% support of the maximum possible, the entire test is characterized by low effort for almost the entire time and only a minimal, almost negligible, portion of 2% or 3% of medium effort.

4.2.4 Time Trend of Torque

The temporal trends of the values of the torque acting on the scapulohumeral joint in cases with and without an exoskeleton were obtained by plotting the values of the acting torque with the corresponding instants sampled by the sensor program.

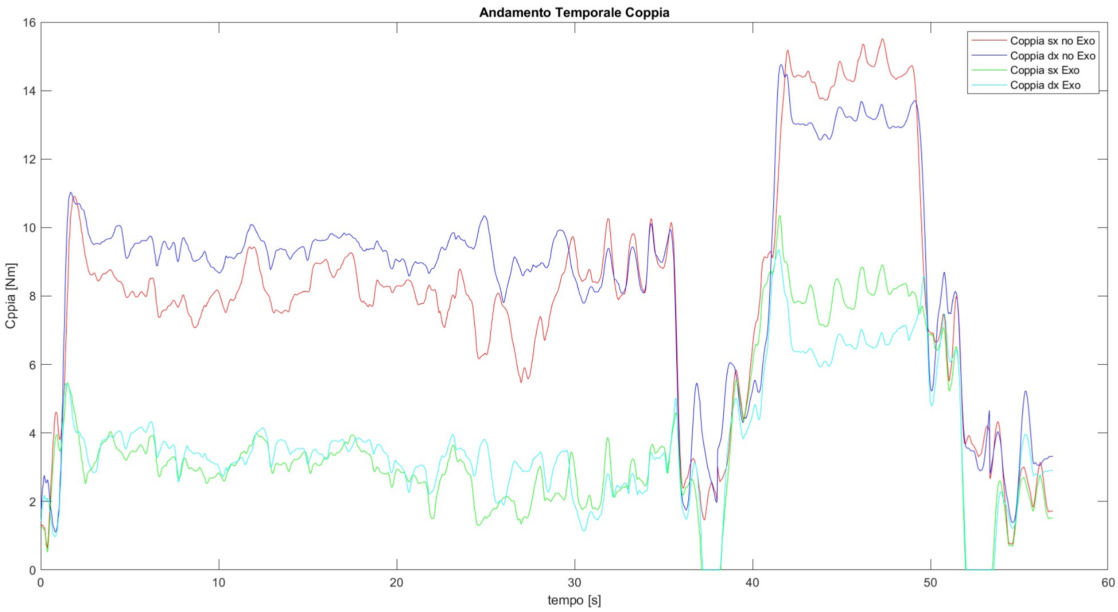


Figure 4.3. Temporal trend of torque values

As can be seen from the graph, when using the exoskeleton, the curve of values remains significantly below the values without the exoskeleton. This trend is particularly noticeable in the plateau areas, corresponding to the test periods in which the operator kept their arms raised at a constant height above their head. In particular, both in the first, between 5 s and 35 s, where there is a very significant decrease in trends around 9 Nm, which drop to about 3 Nm with the use of the exoskeleton, and in the second, between 40 s and 50 s, where the trend, instead of remaining around 14 Nm, settles at 8Nm with the use of the exoskeleton.
Other areas of the graph that are useful to analyze are the dips just before and just after the second plateau, at 37 s and 53 s. These two areas correspond to the intervals in which the operator bent down to pick up or put down the screwdriver. During these phases, when the operator bent forward and abducted his arms from his body while holding the screwdriver to pick it up or put it down, the exoskeleton provided 100% mechanical relief, causing the torque acting on the scapulohumeral joint to be completely eliminated, as can be clearly seen from the corresponding curves in the graph.

Chapter 5

Conclusions

The thesis presented aimed to design and evaluate the integration of an exoskeleton for the upper limbs into an assembly line in the automotive sector, following a small-scale experimental testing campaign. This activity allowed for an in-depth and systematic analysis of both the ergonomic and biomechanical aspects related to the operations performed by operators and the practical implications of integrating an innovative technological device into a complex production context. This chapter summarizes the main results obtained, discussing their significance and impact in relation to the initial objectives, and then outlines possible future developments.
The decision to conduct a small-scale test campaign was made for two reasons:

- The production line in question, being a recently built state-of-the-art line that uses rotating hooks to transport cars during assembly, had already drastically reduced the number of workstations with tasks in the underbody area that posed a risk of musculoskeletal injuries.
- A previous large-scale study carried out by a Stellantis working group showed that, for the proper introduction of an exoskeleton, a targeted study tailored to individual operators in workstations deemed suitable for implementation is more useful than a massive and indiscriminate introduction in all workstations.[4]

Continuing the study with this method provided an opportunity to focus attention on the individual needs and impressions of each operator involved, allowing for specific analysis of the needs and opinions that arose before, during, and after the tests.

The results obtained from this work show that the device has a clearly positive and beneficial impact on the operator, with a consequent improvement in working conditions. The laboratory measurements, supported by the calculation of average support values, the comparison of behavior curves as a function of time of the torque acting on the scapulohumeral joint and the drastic increase in the time needed to reach the maximum daily cumulative dose when using the exoskeleton, show a decrease in the torque values acting on the scapulohumeral joint and an improvement in working conditions. Of particular importance is the increase of the time needed to reach the maximum daily cumulative dose and the significant decrease in the values of the acting torque, when using the exoskeleton. However, subjective data suggest that this is not enough, as the emotional sphere, the working environment, the predisposition to change, and the choices of working comfort of each individual operator also influence the user's relationship with the device.
Of the total number of operators involved, 50% said they were willing to implement the measure immediately and permanently, 25% were strongly opposed, and the remaining 25% were in favor, subject to changes to certain aspects of their job.
Although the decision to conduct a small-scale, ad hoc trial on each operator was made by choice rather than necessity, it should be noted that, despite the encouraging results, it would be useful to extend this study to more plants, using the same method and paying the same attention to each operator involved, in order to gain a more complete picture and achieve greater applicability of the device. This would also allow the company to save money by purchasing the device in large quantities.
Another important aspect to note is the lack of long-term feedback on the implementation of the device, as well as the significant lack of historical data on the subject in the literature. In this sense, there is a fundamental problem, because until one or more entities take the risk of implementing them on a large scale, it will be impossible to obtain realistic data on the long-term effects, but until this type of massive implementation takes place, data on long-term effects will continue to be scarce and insufficient. As is often the case with innovations, we are faced with a reality where the greatest difficulty in implementation lies in getting people to accept the device psychologically and effectively incorporating it into their daily work. It would therefore be useful to expand this study not only to a larger number of establishments but also to extend it over time, while maintaining the focus and care of the individual subject involved.

In conclusion, based on an in-depth preliminary study, the work carried out in this thesis represents a further fundamental step towards the conscious integration of exoskeletons into automotive production processes, with the ultimate goal of improving workers’ conditions and the sustainability of the industrial system, while keeping the physical and mental well-being of the operators who will be using the exoskeleton at the center of the process.

Appendix

5.1 Appendix A: Excel Tables

Possible Hazard	Situation Description	Comments	Risk Evaluation	Need for action
Mechanical Hazards	Unguarded Moving Parts	Protruding Hooks	Low	No
	Parts with dangerous surfaces	Chassis Underside	Low	No
	Possible falls	Falling Equipment	Medium	No
	Exoskeleton's Unguarded Moving Parts	The joint unit or the Extender	Low	Yes
Biological Hazards	Fungi, bacteria	No		No
	Hygiene	Potential excessive perspiration	Low	Yes
Thermal Hazards	Contact with hot/cold media	No		No
	Overheating due to prolonged use	Requiring Verification		
Physical Hazards	Noise	No		No
	Vibration	Under the limits	Low	No
	Electromagnetic Fields	Requiring Verification	High	Yes
Hazards by conditions of the working environment	Dusty Environment?	No		No
	Catching and dragging	Low line speed with the hook safely secured.	Low	No

Table 5.1. Risk Table 1

Possible Hazard	Situation Description	Comments	Risk Evaluation	Need for action
Mental Factors	Mental Stress?	No pre-application, Requiring Verification post-application	Low	Yes
	Social Isolation?	Requiring Verification		
Physical Stress/Work Intensity	Physical Stresses caused by the exoskeleton	Requiring Verification		
	Posture Adaptation	Requiring Verification		
Work Organization and Behaviour	Workspace suitable?	Yes		No
	Combination of exoskeleton and other personal protective equipment	Requiring Verification		
	Safety and Health rules during Emergencies	Already Established Guidelines		No
Other Hazards	Constrained Mobility	Requiring Verification		
	Hazards from Secondary Tasks	No		No
Ergonomic Issues	Misalignments with the human body	Requiring Verification		
	Parasite forces and unwanted compressions	Requiring Verification		
	Dynamic Adaptation	Requiring Verification		
	Unfavorable Position	Component picking from a side-line container (waist height)	Low	No

Table 5.2. Risk Table 2

Safety Objective	Measure/Comment	Person Responsible	Deadline	Completed?	Effectiveness
Protection of lower extremities from falling heavy objects	Safety shoes			Yes	Yes
Protection of upper extremities from hazardous mechanical stresses	Protective gloves against mechanical risks			Yes	Yes
Head protection from impacts and falling heavy objects	Helmet			Yes	Yes
Protection from entanglement, impact, and pinching in moving objects	Rubber guards on protruding parts of swivel hooks			Yes	Yes
Protection from entrapment in exposed moving mechanisms of the exoskeleton	Protective gloves against mechanical risks; appropriate training for at-risk personnel			Yes	Yes
Protection of long hair from entanglement in exposed moving mechanisms	Requirement for appropriate hair management; protective helmet; verification of presence of at-risk individuals			Yes	Yes
Maintenance and hygiene of the exoskeleton to mitigate excessive sweating	Cleaning of the exoskeleton by designated personnel during breaks and between test sessions using alcohol-based disinfectant wipes (ACE brand) without the need for washing off			Yes	Yes
Prevention from magnetic fields of the exoskeleton	Preliminary consultations with the plant's occupational health specialist, who confirmed that none of the operators involved were carriers of active implantable devices.			Yes	Yes

Table 5.3. List of measures

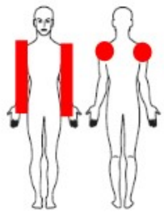
Task: Workstation 140 Fix Bielletta UTE Chassis			Comments
Identification of regions to be relieved	Location of complaints (pain, discomfort, numbness) Indicate them on the diagrams beside.		Work on upper limbs, with primary stress on the shoulder joint
	Presence of occupational accidents/diseases	No	
Description of physical characteristics (efforts, postures, etc.)	Manual handling/Load carrying	Yes	Handling of right and left studs (3.5kg each)
	Postures: – dynamic postures? – long, static postures?	Dynamic postures but static shoulder posture	
	Use of tools or equipment	Yes	Screwdrivers 2kg; screwdriver on reaction arm (linkage fastening)
Description of environmental characteristics	Configuration of the work space (dimensions, circulation, etc.)	Workers not in close proximity, spacious work environment	Presence of a transport cart following the car body, with the car body attached to slightly protruding swivel hooks
	Physical work environment (temperature, humidity, etc.)	All within average values and compliant with standards	
	Floor (quality of the floor, uneven floor heights, etc.)	No risk arising from the floor composition	Work on a fixed platform
	Protective equipment (personal and collective)	Safety shoes, protective gloves and protective helmet	
Description of work organisation	Individual work or team work?	Individual	
	Possibility of breaks?	Three fixed 10-minute breaks during the shift, with a lunch break at the end of the shift	

Table 5.4. Task Table - Workstation 140

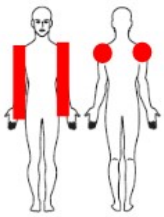
Task: Workstation 147 Left Wheel Well UTE Chassis			Comments
Identification of regions to be relieved	Location of complaints (pain, discomfort, numbness) Indicate them on the diagrams beside.		Work on upper limbs, with primary stress on the shoulder joint
	Presence of occupational accidents/diseases	No	
Description of physical characteristics (efforts, postures, etc.)	Manual handling/Load carrying	No	
	Postures: – dynamic postures? – long, static postures?	Dynamic postures but static shoulder posture	
	Use of tools or equipment	Yes	2kg screwdrivers, small hammer, punch
Description of environmental characteristics	Configuration of the work space (dimensions, circulation, etc.)	Workers not in close proximity, spacious work environment	Presence of a transport cart following the car body, with the car body attached to slightly protruding swivel hooks
	Physical work environment (temperature, humidity, etc.)	All within average values and compliant with standards	
	Floor (quality of the floor, uneven floor heights, etc.)	No risk arising from the floor composition	Work on a fixed platform
	Protective equipment (personal and collective)	Safety shoes, protective gloves and protective helmet	
Description of work organisation	Individual work or team work?	Individual	
	Possibility of breaks?	Three fixed 10-minute breaks during the shift, with a lunch break at the end of the shift	

Table 5.5. Task Table - Workstation 147

Possible Hazard	Situation Description	Comments	Risk Evaluation	Need for action
Mechanical Hazards	Unguarded Moving Parts	Protruding Hooks	Low	No
	Parts with dangerous surfaces	Chassis Underside	Low	No
	Possible falls	Falling Equipment	Low	No
	Exoskeleton's Unguarded Moving Parts	The joint unit or the Extender	Low	No
Biological Hazards	Fungi, bacteria	No		No
	Hygiene	Potential excessive perspiration	Low	No
Thermal Hazards	Contact with hot/cold media	No		No
	Overheating due to prolonged use	No		No
Physical Hazards	Noise	No		No
	Vibration	Under the limits	Low	No
	Electromagnetic Fields	No	Low	No
Hazards by conditions of the working environment	Dusty Environment?	No		No
	Catching and dragging	Low line speed with the hook safely secured.	Low	No

Table 5.6. Risk Table 1 post introduction of the Exoskeleton

Possible Hazard	Situation Description	Comments	Risk Evaluation	Need for action
Mental Factors	Mental Stress?	No		No
	Social Isolation?	Sometimes the worker wearing the device was the target of ironic jokes from colleagues. Depending on the subject, this was either welcomed positively with irony or not.	Low	Yes
Physical Stress/Work Intensity	Physical Stresses caused by the exoskeleton	Weight felt only when lowering the line height, forcing the operator to arch their back backward	Low	No
	Posture Adaptation Problems	No		No
Work Organization and Behaviour	Workspace suitable?	Yes		No
	Problems of combination of exoskeleton and other personal protective equipment	No		No
	Safety and Health rules during Emergencies	Already Established Guidelines		No
Other Hazards	Constrained Mobility	In line lowering, depending on the subject and the customization of the device measurements	Low	No
	Hazards from Secondary Tasks	No		No
Ergonomic Issues	Misalignments with the human body	No		No
	Parasite forces and unwanted compressions	No		No
	Problems of Dynamic Adaptation	No		No
	Unfavorable Position	Component picking from a side-line container (waist height)	Low	No

Table 5.7. Risk Table 2 post introduction of the Exoskeleton

durata prova in minuti	1:00:00
tempi cronometrati in secondi	00:34:16
	00:02:35
	00:08:23
	00:03:19
tempo totale supporto in secondi	0:48:33
tempo non supporto	0:11:27

Table 5.8. Support Times Table

5.2 Appendix B: Matlab Scripts

```
close all
clearvars
pack
clc

%Caricamento tabella excel
tab=readtable("tabella valori sensori.xlsx");
%inizializzo vettori di zeri
Cs=zeros(height(tab),1);       %Vettore coppia media tra dx
    e sx in ogni istante, caso senza esoscheletro
Cc=zeros(height(tab),1);       %Vettore coppia media tra dx
    e sx in ogni istante, caso con esoscheletro
DeltaC=zeros(height(tab),1);   %Vettore differenze tra
    coppie in ogni istante

%Calcolo per ogni istante
for i=1:height(tab)
Cs(i)=(tab{i,2}+tab{i,3})/2;
Cc(i)=(tab{i,6}+tab{i,7})/2;
DeltaC(i)=Cs(i)-Cc(i);
end

VMsupp = mean(DeltaC);            %Valor medio del supporto

%Calcolo range di valori
%Caso senza esoscheletro
Csmax=max(Cs);
Range_s = max(Cs)-min(Cs);
%Caso con esoscheletro
Ccmax=max(Cc);
Range_c = max(Cc)-min(Cc);

%Grafico andamento temporale coppia
asset = tab{:,1};
Cs_sx = tab{:,2};
Cs_dx = tab{:,3};
Cc_sx = tab{:,6};
Cc_dx = tab{:,7};


figure (1)
```

```
plot (asset,Cs_sx,'r', asset,Cs_dx,'b', asset,Cc_sx,'g',
   asset,Cc_dx,'c');
xlabel('tempo [s]'); ylabel('Cppia [Nm]');
title('Andamento Temporale Coppia');
legend('Coppia sx no Exo','Coppia dx no Exo', 'Coppia sx
   Exo','Coppia dx Exo');
```

Listing 5.1. Script Matlab

5.3 Appendix C: OCRA Checklist Tables

MULTIPLIER OF THE NET DURATION OF THE REPETITIVE WORK PERFORMED DURING THE SHIFT	
Net duration of repetitive work (minutes)	Duration multiplier
60-120	0.5
121-180	0.65
181-240	0.75
241-300	0.85
301-360	0.925
361-420	0.95
421-480	1
Over 480	1.5

Table 5.9. Duration Multiplier Conversion Table [6]

No. of hours without adequate recovery time	Recovery multiplier	Difference for 4 hours without recovery (%)
0	1	-24.8%
0.5	1.025	-22.9%
1	1.05	-21.1%
1.5	1.086	-18.3%
2	1.12	-15.8%
2.5	1.16	-12.8%
3	1.2	-9.8%
3.5	1.265	-4.9%
4	1.33	0.0%
4.5	1.4	5.3%
5	1.48	11.3%
5.5	1.58	18.8%
6	1.7	27.8%
6.5	1.83	37.6%
7	2	50.4%
7.5	2.25	69.2%
8 or more	2.5	88.0%

Table 5.10. Recovery Multiplier Conversion Table [6]

FREQUENCY	A	B
	Frequency factor score when brief interruptions ARE possible	Frequency factor score when brief interruptions ARE NOT possible
<22.5	0.0	0.0
22.5 to 27.4	0.5	0.5
27.5 to 32.4	1	1
32.5 to 37.4	2	2
37.5 to 42.4	3	4
42.5 to 47.4	4	5
47.5 to 52.4	5	6
52.5 to 57.4	6	7
57.5 to 62.4	7	8
62.5 to 67.4	8	9
67.5 to 72.4	9	10
> 72.4	9	10

Table 5.11. Frequency Factor Conversion Table [6]

FORCE OF 3-4	
Time as %	Score
5	0.50
10	0.50
18	1.00
26	1.50
33	2.00
37	2.50
42	3.00
46	3.50
50	4.00
54	4.50
58	5.00
63	5.50
67	6.00
75	6.50
83	7.00
92	7.50
100	8.00

Table 5.12. Force Factor Conversion Table [6]

Time in awkward posture	Score
Shoulder The arms are kept at about shoulder height, without support, (or in other extreme postures) for	
10% - 24% of the time 25% - 50% of the time 51% - 80% of the time more than 80% of the time	2 6 12 24
Elbow The elbow executes sudden movements (wide flexion-extension or prono-supination, jerking movements, striking movements) for	
25% - 50% of the time 51% - 80% of the time more than 80% of the time	2 4 8
Wrist The wrist must bent in an extreme position, or must keep awkward postures (such as wide flexion/extension, or wide lateral deviation) for	
25% - 50% of the time 51% - 80% of the time more than 80% of the time	2 4 8
Hand The hand take objects or tools in pinch, hook grip, pinch or other different kinds of grasp for	
25% - 50% of the time 51% - 80% of the time more than 80% of the time	2 4 8

Table 5.13. Posture Factor Conversion Table [6]

ADDITIONAL FACTOR	
Choose one answer per block. The final score is the sum of the two partial scores.	
Block A: Physico-mechanical factors	
2	**Inadequate** gloves (uncomfortable, too thick, wrong size) are used more than half the time for the task.
2	Presence of 2 or more sudden, jerky movements per minute.
2	Presence of at least 10 repeated impacts (use of hands as tools to hit) per hour.
2	Contact with cold surfaces (less than 0ºC) or performance of tasks in cold chambers for more than half the time.
2	Use of vibrating tools at least one third of the time. **Assign a score of 4** if these tools involve a high degree of vibration (e.g., pneumatic hammers, etc.).
2	Tools are used that cause compression of muscle and tendon structures (check for the presence of redness, calluses, wounds, etc., on the skin).
2	More than half the time is spent performing precision tasks (tasks on areas of less than 2 or 3 mm), requiring the worker to be physically close to see.
2	More than one additional factor (e.g., ...) is present at the same time for more than half the time.
3	One or more additional factors (e.g., ...) are present almost the entire cycle.
Block B: Socio-organisational factors.	
1	The work rate is determined by the machine, but 'recovery spaces' exist allowing the rate to be sped up or slowed down.
2	The work rate is entirely determined by the machine.

Table 5.14. Assessment of Additional Factors Table [6]

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