POLITECHNIC OF TURIN

Department of Mechanical and Aerospace engineering

Master of Science in Automotive Engineering

Final Dissertation

Industry 4.0 and process ergonomics:

Exoskeletons application in Automotive

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Il progresso è impossibile senza cambiamento.

Coloro che non cambiano le loro menti,

non potranno mai cambiare null'altro

To my parents,

who have always supported me

in every challenge undertaken,

especially in this one.

To my sister, Eleonora,

who always urged me to my best

and to do it best.

To my grandparents,

the ones still alive and the ones

who are no longer there.

To my boyfriend, Alberto,

partner of study, of exams and,

above all, of adventures.

Thank you for enduring

and supporting me

along this journey.

To my professor Maria Pia Cavatorta,

who made me discover the ergonomics world

and has followed me in this

Master thesis journey.

In general, to everyone who

was able to give me a smile

and, in some way,

a piece of Happiness.

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List of abbreviations

MSD	Muscle Skeletal Disorder
ISO	International Organization for Standardization
UNI	Ente nazionale Italiano di Unificazione
OSHA	Occupational Safety and Health Act
EMG	Electromyography
INAIL	Istituto Nazionale Assicurazione Infortuni sul Lavoro
BCG	Boston consulting group
GE	General Electrics
OEM	Original Equipment Manufacturer
GDP	Gross Domestic Product
TL	Team Leader

Executive summary

In the era of continuous improvement, in the mindset of continuous evolution, in the middle of a completely new technological revolution, the interaction between human being and new technology has become a key component for the development of a new type of manufacturing.
The introduction of "smart factory" and "intelligent production" concepts took with them challenge of good human-machine interaction, not only in terms of use but also in terms of acceptability from workers' point of view.

A new frontier of human-machine interaction, beyond the known interaction robot(automation)-operator, has emerged: the human-exoskeleton interaction.

History told us that every progress is characterized by a change, most of the time a drastic change. Meanwhile, it told us also that changes could be very difficult, because it is linked with people change of mind, which is not so easy as it seems.
Every individual, with its mindset, with its culture, is unique and thus, he will interact and react to a new technology in a wonderful and unique way.

With the tendency to progress to industry 4.0, OEMs and Car Makers must carefully manage the introduction of new technologies, taking into consideration operators mindset, in order to make the change not only possible, but also effective, efficient and a great success for the company.

Someone said: "Progress cannot be done without a change, nobody that is not able to change his mind, can change everything else". Well, after this Master Thesis, I can reasonably state that, if we are able to understand and interpret the needs of the operators in the interaction with new technologies, probably they will give us more ideas to progress that the ones we have thought, and the progress will happen faster and more naturally.

It is true that we cannot change anything without changing our minds but, more important, we cannot think to progress without playing in team. Playing in team means also to have the capability to understand the limits of ideas only studied on the paper or in laboratory.

Moreover, it means to understand that experimentations in plants are not only a mere collection of results, but rather a great collection of ideas from people that really perform the tasks every day, thousand times per day.

The study presented in the following pages would present thus, not only the benefits, in economics terms, of human-exoskeleton interaction (computed virtually for the Chairless Chair exoskeleton), but also the problems related to the creation of a completely new technology that is in contact with human body and must interact with him, as COMAU prototype is, and its introduction in a manufacturing field as FCA plants are.

Study objectives

The primary objective of this study is to analyze possible application of industrial exoskeleton in a real industrial field as FCA is in order to improve workers' behavior.
To better understand applications and drawbacks of this new type of technology, three types of exoskeleton are tested currently in FCA: one for the upper body, one for the legs and one for the back.
The first chapter is devoted to the background and external factors that led to the development of this study, in particular to the concept of industry 4.0, ergonomics and process ergonomics, and finally to the new technology under study: the exoskeletons.
The second chapter is devoted to the analysis of one commercial exoskeleton: Chairlesschair by Noonee. The analysis conducted is based on virtual simulation of the different posture assumed by the operator during the task (with and without exoskeleton) through the use of 3DSSPP software and output data coming from Anybody software.
In the third chapter instead, an analysis related to the application of an exoskeleton for the back (Laevo) in an industrial field is deployed, in order to underline and point out the main problems related to the application in a manufacturing field of a technology developed and tested only in laboratory.
The fourth chapter is centered on the evaluation of a new type of technology created in partnership with COMAU/IUVO/OSSUR. Some trials in line are conducted, through the use of a prototype, in order to better understand the applicability of this device in an industrial environment, in particular in an automotive production environment in which one of the main problems is the lack of space and the risk to damage the final product, even with small tools.
The fifth chapter is devoted mainly to strategy and business considerations. A more detailed analysis of the characteristics of the operators is conducted through the use of McKinsey matrix, in order to evaluate some guideline to select the operators for the new trials. In the meantime, due to the widespread presence of underbody workstations in FCA (about 200 workers), a study of economic benefits with respect to costs was developed to better understand this new fast-growing market, not only from COMAU point of view, but for all exoskeleton industries in general.
To sum up, a chapter related to the final conclusion was deployed in order to summarize the results of the study and have a clear view of the whole work done.

1. Industry 4.0

Industry 4.0 could be defined as the next phase of the manufacturing sector digitalization, driven by four main challenges:

1. the amazing rise in data volumes, computational power, and connectivity, especially new low-power wide-area networks;
2. analytics and business-intelligence capabilities birth;
3. new forms of human-machine interaction (e.g. touch interfaces, augmented-reality systems);
4. improvements in digital instructions transfer to the physical world (e.g. advanced robotics and 3-D printing).

The reason for the "4.0" is that this is considered the fourth major evolution in modern manufacturing, following the lean revolution of the 1970s, the outsourcing phenomenon of the 1990s, and the automation in the 2000s (1).

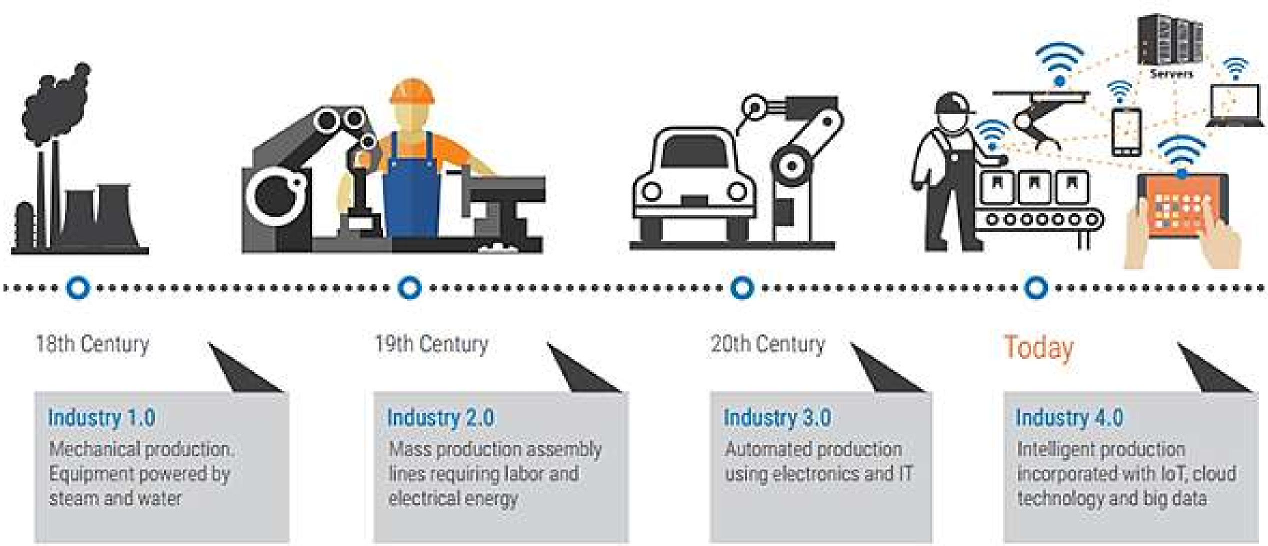


Figure 1. The four main Industrial revolutions [BCM Advanced Research, November 2017]

Industry 4.0 offers to the manufacturing field new tools for smarter energy consumption, greater information storage in products and pallets (so-called intelligent lots), and real-time yield optimization.

The term Smart Factory, strictly related to industry 4.0, describe an environment where machinery and equipment are able to improve process through automation and self-optimization. The benefits extend beyond just production into functions like planning, supply chain logistics and product development.

At the center of Smart Factory development, we find the technology that make data collection possible, like sensors, motors, robotics present on the line.

Pillars of Industry 4.0 are essentially nine (2):

1) ***Autonomous robots***. Robots provide an ever-wider range of services and are becoming more autonomous, flexible, and cooperative. They will interact with one another and work safely with humans. Eventually, they will be able to learn from humans.
2) ***Simulation***. 3D simulation of product development, material development and production processes will become widespread. It will leverage real-time data to mirror the physical world in a virtual model that will include machines, products, and humans. Operators will be able to test and optimize the machine settings for the next product even before production starts improving quality.
3) ***Horizontal and vertical system integration.*** Today, information systems are not fully integrated. Companies are rarely connected with their suppliers and customers. With Industry 4.0 the entire organization will be interconnected.
4) ***The Industrial Internet of Things***. With the Industrial Internet of Things, an ever-greater number of products will incorporate intelligence and be connected using standard protocols. This will enable real-time responses.
5) ***Cybersecurity***. Connectivity and communication protocols are becoming the norm. Protecting information systems and manufacturing lines from cybercrime threats is becoming a critical issue. Sophisticated identity and machine access management systems will be used to provide secure, reliable communications.
6) ***The Cloud.*** The operating processes of Industry 4.0 require more data sharing across sites and companies. The performance of cloud technologies will improve, achieving response times of mere milliseconds.
7) ***Additive manufacturing***. With Industry 4.0, these technologies will be chosen for their very high performance in producing small batches of customized products. Decentralized systems will reduce transportation and inventory management costs.

8) ***Augmented reality***. Augmented-reality tools will provide operators with the real-time information they need for faster decision-making and for improving work processes.
9) ***Big data and analytics***. There are still massive sets of untapped data in the industrial world. Their analysis will optimize production quality, save energy, and improve services. The goal is to allow real-time decision-making.

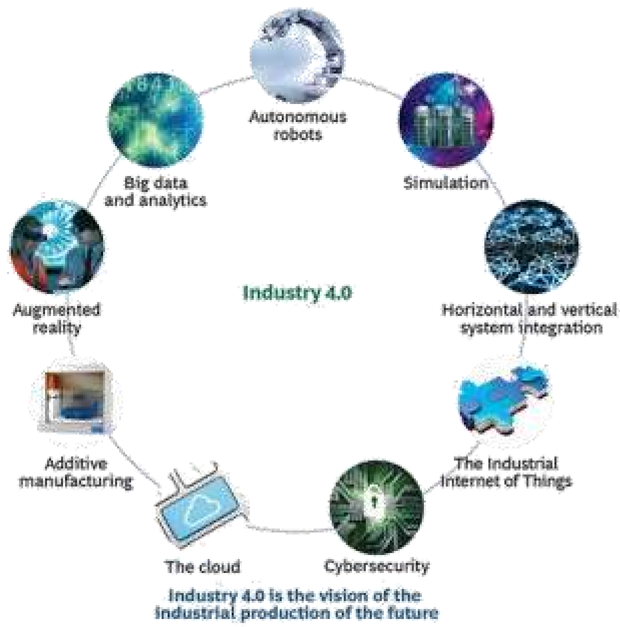


Figure 2 Industry 4.0 nine pillars [www.bcgperspectives.com, November 2017]

Industry 4.0 is a social and economic challenge that rethinks the factories through the digital, how to design objects, to create prototypes, monitoring the assembly line in real time. It has the main objective to boost the economy, offering innumerable opportunities to the manufacturing system and a new life and identity to the factories through the connection between the real and the virtual world. (3)

At the center of the great digital revolution there is the "Man" with his needs and requirements.

Men and machine work together but the user centrality is the main guideline for digital transformation, demonstrating the superiority of man work on the machine.

Nowadays, due to the fast evolution of manufacturing technologies and due to the propensity of industries to evolve to *Industry 4.0*, people are expected to interact more and more with sophisticated hardware and software. The roles that people take on will evolve from what they are currently doing in today's factories. People will take on more complex roles while automation will conquer the tasks that are repeatable.

In the mindset of industry 4.0, virtual reality is considered as an innovative tool to manage and optimize a production process, considering every aspect. The enjoyment of a virtual environment has the purpose to increase the productivity of a production plant.

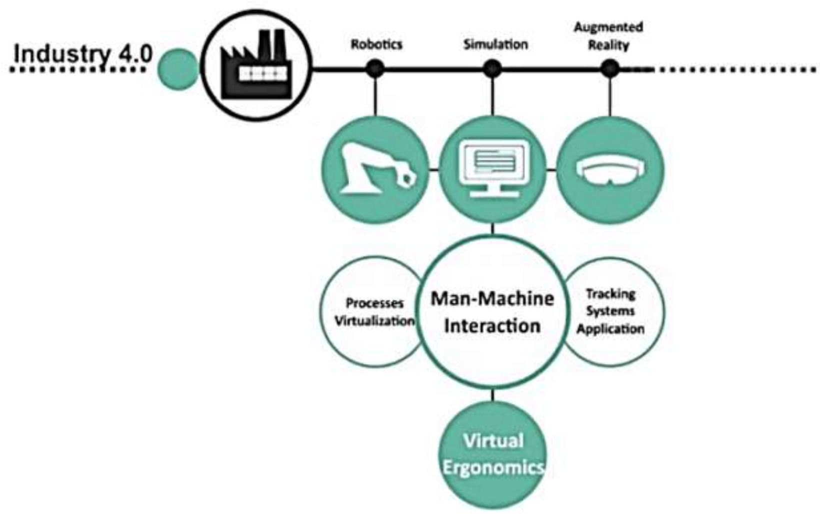


Figure 3 Virtual simulation and ergonomics in industry 4.0 [*Design and Digital Manufacturing: an ergonomic approach,* Laudante Elena and Caputo Francesco, 2016]

1.1.Ergonomics

In the mindset of Industry 4.0, the role of ergonomics specialists become more and more important to optimise work performance and worker health and safety.
The ergonomics specialist became more and more important due to the increased number of technical evolutions and the increased number of interactions between humans and machine.
Ergonomics is defined as the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimise human well-being and overall system performance [*International ergonomics association*].
The terms "Ergonomics" and "human factors" can be used interchangeably, even if with "human factor" term is usually related to the total system in which people work, whereas "Ergonomics" is related to the physical aspect of the work environment. (4)
The term Ergonomics derive from the Greek *ergon* (work) and *nomos* (laws) to denote the science of work, ergonomics is a systems-oriented discipline which now extends across all aspects of human activity.
Ergonomists and human factors specialists contribute to the design and evaluation of tasks, jobs, products, environments and systems in order to make them compatible with the needs, abilities and limitations of people.

Figure 4 Ergonomics help harmonize things that interact with people [http://www.iea.cc, October 2017]

It is possible to define two types of ergonomics:

- *Proactive ergonomics*: is the practice of planning an ergonomic process early in to product development. The intention is to preemptively reduce the risk of any human-error that may affect production somewhere down the line.
- *Reactive ergonomics*: is implemented after a problem has already occurred, such as a risk report written to suggest measures to reduce the risk that the same errors will occur again during production.

Furthermore, it is possible to split Ergonomics into Process and Product Ergonomics, considering the field of application.

For the purpose of this document we will only deploy Process Ergonomics, which is the one strictly related to the production line.

1.2.Process ergonomics

Process Ergonomics is the branch that strictly relate to the design of the workstations, it is focus on workers.

Nowadays process ergonomics is trying to increase emphasis on equal opportunities, considering the problem of increasing ageing workforce, "humanize" work for a stable, motivated and productive workforce, try to reduce costs related to MSD and reintegrate people at work.

Through the analysis of the data coming from OSHA perspectives and studies, it is possible to notice that workforce's age will grow during the years up to 2060.

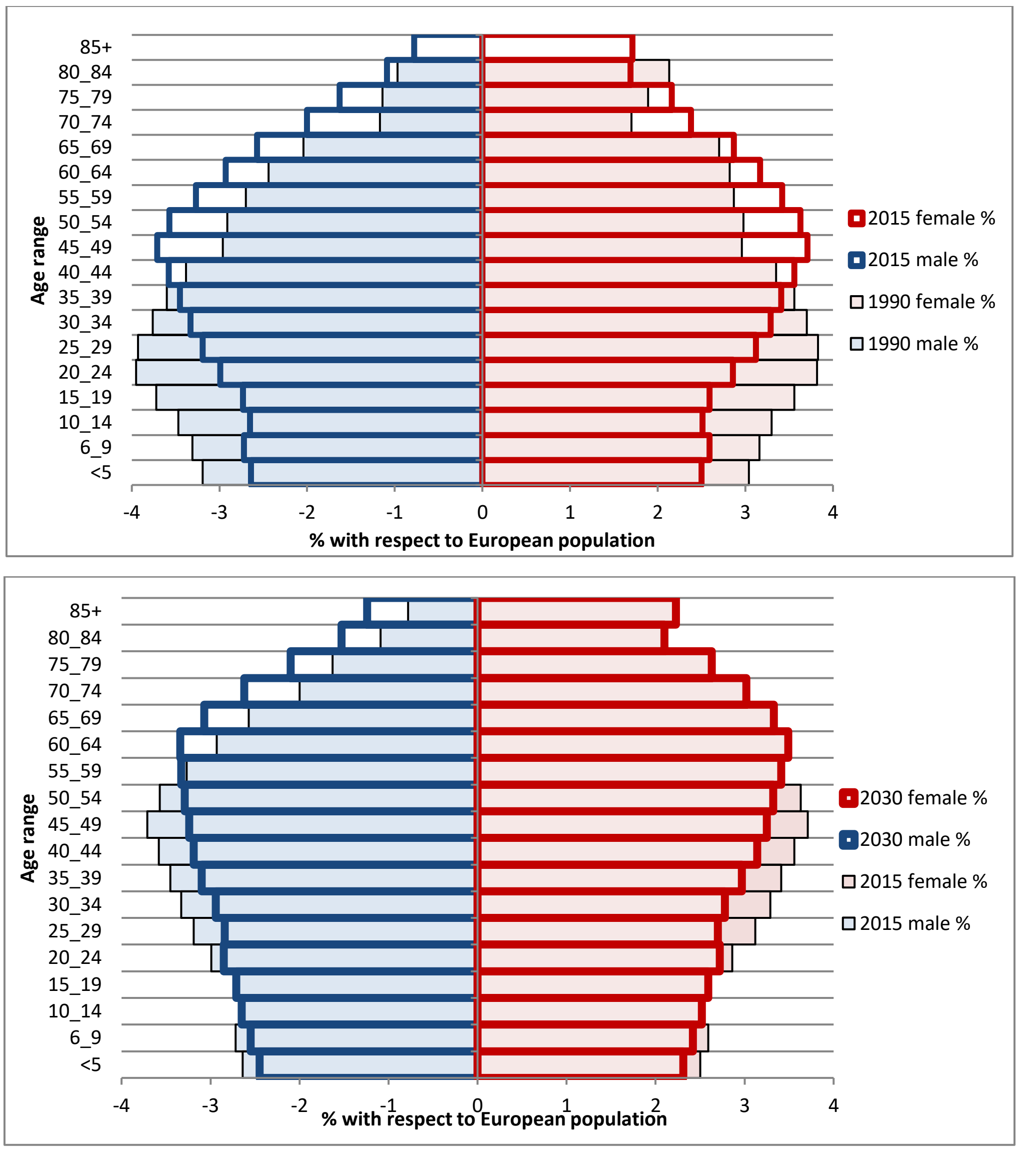


Figure 5 Age pyramids related to OSHA projection, [elaboration of data November 2017]

If, in particular, we analyse the trend related to male gender (the one analysed for the experimentations) in work age range, it is possible to see that the percentage of male in the 45-64 age range is growing more and more through the years.

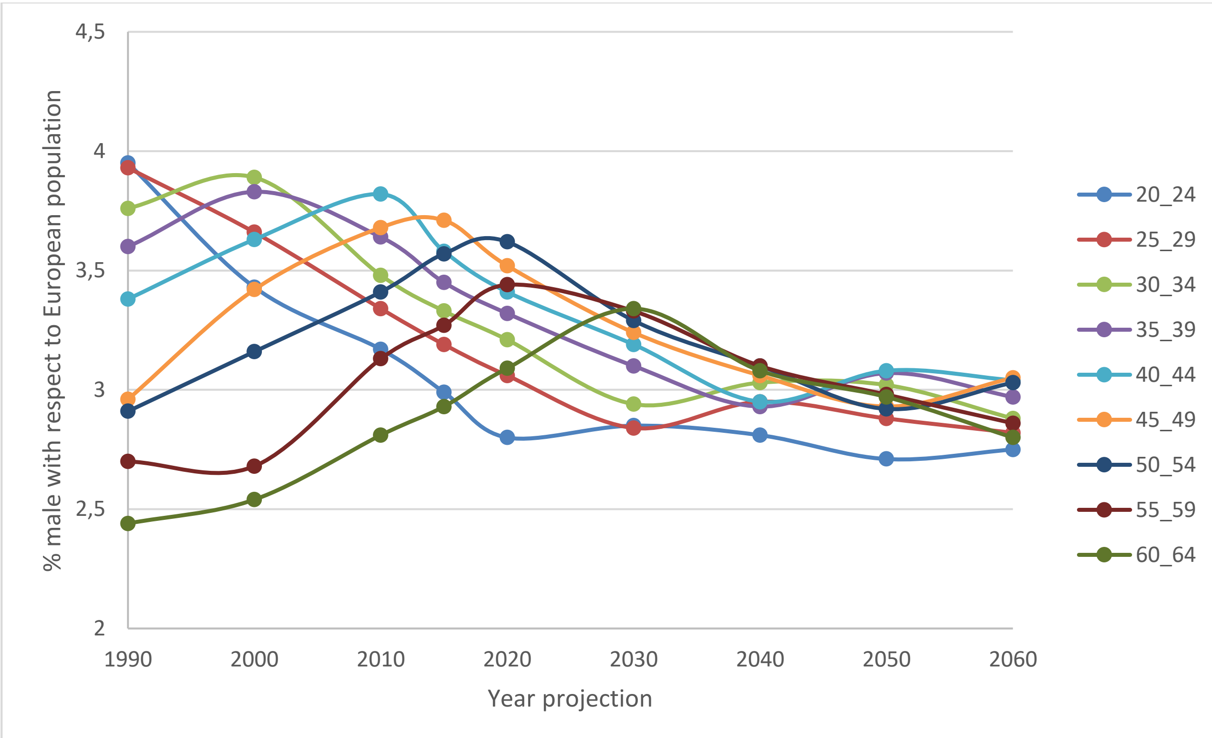
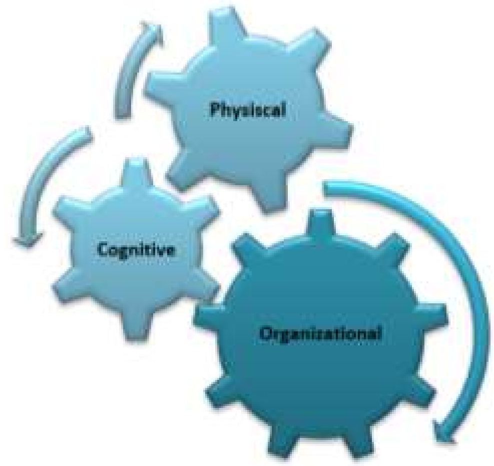


Figure 6 Trend of male % with respect to age range [OSHA data, November 2017]

Due to the fast evolution of manufacturing technologies and due to the propensity of industries to evolve to *Industry 4.0*, people are expected to interact more and more with sophisticated hardware and software. The role of ergonomics and human factors specialists become more and more important in order to better optimise work performance and worker health and safety.

Inside Process Ergonomics discipline, three main domains are present:

- ***Physical Ergonomics***: is concerned with human anatomical, anthropometric, physiological and biomechanical characteristics as they relate to physical activities.
- ***Cognitive Ergonomics***: is concerned with mental processes, such as perception, memory, reasoning, and motor response, as they affect interactions among humans and other elements of a system.
- ***Organizational Ergonomics***: is concerned with the optimization of sociotechnical systems, including their organizational structures, policies, and processes.



Ergonomics and human factors have always been important for manufacturing, particularly from the industrial revolution when people and machinery were forced together in large-scale mass-production factory environments and sociotechnical problems began to emerge as a result. Although manufacturing engineers and managers have traditionally focused on developing technical systems to replace people, there is now an increasing recognition that even in highly advanced and automated production processes people are still essential for various roles and therefore we must develop an equivalent understanding of human/social systems.

The importance of ergonomics was clearly affirmed, for what concern the Italian legislation, in 2008 with the "decreto legislativo 81/08" where it is stated:

Article 15 - *requires "the compliance with ergonomic principles in work organization, in workplace design, in the choice of work tools as well as in the definition of work and production methods", especially for what concern effects of repetitive work*.

Article 17 - *obliges the employer to "evaluating all risks" for the health and safety of workers*

Article 22 - *obliges workplace and plant designers to compliance with general principles of prevention and protection of the health and safety of workers already in design phase*.

Strictly correlated to it, it is important to remind three European legislations:

UNI EN 1005 which evaluates the directive related to Safety and Ergonomics for all new or updated machineries (2-Manual handling of machinery and component parts of machinery, 3-Recommended force limits for machinery operations, 4-Evaluation of working postures in relation to machinery, 5-Risk assessment for repetitive handling at high frequency)

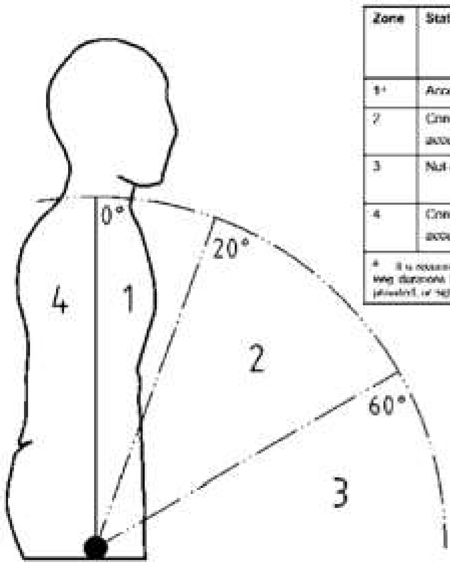
ISO 11128 related to manual handling (1-Lift&carrying, 2-Pushing&pulling, 3-Handling of low loads at high frequencies)

ISO 11226 related to the Evaluation of working postures.

A more detailed analysis of the norms must be done in order to better understand the main ergonomics criticalities that must be faced.

One of the main focal point of the ergonomics and of the related norms, as said before, is the analysis of the posture of the operators in a workstation. Posture analysis could be considered focal due to its presence in every method developed to analyse workstation task.

If we consider the analysis related to posture (UNI EN 1005-4), in particular the analysis related to trunk bending in static posture, we can see that trunk bending after 20° could be considered conditionally acceptable, but after 60° is Not Acceptable. This limitation is extremely problematic if we think about, for example, workstations in which the operator must bend into the vehicle to mount cables or parts inside it.



Zone	Static posture	Movement	
		Low frequency (< 2/min)	High frequency (≥ 2/min)
1ᵃ	Acceptable	ACCEPTABLE	Acceptable
2	Conditionally acceptable (Step 2a)	Acceptable	Not acceptable
3	Not acceptable	Conditionally acceptable (Step 2c)	Not acceptable
4	Conditionally acceptable (Step 2b)	Conditionally acceptable (Step 2c)	Not acceptable

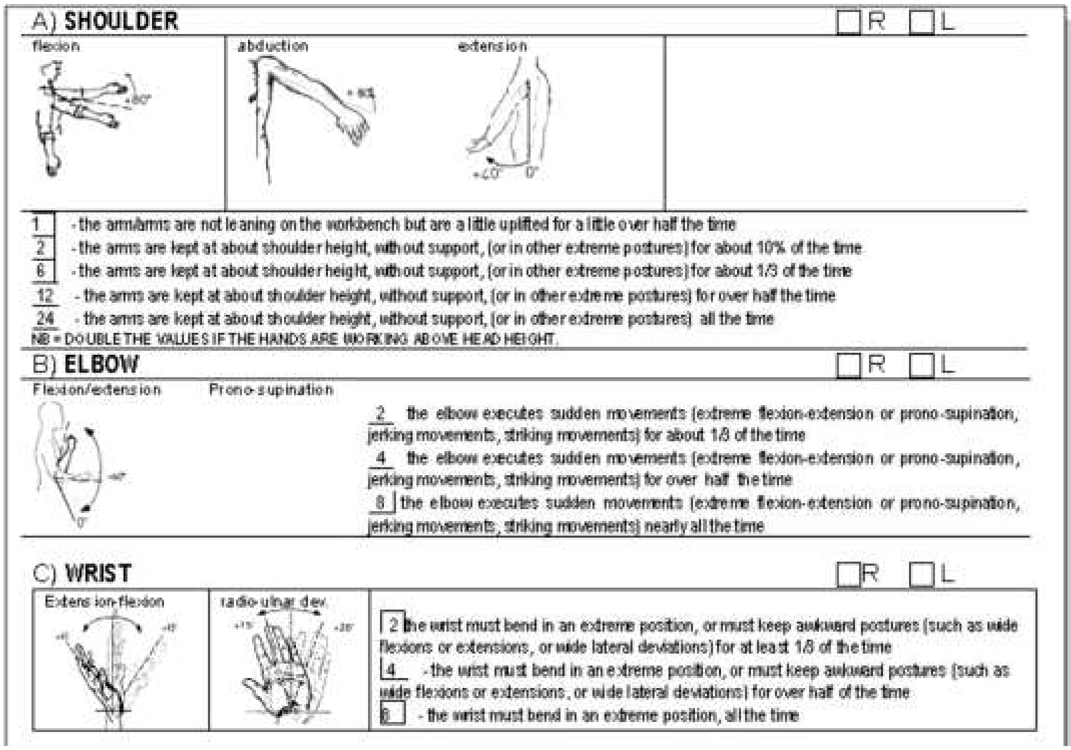
a It is recommended that working postures with an upright trunk be achieved, in particular if the machinery may be used for long durations by the same person, requiring static posture without adequate recovery time or body support being provided, or high frequency movements.

TRUNK FLEXION

Figure 7 Abstract from UNI EN 1005-4

If we, instead, analyse the posture related to the arms, it is possible to see that the joint that most influence index posture is shoulder one (see OCRA index). In particular, the posture in which arms are kept about shoulder height, without support, all the time, is the most demanding (about 24 points in OCRA method).

This critical position must be carefully taken into consideration, if we think that in the manufacturing industries there are many underbody workstations or, more in general, workstations in which workers works almost all the time with workers at about shoulder height.



A) SHOULDER ☐R ☐L

flexion / abduction / extension

1 - the arm/arms are not leaning on the workbench but are a little uplifted for a little over half the time
2 - the arms are kept at about shoulder height, without support, (or in other extreme postures) for about 10% of the time
6 - the arms are kept at about shoulder height, without support, (or in other extreme postures) for about 1/3 of the time
12 - the arms are kept at about shoulder height, without support, (or in other extreme postures) for over half the time
24 - the arms are kept at about shoulder height, without support, (or in other extreme postures) all the time
NB = DOUBLE THE VALUES IF THE HANDS ARE WORKING ABOVE HEAD HEIGHT.

B) ELBOW ☐R ☐L

Flexion/extension / Prono-supination

2 the elbow executes sudden movements (extreme flexion-extension or prono-supination, jerking movements, striking movements) for about 1/3 of the time
4 the elbow executes sudden movements (extreme flexion-extension or prono-supination, jerking movements, striking movements) for over half the time
8 the elbow executes sudden movements (extreme flexion-extension or prono-supination, jerking movements, striking movements) nearly all the time

C) WRIST ☐R ☐L

Extension-flexion / radio-ulnar dev.

2 the wrist must bend in an extreme position, or must keep awkward postures (such as wide flexions or extensions, or wide lateral deviations) for at least 1/3 of the time
4 - the wrist must bend in an extreme position, or must keep awkward postures (such as wide flexions or extensions, or wide lateral deviations) for over half of the time
8 - the wrist must bend in an extreme position, all the time

Figure 8 Abstract from OCRA checklist

Analysing the different body postures, we must at the same time evaluate the time for which we maintain the same posture. Time evaluation is extremely important.

As it is possible to see, each factor is strictly related to some ergonomics indexes that could be considered, in some way, the output of the ergonomics work. An ergonomic improvement could be evaluated, in these terms, through a reduction of these indexes.

One of the main challenges that automotive industries (and manufacturing industries in general) must face nowadays, is the need to find new ways in order to try to improve the ergonomics issues and reduce the indexes. One of the main problem is the ability to find a new type of technology capable of following the worker along the task, without creating any type of constrains or encumbrances, due to the impossibility to totally change the workstation (e.g. underbody workstations) for economical/spatial/productive problems (e.g. impossibility to rotate the vehicle in the latest part of the production line due to the presence of fluids inside it).

In the mindset of the industry 4.0, considering line limitations and vehicle production constraints, a possible solution, in order to improve ergonomics issues and reduce production costs, increasing at the same time production rate, could derive from a new frontier which is still under development and study: The Exoskeletons.

1.3. Exoskeleton

We define an exoskeleton as a wearable device (external to the body) that works in tandem with the user. The exoskeleton is placed on the user's body and acts as amplifier in order to augment, reinforce or restore human performance.

Exoskeletons can support the entire body, just the upper or lower extremities, or even a specific body segment such as the ankle or the hip.

We can say that exoskeleton is the application of robotics and bio mechatronics towards the augmentation of humans in the performance of a variety of tasks.

An advanced ergonomic design moves naturally with the body and adapts to different body types and heights.

We can subdivide the exoskeletons into passive, pseudo-passive and active exoskeletons.

Passive exoskeletons**:** do not have any electrical power source and can be used for weight re-distribution, energy capture, damping, locking.

Pseudo-passive exoskeletons: have batteries, sensors and other electronic devices, but they are not used to provide actuation.

Active exoskeletons**:** use of batteries or electric cable connections to run sensors and actuators.

Exoskeletons were born as a rehabilitation application, grown as military purpose and only in the last few years this technology has become a concrete possibility for industrial purpose, as an implementation of ergonomics issues.

Exoskeleton application for rehabilitation purpose

We can define an exoskeleton for medical purpose as a wearable robotics designed to be used as a rehabilitation or augmentation medical device.

Rehabilitation field is the second oldest field of exoskeleton development. The first working medical exoskeleton was created in 1972.

One breakthrough was the recognition that exoskeletons can perfectly recreate the same motion thousands of times. This translates to patients being able to perform more exercise repetitions in the same amount of time with higher consistency.

Exoskeleton systems for assistance and rehabilitation focus on providing missing movements and sensing, providing safer environments and environments that make regaining movement-related function easier and faster.

Example of medical exoskeleton are shown below.

- Stationary lower body exoskeletons (Lokomat by Hocoma)

Figure 9 Lokomat by Hocoma [www.hocoma.com, November 2017]

- Mobile lower body rehabilitation exoskeletons (ReWalk by ReWalk Robotics)

Figure 10 ReWalk by ReWalk Robotics [rewalk.com, November 2017]

Exoskeleton application for military purpose

Wearable robotics for military applications is the most dynamic subset of the exoskeleton industry. The evolution of military exoskeletons has been in development for over 50 years, but only after 1990s the interest in this specific subject started to grow up exponentially. Military exoskeletons are being tested by the U.S., China, Canada, South Korea, Great Britain, Russia and Australia, and these are just the projects that the public is aware of.

Military exoskeletons face many of the same challenges as their industrial counterparts: being comfortable to wear for many hours and integration with already established equipment and standards. Military exoskeletons must work with what is already accepted military equipment.
Soldier's personal equipment can weight up to 50 kg, which increases the risk of MSD and increase in physical fatigue, decreasing the ability to perform and protect against injury.
Nowadays exoskeletons vary in application, but almost all allow soldiers to carry 17 times more weight than normal and to march with significant less strain on the body.

Exoskeleton application for industry purpose

Wearable robotics designed to be used in an industrial setting is the fastest growing field of exoskeleton research.
Exoskeletons for industry and the workplace offer three main advantages: Reduction in work related injuries, saving billions of dollars in medical fees, sick leave and lawsuits. Lowered worker fatigue, leading to increased worker alertness, productivity and work quality.
Below, some example of industrial application of exoskeleton technology:

- Chairless Chair by Noonee

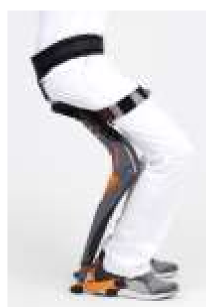


Figure 11 Chairless Chair by Noonee [www.noonee.com, November 2017]

- Laevo by Laevo exoskeleton

Figure 12 Laevo V2 by Laevo [www.laevo.nl, November 2017]

For the purpose of this analysis, it is worth of notice that we will use only passive exoskeletons. This is due to the fact that, for what concern the legislation point of view, the exoskeleton technology is still not present and regulated. Furthermore, as far as active exoskeletons are concerned, they could be considered as "robot" due to the use of electric power and the actual regulation related to robot and robotic devices (ISO 10218-1:2011) stated that the robot must be isolated from the surround through protection grids in order to avoid the interaction between human and robot for safety issues.

Exoskeleton application for Automotive (Benchmark)

Exoskeletons have become, as stated before, a new fast-growing frontier for productivity and ergonomic issues in Automotive manufacturing.

Many European Car player are trying to follow this new technology and to apply it in order to improve quality, productivity and reduce absenteeism due to MSDs.

A sum up of the most important Automotive application (OEM-type of exoskeleton), found through a benchmarking analysis, is presented below.

Table 1 OEM Automotive exoskeletons application and test

OEM	Exoskeleton	Status
BMW	EksoVest	Adoption in Plant
	Chairless Chair	
	Levitate	
AUDI	Chairless Chair	Test in Plant
	Upper-Body	Prototype, laboratory test
PSA	ABLE upper-limb	Laboratory test
TOYOTA	Chairless Chair	Test
RENAULT	Chairless Chair	Test in Plant
	Upper-limb	
FORD	Lucy	Test in Plant
	ShoulderX	
	BackX-S	
	EksoVest	

EksoVest by Eksobionics is an upper body exoskeleton that elevates and supports a worker's arms to assist them with tasks ranging from chest height to overhead. It is lightweight and low profile making it comfortable to wear in all conditions while enabling freedom of motion.

Chairless Chair by Noonee is a flexible wearable ergonomic sitting support. The device is usually applied for workers who are required to stand for long period, and traditional sitting support are not suitable

Levitate AIRFRAME is a wearable technology engineered to support the arms of professionals and skilled trade workers who are exposed to repetitive arm motion and/or static elevation of the arms.

ShoulderX augments its wearer by reducing gravity-induced forces at the shoulder complex, enabling the wearer to perform chest to ceiling level tasks for longer durations and with less effort.

BackX-S is a novel industrial exoskeleton that substantially augments its wearer and reduces the forces and torques on a wearer's lower back region (L5/S1 disc) by an average of 60% while s/he is stooping, lifting objects, bending or reaching.

2. Chairless Chair by Noonee

2.1. Exoskeleton description

Chairless chair is a flexible wearable ergonomic sitting support. The device is usually applied for workers who are required to stand for long period, and traditional sitting support are not suitable. CC is a passive exoskeleton.

While wearing Chairless Chair, workers can walk along the line (a short distance to cover must be considered), stop and seat where needed, avoiding squatting, bending or crouching.

Chair frame can be adjusted to suit people of different height. The seat is adjustable with four positions, it is possible to lock it in the wished position. At the same time, the shoe connectors are adjustable with four positions, to best fit most of the shoes for industrial environments.

Chairless Chair was developed by the Swiss company Noonee, in partnership with automotive companies' workers from Audi, Seat, Skoda, Daimler, BMW and Renault in order to better understand possible applications and drawbacks of the device.

Chairless Chair is made up by two "mechanical" legs, composed by a high-tech composite polymer. The two legs are linked with the worker's body through a belt and a sling.

Figure 13 CHAIRLESS CHAIR components

The device weight in total 3.5 kg, and it is able to support at most a user with a weight of 115 kg. A brief summary of the main characteristics of the device and of the anthropometry of the user are reported below.

Main characteristics:

- Flexibility: individual sitting height adjustment
- Work support: sitting support for standing workplaces
- Freedom of movement: fast switch between sitting, standing and walking
- Individualization: adapts to different body sizes and safety shoes
- Reduction of physical strain during work
- Reduction of employee absence
- Affordable walking path below 2 meters

Anthropometric characteristics of the user:

Weight: < 115 kg

Height: 155-195 cm

Belt length: 65-130 cm

2.2.MSDs correlation

The incongruent posture related to the work task at a height below the hip, create a condition for which the muscles of back are continuously solicited. This type of situation could give rise to MSDs that can affect the entire body, in particular ligaments and blood circulation.
Standing up causes a permanent contraction of the muscles of the body and legs. The muscles perform a static job and if they cannot relax they quickly fatigue. In addition, the joints, ligaments and intervertebral discs are strongly stressed. Standing increases the blood circulation more and requires more energy than sitting.
Standing for a long period of time can however cause fatigue and suffering: the tendons and muscles are in a condition of overload, the joint structures are compressed, increasing the likelihood of a venous stagnation in the lower limbs. First there is a feeling of fatigue that turns into pain: if this condition continues over time you can get to a real syndrome that can heavily condition the work and social life of these workers.
A group of researchers from the ETH Zurich found that even the other way around, standing up too much, can cause problems. In a study published in the journal Human Factors, researchers have shown that standing on their feet can, in the short term, cause joint and foot pain and, in the long run, can cause back problems and permanent muscle damage.
The analysis of the European Survey of Working Conditions (5) reveals that 47% of employees stand for more than 75% of their work time. In addition, prolonged standing at work was associated with reports of fatigue, leg muscle pain, and back-ache (6).

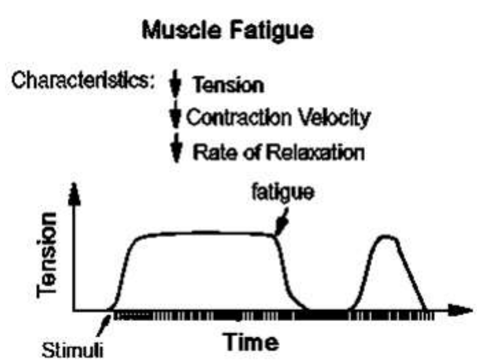


Figure 14 Energy Metabolism of Muscles, January 2018

According to the researchers, the problems deriving from staying on their feet would also compromise the productivity of companies and society in general. (7)

2.3.State of art

Up to September 2017, two types of trials were conducted:

- Ergolab Tests
- Test in plant (Bielsko Biala, Poland)

For what concern Ergolab tests, some tests with a skilled operator were conducted in order to simulate some workstations and easy tasks.

In particular, the workstation related to doors assembly, which is outside the ongoing line but is in some way correlated to it and its pace is simulated.

Through this simulation it was possible to evaluate the incompatibility of the multiple tasks of this workstation with the exoskeleton.

Behind that, the tests conducted in Ergolab (task: fastening/unfastening the bolt) were useful in order to analyze the difference of posture in performing the task with and without the exoskeleton.

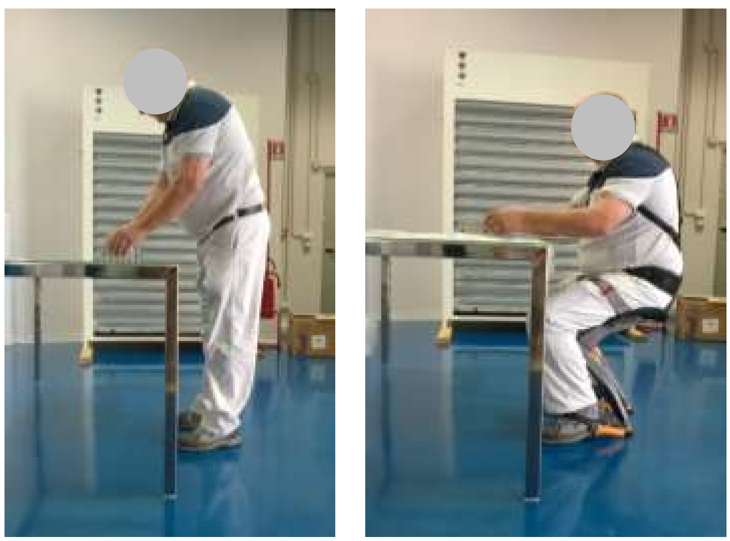


Figure 15 Chairlesschair Ergolab tests (fastening/unfastening the bolts), 16/05/2017

For what concern Bielsko Biala plant tests, two workstations were tested:

- Flywheel assembly
- Chamfering tool assembly

The tests were conducted in line during a normal working day, and were performed by skilled operators.

The results show the compatibility of the flywheel assembly workstation, with an improvement of the body posture.

Figure 16 Flywheel assembly workstation [August 2017, Bielsko Biala plant]

For what concern the chamfering tool assembly workstation, the incompatibility was mainly related to the presence of the conveyor that increases the distance between worker and parts, introducing a problem related to reduced reachability.

Figure 17 Chamfering tool assembly workstation with and without CC [August 2017, Bielsko Biala plant]

One of the main problem related to both trials was the inability for the workers to describe if they really perceive a help or not.
This difficulty in describing the feedback of the device is strictly correlated to the complete change in posture. In order to try to evaluate the real benefits of the device, beside the feeling of the operators, some virtual trials are developed, in order to try to quantify the influence of the device on joints.

2.4. Virtual trial

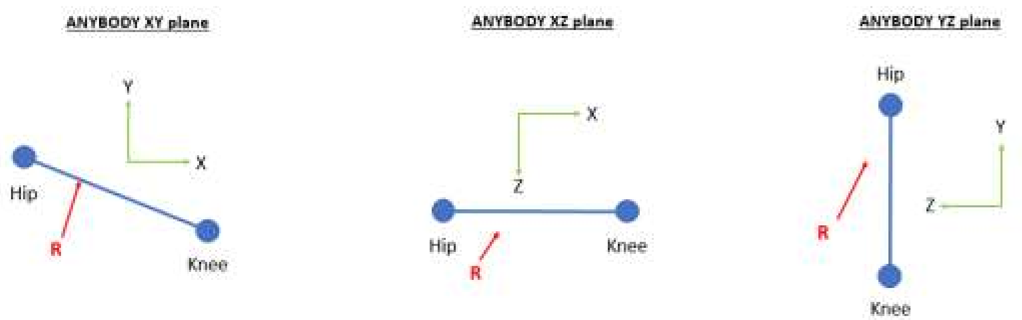
In order to try to evaluate how the posture changes correlated to the application of the exoskeleton could influence body joints and muscles, two simulation software and their comparison were adopted: Anybody and 3DSSPP.

Through the use of a force platform it was possible to see that the percentage of body weight discharged by the exoskeleton on the floor vary depending of the position of the upper part of the body and, in particular, of the arms.

A Comparison between the postures of the operator with and without the exoskeleton (forces coming from Anybody) was conducted.

The comparison was based on the task studied in Ergolab (see chapter 2.3) and reproduced in the software through the use of photos and Kinovea software.

We must point out that while in Anybody software the reaction given by the exoskeleton is represented by a cad of the exoskeleton itself through a composition of a multiple point contact area, in 3DSSPP it is possible to apply external forces only on joints. Due to this fact, a transportation torque must be computed on the upper leg.



Torque around HIP:

$$R_x \cdot y + R_y \cdot x \rightarrow RightLeg$$
$$R_x \cdot y + R_y \cdot x \rightarrow LeftLeg$$

Torque around HIP:

$$R_x \cdot z + R_z \cdot x \rightarrow RightLeg$$
$$-R_x \cdot z - R_z \cdot x \rightarrow LeftLeg$$

Torque around HIP:

$$R_z \cdot y - R_y \cdot z \rightarrow RightLeg$$
$$-R_z \cdot y + R_y \cdot z \rightarrow LeftLeg$$

Besides, at first a comparison between the two software was done in order to set exactly the same mannequin.

<u>Mannequin anthropometry</u>

In order to have results comparable with the real worker, the mannequin anthropometry was settled as the one of the worker. Mannequin body segments and center of gravity were settled starting from Anybody mannequin (which could be considered more precise with respect to 3DSSPP mannequin, due to the presence of muscles and tendons).

Worker anthropometry	
Height	165 cm
Weight	86,8 kg

2.4.1. Evaluation of the comparability between the two software

In order to obtain an objective comparison, the mannequin basic standing neutral position was adopted.

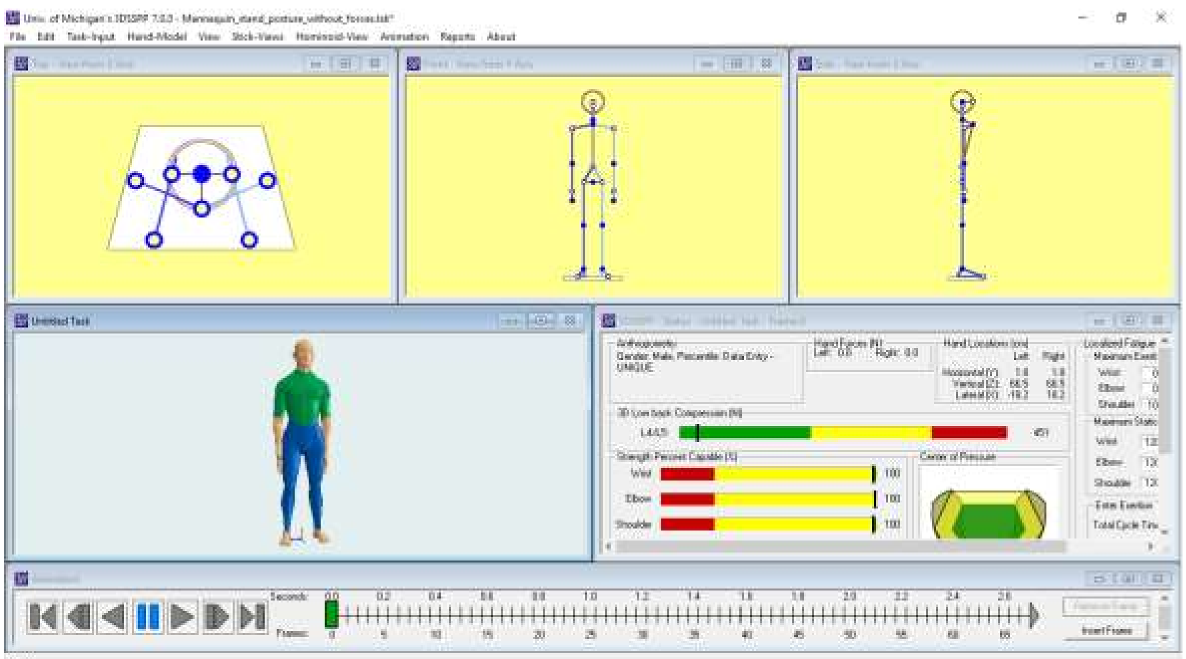


Figure 18 3DSSPP window screen, stand position mannequin, December 2017

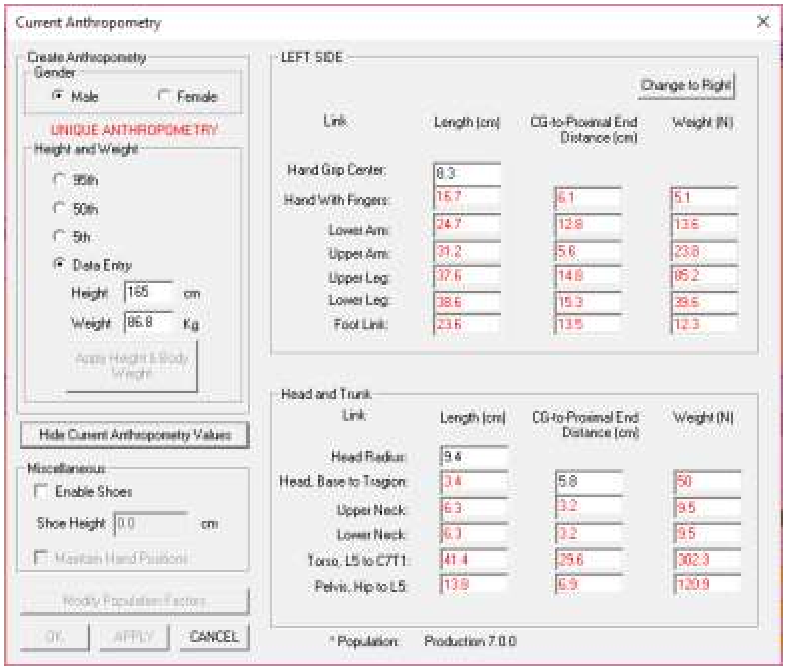


Figure 19 Screen of 3DSSPP anthropometry window, December 2017

Center of mass comparison (CoM)

Table 2 Anybody vs 3DSSPP CoM output

	System axes	Anybody [cm]	3DSSPP [cm]
CoM	X	0	0
	Y	0,38	0,4

As it is possible to see from the Table 2, setting the same length of body segments, the same mass and the same CoM of each segment, it was possible to obtain a mannequin comparable with the one created by Anybody, with the same body Center of Mass.

Ground reaction floor comparison (GRF)

Table 3 Anybody vs 3DSSPP GRF output

	Body side	Anybody [N]	3DSSPP [N]
GRF	L	428,6	425,7
	R	428,6	425,7

The same result could be derived from the analysis of the ground reaction force, by which we can see that the values obtained by the two software could be considered comparable. Moreover, the discrepancy between the values of the two software, which is 2.9 N, could be considered as negligible with respect to order of magnitude of GRF.

Ground reaction floor comparison (GRF)

If, instead, we analyze the output of the two simulations software related to the reaction moments, it is possible to see that the discrepancy related to the lower part of the body is extremely high.

Table 4 Anybody vs 3DSSPP joint reaction moments results

			Anybody [Nm]	3DSSPP [Nm]
Joint Moment	Right	GlenoHumeralFlex	0,38	0
		ElbowFlex	0,25	0
		HipFlex	-4,67	-1
		KneeFlex	5,95	1
		AnkleDorsiFlex	-6,24	-1
	Left	GlenoHumeralFlex	0,38	0
		ElbowFlex	0,25	0
		HipFlex	-4,67	-1
		KneeFlex	5,95	1
		AnkleDorsiFlex	-6,24	-1

This discrepancy could influence the results of the simulation due to the fact that the part of the body under study is the lower one and, in particular, the reaction moment at the hip, knees, ankles, which are the most solicited in the changing position.

2.4.2. 3DSSPP analysis of operator postures with and without the exoskeleton

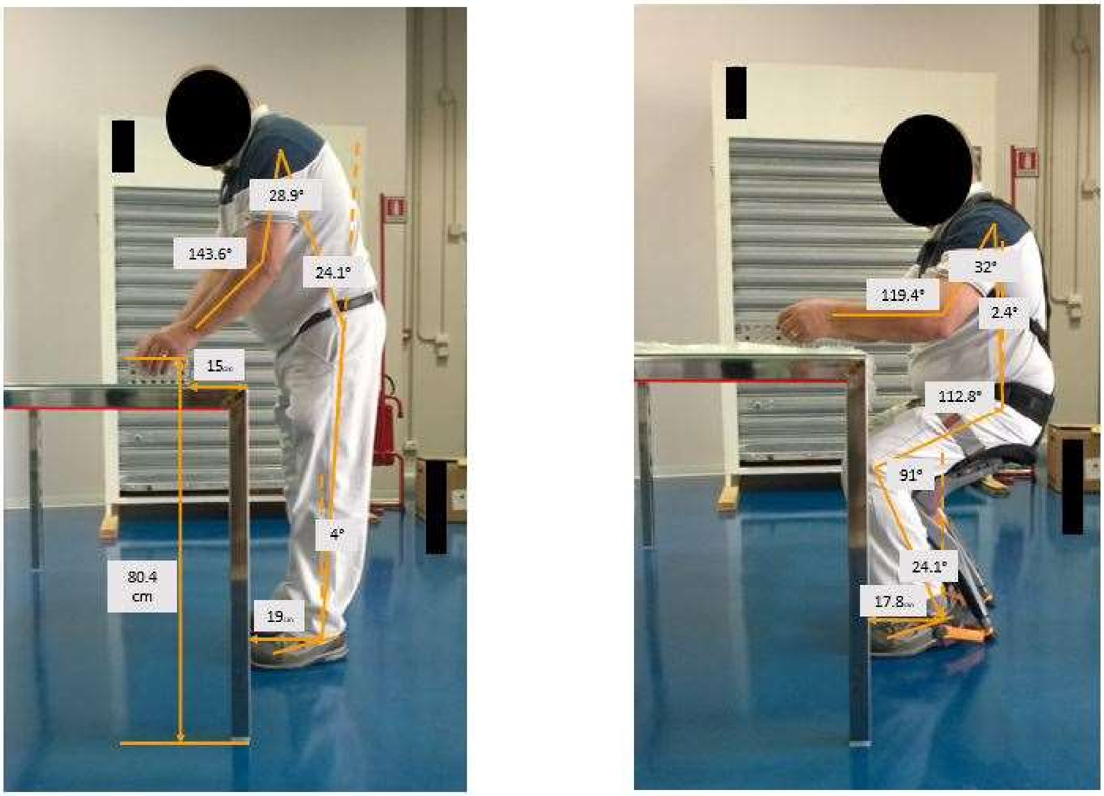
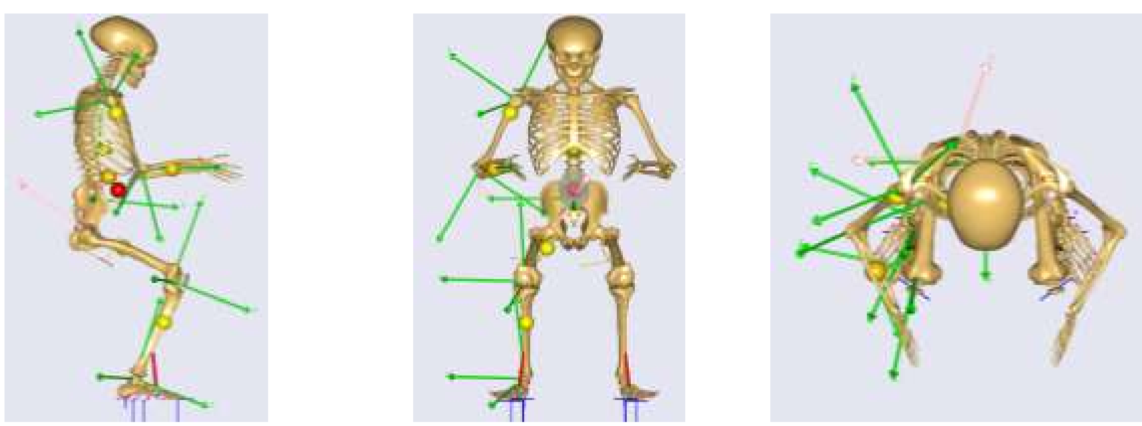


Figure 20 Ergolab test- Operator without and with exoskeleton

As it is possible to see from Figure 20, operator posture with the use of the exoskeleton has completely changed.

The mannequin used for the simulations is the one set in chapter 2.4.1.



Side view **Front view** **Top view**

Figure 21 Anybody operator with exoskeleton

For what concern the reaction forces instead, the forces computed by Anybody software were used as input for 3DSSPP external forces at hip joint (with some adjustment as stated before).

Table 5 Predicted reaction forces at exoskeleton-operator interface

Anybody System of Reference		Seated Normal[kgF]	Seated Normal[N]
RIGHT	**ExoThigh_X**	1,40	13,73
	ExoThigh_Y	28,70	281,46
	ExoThigh_Z	-3,20	-31,38
LEFT	**ExoThigh_X**	1,50	14,71
	ExoThigh_Y	29,00	284,40
	ExoThigh_Z	3,30	32,36

Through the computations, the torques obtained are reported in Table 6:

Table 6 Transportation Torques computation

PLAN	Leg	Torque [Nm]	3DSSPP reference Torque
XY	**Right**	16,78	**X**
	Left	17,00	
XZ	**Right**	-1,47	**Z**
	Left	1,53	
YZ	**Right**	15,94	**Y**
	Left	-15,78	

The forces obtained from Anybody and the torques computed, were applied to the hip joints in 3DSSPP as external forces and moments.

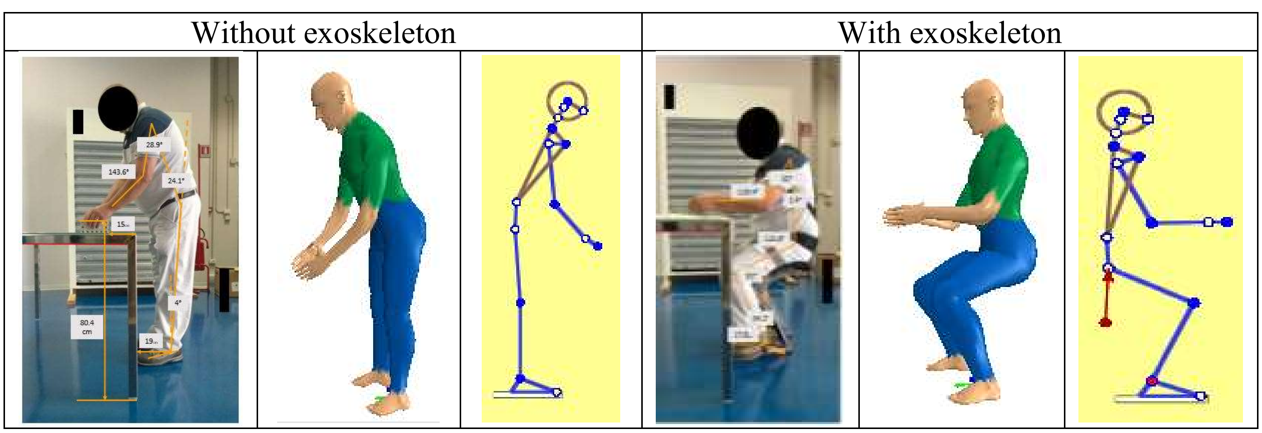
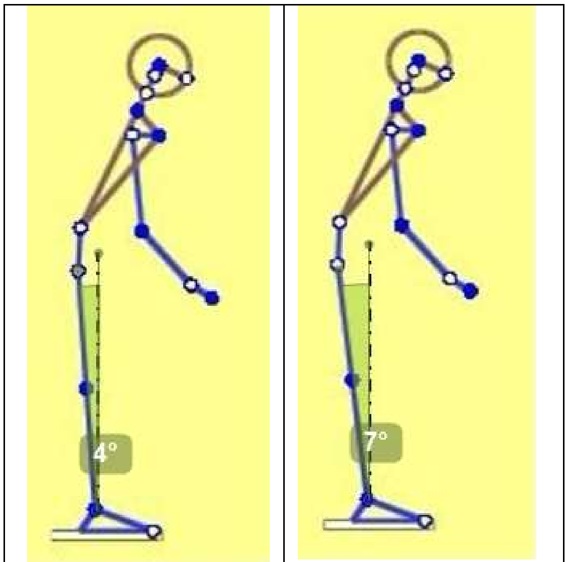


Figure 22 Comparison between postures (with/without exoskeleton)

In order to better understand benefits, drawbacks and joint moments correlation with minimal posture changes, two similar postures without the exoskeleton and two with it are analyzed.

Postures without exoskeleton

The two postures analyzed differs only for legs inclination, as it is possible to see from Figure 23.



Posture 1	Posture 2

Figure 23 Representation of the two mannequin postures without exoskeleton

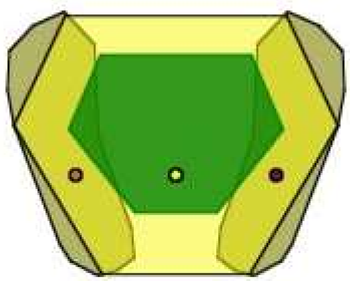
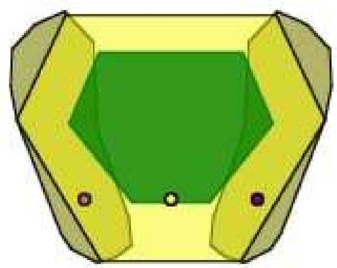
Joint moments resulting from these two postures differ only for knee and ankle joints, as it is possible to see in Table 7.

Table 7 Joint moments for postures without the exoskeleton

			Without (posture-1)	**Without (posture-2)**
Joint Moment [Nm]	**Right**	**GHFlex**	2,7	2,7
		ElbFlex	2,4	2,4
		HipFlex	-39,6	-39,6
		KneeFlex	31,5	24.4
		AnkleDorsiFlex	-21,4	-6.8
	Left	**GHFlex**	2,7	2,7
		ElbFlex	2,4	2,4
		HipFlex	-39,6	-39,6
		KneeFlex	31,5	24.4
		AnkleDorsiFlex	-21,4	-6.8

The main cause of the discrepancy highlighted could be easily identified in the different position of the Center of Mass that results in different reaction moments around the body that counteract this difference in balance.

Table 8 CoM postures without exoskeleton

Center of Mass coordinates (yellow point) [cm]			
Without (posture-1)		**Without (posture-2)**	
x	**y**	**x**	**y**
0	5	0	1.7
			

The decrease of the CoM position in the sagittal plane results in a decrease of knee and ankle joint moments.

<u>Postures with exoskeleton</u>

The two postures analyzed differs only for trunk (88°-86°) and head inclination (72°-65°), as it is possible to see from Figure 24.

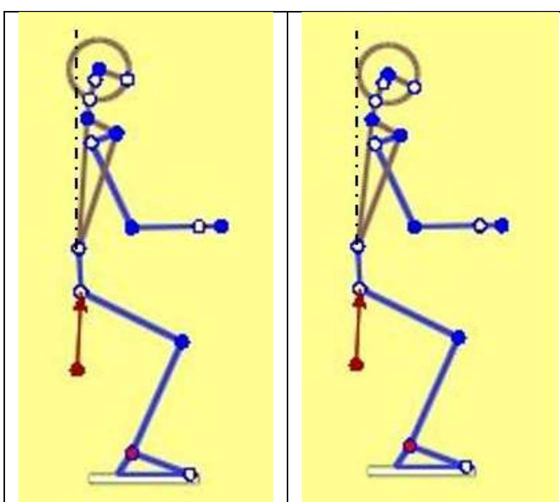


Figure 24 Representation of the two mannequin postures with exoskeleton

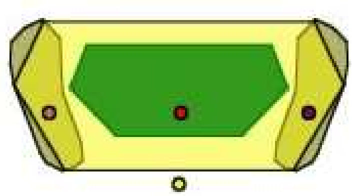
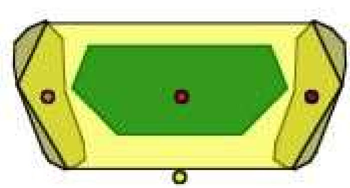
Joint moments resulting from these two postures differ only for knee and ankle joints, as it is possible to see in Table 9

Table 9 Joint moments for postures without the exoskeleton

			With (posture-3)	**With (posture-4)**
Joint Moment [Nm]	**Right**	**GHFlex**	5,2	5,2
		ElbFlex	2,9	2,9
		HipFlex	-11,1	-15,0
		KneeFlex	-15,2	-11,2
		AnkleDorsiFlex	-5,9	-10,0
	Left	**GHFlex**	5,2	5,2
		ElbFlex	2,9	2,9
		HipFlex	-10,8	-14,6
		KneeFlex	-14,4	-10,5
		AnkleDorsiFlex	-5,8	-9,7

The main cause of the discrepancy, as stated before, could be easily identified in the different position of the Center of Mass that results in different reaction moments around the body that counteract this difference in balance.

Table 10 CoM postures without exoskeleton

Center of Mass coordinates (yellow point) [cm]			
Without (posture-3)		**Without (posture-4)**	
x	**y**	**x**	**y**
0	-7	0	-6,1
			

The decrease of the CoM position in the sagittal plane results in a decrease of knee joint moments and an increase in hip and ankle joint moments.

Postures comparison (without vs with exoskeleton)

Table 11 Postures comparison (with and without)

			Without (posture-1)	**Without (posture-2)**	**With (posture-3)**	**With (posture-4)**
Joint Moment [Nm]	**Right**	**GHFlex**	2,7	2,7	5,2	5,2
		ElbFlex	2,4	2,4	2,9	2,9
		HipFlex	-39,6	-39,6	-11,1	-15,0
		KneeFlex	31,5	24.4	-15,2	-11,2
		AnkleDorsiFlex	-21,4	-6.8	-5,9	-10,0
	Left	**GHFlex**	2,7	2,7	5,2	5,2
		ElbFlex	2,4	2,4	2,9	2,9
		HipFlex	-39,6	-39,6	-10,8	-14,6
		KneeFlex	31,5	24.4	-14,4	-10,5
		AnkleDorsiFlex	-21,4	-6.8	-5,8	-9,7
	-	**TorsoFlex**	-75,8	-75.8	-25,8	-33,5
CoM [cm]		**x**	0	0	0	0
		y	5	1,7	-7	-6,1
Low back compression L4/L5 [N]			1377	1378	725	848

As it is possible to notice from Table 11, the change in position (adequately supported) provides a reduction in torso flexion and hip flexion joint moments and, as consequence, a reduction in low back compression (L4/L5). This reduction can be intuitively observed because the use of exoskeleton allows the operator to maintain a more erect posture for what concern the back.

Another consideration coming from the data comparison is the reduction in knee joint moment. While back effort reduction could be easily noticed, knee joint moment reduction is not so intuitive. If we think about the two positions, intuitively we state that the more comfortable (in legs terms) is the one in which the legs are completely distended, by the way through the use of the software it is possible to highlight that this statement it is definitely not true.

For what concern instead, the joint moment related to the ankle, it is not possible to univocally state if the joint receives benefit from the use of the exoskeleton due to the fact that in the posture without exoskeleton the change in legs angle results in a drastic reduction of knee joint moment and thus it is not possible to state univocally if there is a benefit or not.

Table 12 3DSSPP results comparison without vs with exoskeleton [Worst case]

			Without (posture-2)	With (posture-4)	Delta [%]
Joint Moment [Nm]	Right	GHFlex	2,7	5,2	92,6%
		ElbFlex	2,4	2,9	20,8%
		HipFlex	-39,6	-15,0	-62,1%
		KneeFlex	24,4	-11,2	-145,9%
		AnkleDorsiFlex	-6,8	-10,0	47,1%
	Left	GHFlex	2,7	5,2	92,6%
		ElbFlex	2,4	2,9	20,8%
		HipFlex	-39,6	-14,6	-63,1%
		KneeFlex	24,4	-10,5	-143,0%
		AnkleDorsiFlex	-6,8	-9,7	42,6%
	-	TorsoFlex	-75,8	-33,5	-55,8%
Low back compression L4/L5 [N]			1378	848	-38,5%

Table 13 3DSSPP results comparison without vs with exoskeleton [Best case]

			Without (posture-1)	With (posture-3)	Delta [%]
Joint Moment [Nm]	Right	GHFlex	2,7	5,2	92,6%
		ElbFlex	2,4	2,9	20,8%
		HipFlex	-39,6	-11,1	-72,0%
		KneeFlex	31,5	-15,2	-148,3%
		AnkleDorsiFlex	-21,4	-5,9	-72,4%
	Left	GHFlex	2,7	5,2	92,6%
		ElbFlex	2,4	2,9	20,8%
		HipFlex	-39,6	-10,8	-72,7%
		KneeFlex	31,5	-14,4	-145,7%
		AnkleDorsiFlex	-21,4	-5,8	-72,9%
	-	TorsoFlex	-75,8	-25,8	-66,0%
Low back compression L4/L5 [N]			1377	725	-47,3%

2.5.Results and conclusions

For what concern the virtual trials, the discrepancy between the two software in relation to the lower body could not be considered negligible. In fact, the order of magnitude of the discrepancy is the same as the one of the values we have to measure.

In the analysis of the stand-neutral position, the values obtained for the joint moments could be considered as influenced by the capability of 3DSSPP system to perfectly align the body segments in order to have null or negligible joint moments. Another aspect to be considered in the comparison between the two software in the neutral position, is the presence (Anybody)/absence (3DSSPP) of body muscles which influence the real posture of mannequin body segments and the real torques present at the joints. We must take into account that 3DSSPP analyze the static position only through torques and forces balance, thus it is possible that the software considers the ankle as the joint more demanding in term of equilibrium.

If we, anyway consider only the software 3DSSPP, it is possible to see that, through the simulation of the different postures related to the use or not of the exoskeleton, we obtain a sensible reduction of some joints reaction moments. It is reasonable to state that the change in posture related with the support given by the exoskeleton, results in a stress reduction for operator body, mainly in back, hip and knee benefits. Nothing can be stated about the behavior of the ankle joint.

By the way, it is reasonable to state that the benefits related to the reduction of joint moments is evident for most of the joints solicitated and thus the exoskeleton could be considered as a good solution in posture terms.

It is worth to notice, anyway, that this type of simulation as one main limit: the need to have the exoskeleton reaction forces as input (coming from another software: Anybody) thus, before studying the relevance in changing posture, an accurate evaluation of the forces exchanged between the exoskeleton technology and the operator body must be done.

3. Laevo by Laevo exoskeleton

3.1. Exoskeleton description

Laevo is a passive exoskeleton. It is a wearable back support that supports users while working in a bend-forward posture or lifting objects. The wearable frame carries part of the upper body weight of the user, thereby decreasing the strain on the lower back.

Figure 25 Description of LAEVO exoskeleton

Because it is a wearable device it moves with the user between different workplaces. The Laevo is flexible, just like the human spine, allowing it to move with the upper body and sustaining freedom of movement.

When bent forward, part of the upper body weight rests on the chest pads of the Laevo, this load is then transferred through the framework, unto the upper legs.

The net moment on the vertebrae decreases significantly, both during static (posture) and dynamic use (moving).

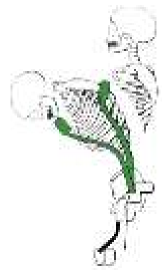


Figure 26 Representation of LAEVO back mobility

Laevo is a device applicable in static or dynamic working postures with trunk bended and in presence of manual material handling (compliant with ISO requirements).

Device weight is about 2.3 kg, and can fit different anthropometry due to the availability of three different sizes (Small, Medium, Large). The device is, furthermore, available in three versions (up to the beginning of 2017) that differs from each other due to the support zones (in term of bending angles):

Zone 1: 10° to 40°

Zone 2: 15° to 60°

Zone 3: >60°

Even if the device is almost adjustable in term of anthropometry, it must be considered that for the 3 sizes workers must have similar characteristics feasible with the device itself. In order to better understand this crucial point an example for the Small size is reported below.

Size: S

Worker’s height: from 165 cm to 175 cm

Worker’s weight: from 70 kg to 80 kg

Worker’s waistline: from 65 cm to 130 cm

Worker’s trunk thickness: from 28 cm to 32 cm

A brief summary of LAEVO characteristics is reported below (LAEVO v2.5).

- Passive exoskeleton
- Weight: 2,3 kg
- No batteries/ only a mechanical system
- On/off support button
- Lightweight and comfortable
- Adjustable fit

3.2.MSDs correlation

Analyzing the trend related to the dorsopathies in the Automotive manufacturing field, the major percentage of MSDs is related to two types of diseases: Herniated disk and disk degeneration.

Herniated disk: A herniated disk refers to a problem with one of the rubbery cushions (disks) between the individual bones (vertebrae) that stack up to make your spine. We can divide the type of pain in two macro categories: Pinched nerve (the disc itself is not painful, but rather the material that is leaking out of the inside of the disc is pinching or irritating a nearby nerve) and disc pain (it is the disc space itself that is painful and the source of pain). Except for Age and Gender causes one main cause of herniated disc could be related to jobs that require heavy lifting and other physical labor. Pulling, pushing, and twisting actions can add to risk if they're done repeatedly.

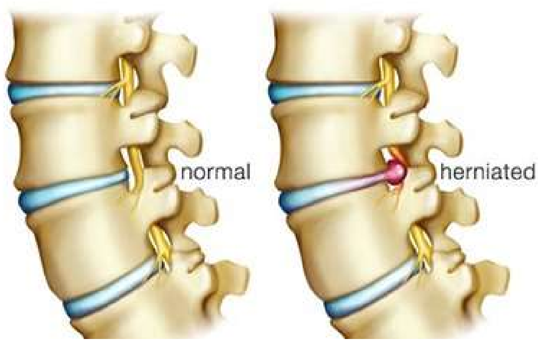


Figure 27 Comparison between a normal and a herniated disc

Degeneration disk: Degeneration due to emptying of the disc with subsequent thinning of the same disk and possible rubbing between two adjacent vertebrae.
In the degeneration of the intervertebral discs due to excess of sporting stress or to a load of other nature, such as compression or distension, in the long run a wear is produced that leads to a decrease in the height of the discs themselves.
This in turn leads to a decrease in the tension of the longitudinal ligaments (anterior and posterior) and consequently the stability of the vertebral rachis will be compromised.
As a result, there is a change in the position of the vertebral bodies which, in turn, involves a narrowing of the intervertebral holes and therefore a compression or inflammation of the respective nerves that cross them. This can lead to various painful symptoms.

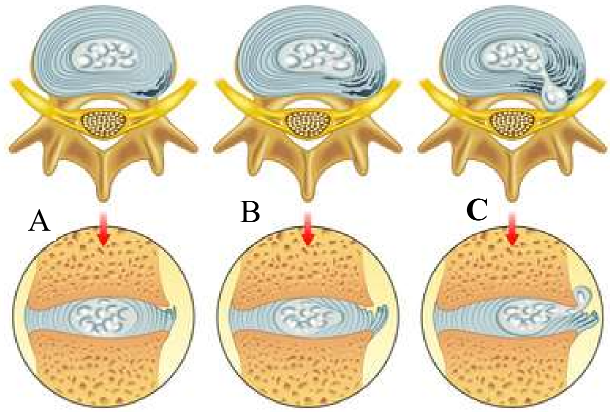


Figure 28 Degeneration (A), Protrusion (B), Herniated disk (C)

3.3.State of art

At the current state of art, two types of test were conducted with Laevo: a first test in Ergolab with not skilled and skilled operator, a second test in Mirafiori plant with skilled operators doing their target job.

For what concern Ergolab tests with skilled operator, two operators in target with exoskeleton fit were selected. The task, performed both with and without exoskeleton, requires the extraction and handling of a bulky object from a caisson to a desk behind the operator.

Figure 29 Ergolab Tests, July 2017 [FCA copyright]

Two types of exoskeleton were tested: v2.4 and v2.5.

From Ergolab test it was possible to observe a reduction in cycle time, an increase in the number of lifting and a reduction in the values of Borg scale assigned by the operators.

For what concern instead plant tests, the tests were conducted in two departments: Mirafiori Presse and Mirafiori Meccaniche.

The tests were performed in order to evaluate the applicability of the exoskeleton in a real working environment.

Mirafiori Meccaniche: the sample of operators was composed by two operators in target with exoskeleton fit. The task required was to extract some pieces of variable weight from a caisson and position them on the line conveyor. To hook the piece a tackle was used. The feedback of the operators in relation to the help provided by the exoskeleton was positive, the main problem was related to the heat and the interface between the exoskeleton and the body which was too rigid and not breathable.

Mirafiori Presse: the sample of operators was composed by three operators in target with exoskeleton fit. The task required was to take some pieces from the line conveyor and put them in a caisson behind them.

The feedback of the operators in relation to the help provided by the exoskeleton was positive, even in these tests the main problem was related to heat.

Figure 30 Mirafiori Presse tests, July 2017[FCA copyright]

The results obtain by these two in-line tests anyway could not be considered as significative in a statistical way, due to the narrow sample and the variability of the trial in relation to the climate.

3.4. Trials in line with LAEVO v2.4

For what concern the trial in line with LAEVO v2.4 only one workstation, considered in an embryonic phase as suitable, was tested.

Protocol followed for the trial:

1. Evaluation, in-line, of the most suitable workstations.
2. Meeting with in-line team leaders to present the project, collect feedbacks and ask to team leaders to find out some volunteers for the trials.
3. Evaluation of the limitation codes and anthropometry of all the operators resulted as volunteers (for this type of trial only workers with no limitation codes are taken into account in order not to influence the results of the experiments).
4. Planning of the in-line trials with a scheme of five days (the worker can stop the trial at any time for any type of problem):

Table 14 Planning of the trials

Day	Hours of trial
1°	2
2°	4
3°	8
4°	8
5°	8

5. Collection and evaluation of workers' feedbacks through the use of cognitive ergonomics.

Table 15 Summary of the workstation tested in Mirafiori and of the anthropometry of the volunteer

Workstation	Male/Female	Weight [Kg]	Height [cm]	Exo size
Cable mounting	Male	69	172	M

<u>Workstation Cable mounting</u>

The operator must work almost all the time with trunk bended in order to mount the cable inside the vehicle and below the steering wheel. The operator works most of the time standing and leaning against the body of the vehicle. Sometimes he will enter partially inside the vehicle in order to better fix the cable below the steering wheel.

Figure 31 Cable mounting workstation (without exoskeleton)

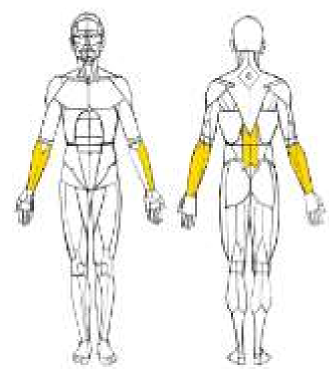
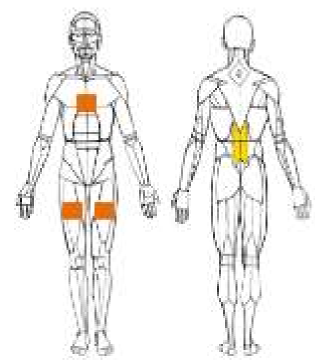
For what concern the trial the operator has decided to stop the trial after 30 minutes of test due to the presence of a knee pain and the impossibility to partially enter in the vehicle and sit in it.

The operator has perceived problems related to the freedom of movements. One of the main problems highlighted is related to the impossibility to work near the vehicle due to the perceived encumbrance of the device. At the same time the operator perceives excessive pressure on the chest and on the lower limbs.

For completeness of the trials, the results obtained with the surveys administered in plant are reported.

Code	Plant	Workstation	day of trials	trial complete (Y/N)	USABILITY F/L day	Likert score	Device usability	Psychological scores		Engineering scores		Workstation scores		Likert score purged (no psycho sphere)	Device usability (purged)
OP004	Mirafiori	Cable assembly	1	N	F	44,5	28,9%	8,0	19,0%	30,5	54,5%	6,0	14,3%	36,5	32,6%

<u>VAS scale</u>

Without	Day1
	

3.5.Conclusions

As highlighted by the trial, the main problem related to this type of exoskeleton is related to the possibility to find a suitable workstation. This type of exoskeleton could be considered as the representation of the limits of the trials performed only in laboratory, testing easy tasks, concentrating the research mainly on the function of the device and less on the possible applications in real life.

LAEVO exoskeleton was developed, as stated by LAEVO exoskeleton itself, for various demanding activities, but it is most suitable for:

•(Static) bend-forward activities and work tasks.

•Regular and repeating bend, squat and lift tasks, in the orange or green NIOSH-classifications.

Examples of suitable work activities are order picking in industrial or logistic sectors, bedside care or ‘table top’ tasks. The Laevo is less suitable in situations where bending and lifting is regularly alternated with sitting and climbing stairs.

As it is possible to see from LAEVO description, this type of technology is applicable in static tasks. The automotive field instead is a dynamic field, in which the cycle time is very important for the production and it does not permit to have static tasks that require only lifts. Thus, we can state that at the actual state of art the LAEVO technology is not suitable for the automotive production, especially for the ones with a very short cycle time.

4. Exoskeleton Comau/Iuvo/Ossur

4.1. Exoskeleton description

It is a passive exoskeleton designed to help workers which work with hands at/above shoulder height.

It is composed by a T frame, a belt, and two cassettes in which two springs are positioned to sustain the arm. Two additional tabs are present at belt height to regulate, through the traction of the same, the discharge of exoskeleton's weight on the pelvis.

It is an anthropomorphic exoskeleton, which means that it completely follows the movements of the arm and especially the one of the shoulder.

The exoskeleton is designed to support at most 50% of the weight of each arm (Declared by COMAU). The point of maximum sustain is at 90° in flexion/extension phase. At the current state of art nothing can be stated about the sustain related to the abduction phase.

Cassettes are made through rapid prototyping technique; the structure is composed by aluminum and carbon fiber in order to reduce the weight of the exoskeleton.

COMAU exoskeleton is developed starting from an existent exoskeleton, previously tested, and from a workshop in which feedbacks and suggestions of the operators were collected.

Figure 32 Representation of COMAU proto3 [COMAU copyright, December 2017]

4.2.MSDs correlation

For what concern the Automotive field, analyzing the data related to soft tissues MSDs, one MSD is predominant: the rotator cuff syndrome.

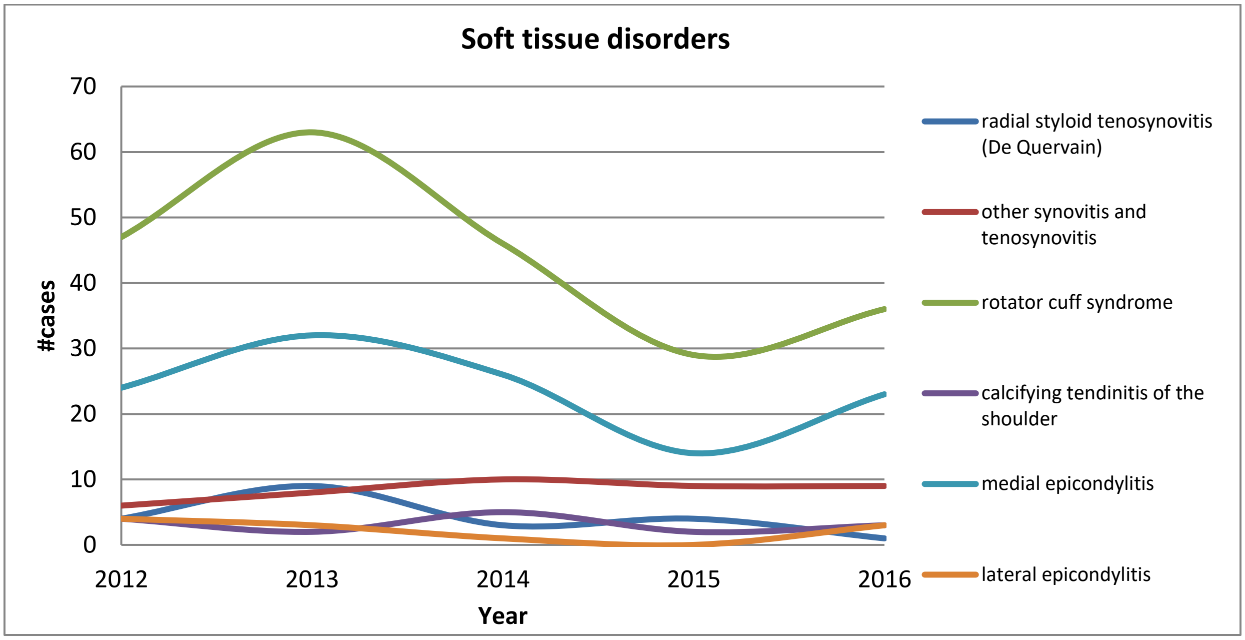


Figure 33 MSDs (soft tissue) trend from 2012 to 2016 [data from INAIL database, November 2017]

Rotator cuff impingement syndrome: is a condition in which rotator cuff tendons are compressed during shoulder movements, this condition causes shoulder tendons injury. Rotator cuff is a group of four tendons that stabilize the shoulder joint.

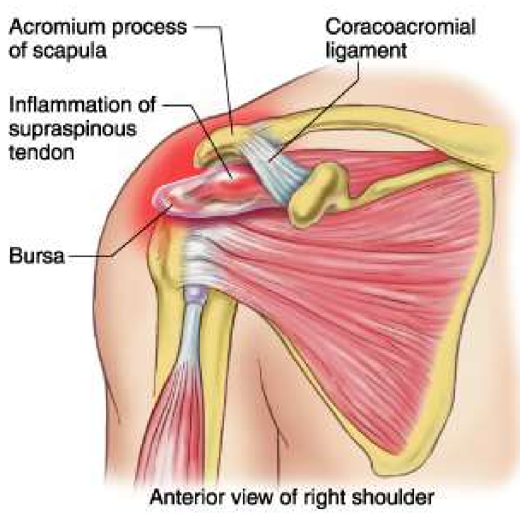


Figure 34 Rotator cuff syndrome [http://www.mdguidelines.com/rotator-cuff-syndrome, December 2017]

4.3.State of art

The development of COMAU passive upper limb exoskeleton derive from the necessity to meet workers' needs after a first experimentation with another upper limb exoskeleton: LEVITATE.
Levitate by Levitate technologies is a passive upper limb exoskeleton based on the same principle as the one described in COMAU exoskeleton description.
It is based on two cassettes, that are near the upper arms and contain two springs to sustain the weight of the upper limbs, one belt and a T shape on the back.
The main deficit encountered in the trials with Levitate (all trials were performed in the ERGOLAB and not in line-2016) are:

- Sizes and adaptability to the anthropometry of the user
- Force needed to come back to the resting position
- Continuity of the supplied torque
- Abduction complete control
- Durability of the setting during the trials

Some other problems were considered due to the not complete compliance with workers' needs, such as:

- Vehicle interference
- Level of assistance regulation
- Lumbar comfort and body fit
- Degree of freedom
- Contact with the arms
- Breathability

In order to better understand the needs of the workers, in September 2016 a workshop was organized in order to collect the feedback and suggestions of the operators, to create a new upper limb exoskeleton: COMAU exoskeleton.
The workshop, and the subsequent prototypes, were based on an iteration process to better understand and clarify problems and needs of real workers.

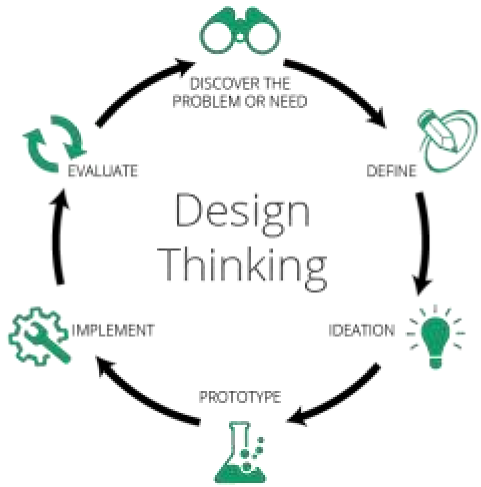


Figure 35 Workshop iteration process [www.arrkgroup.com, September 2017]

A first prototype was born in March 2017: prototype #1.

Figure 36 COMAU first prototype, March 2017, FCA copyright]

COMAU first prototype was tested only in Ergolab with real operators. Through workers' interview some main deficit to be implemented were highlighted:

- Sizes (adaptability to workers' anthropometry)
- Vehicle interference
- Weight
- Lock in safety position for dressing

Through the evaluation of the Ergolab test a new prototype was developed in July 2017: prototype #2.

Figure 37 COMAU second prototype, July 2017, FCA copyright]

COMAU second prototype was tested in Ergolab and in some plants. Through trials, some improvements and one main problem have emerged.

Main problem:

- Lock in safety position for dressing

Main improvements:

- Sizes and adaptability to the anthropometry of the user
- Continuity of the supplied torque
- Durability of the setting during the trials
- Lumbar comfort ad body adherence
- Contact with the arms

Through Ergolab test, some test conducted in plants (Bielsko Biala, Mirafiori Presse) a new prototype was developed in October 2017: prototype #3.

Figure 38 COMAU third prototype, July 2017, COMAU copyright]

COMAU prototype #3 is the one used for the tests under study.

4.4. Trial in line (AGAP & Mirafiori Plant)

COMAU exoskeleton used for the in-line trials is a prototype and not a pre-series. Some problems encountered during the tests could be related to the use of prototypes instead of a finite product. Those trials are devoted to find not only compatible workstations, but also to find drawbacks related to long range use and to the use in relation to a real working task (workers feedbacks).

For both trials, the protocol followed is the same:

1. Evaluation, in-line, of the most suitable workstations.
2. Meeting with in-line team leaders to present the project, collect feedbacks and ask to team leaders to find out some volunteers for the trials.
3. Evaluation of the limitation codes and anthropometry of all the operators resulted as volunteers (for this type of trial only workers with no limitation codes are taken into account in order not to influence the results of the experiments).
4. Planning of the in-line trials with a scheme of five days (the worker can stop the trial at any time for any type of problem):

Table 16 Planning of the trials

Day	Hours of trial
1°	2
2°	4
3°	8
4°	8
5°	8

5. Collection and evaluation of workers' feedbacks through the use of cognitive ergonomics.

The analysis presented is devoted to the evaluation of the engineering part of the device.

For sake of simplicity the results obtained by the psychologist through cognitive ergonomics, with some observations, are reported in **Errore. L'origine riferimento non è stata trovata.**.

Due to this reason, for each workstation a brief description of the task and some considerations coming from the trials observation are reported. Then, an analysis of the results coming from the trials is conducted.

In the mindset of the trials presented in this study, a little excursus about cognitive ergonomics and its tools, in order to better understand the tests carried out and the results analysed, must be done.

4.4.1. Cognitive ergonomics and its tools

As said before we define Cognitive ergonomics as ergonomics concerned with mental processes, such as perception, memory, reasoning, and motor response, as they affect interactions among humans and other elements of a system. [Def. from International ergonomics association]
Through the application of cognitive ergonomics, it is possible to investigate three main aspect related to the use of a new device and the interaction between the device and the human being:

- Usability
- Acceptability
- Effort evaluation

Usability

Usability can be defined as a quality or characteristic of a product, denoting whether it is efficient, effective and satisfying. (8)
According to ISO 9241, part 11 (1998), Usability is defined as the effectiveness, efficiency and satisfaction with which specific users achieve goals in particular environments. It applies equally to both hardware and software design. The definitions of the three key terms are:
Effectiveness: is the accuracy and completeness with which specific users achieve their own goals with the system
Efficiency: is the resources expended in relation to the accuracy and completeness of goals achieved
Satisfaction: is the comfort and acceptability of the system to the users and other people affected by its use

It is important to realize that usability is not a single, one-dimensional property of a user interface. Usability has multiple components and is traditionally associated with these five usability attributes: learnability, efficiency, memorability, errors, satisfaction (9).

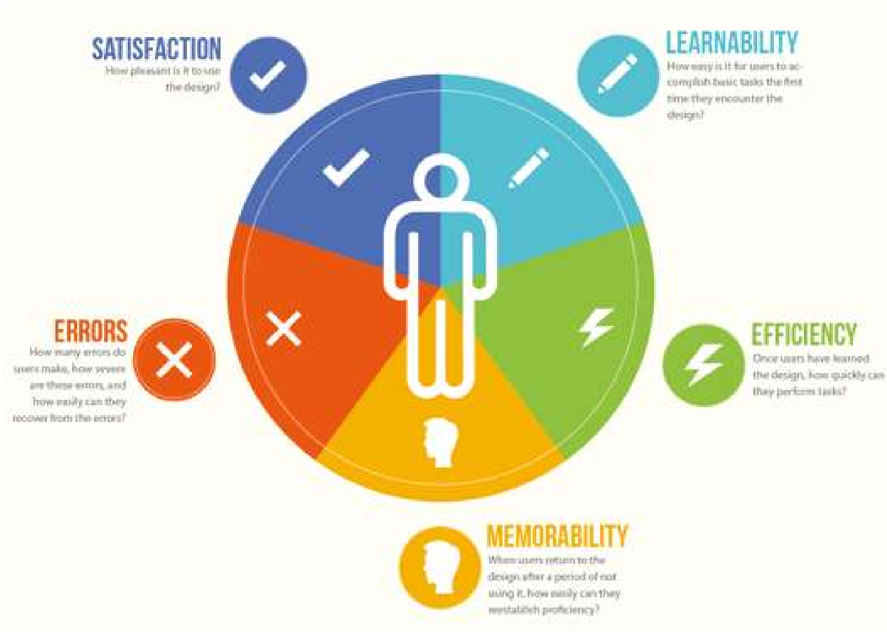


Figure 39 Usability elements, Nielsen, [Google November 2017]

In the trials, Usability is measured through the use of a questionnaire created ad hoc for the type of device and the specific context (industrial production context) of the trials. [Appendix 1]

<u>Acceptability</u>

Acceptability can be defined as how willingly the user uses the product, it coincides with the satisfaction and dissatisfaction that he / she has in using it.

Acceptance addresses the learners' desire to use a device/technology. It answers the following question: is the external representation compatible with a learner's motivation, affect, culture, values, and also does it fit within the constraints of the context. (10)

In order to evaluate the acceptability, TAM2 (Technology acceptance model 2) was used. [Appendix 2]

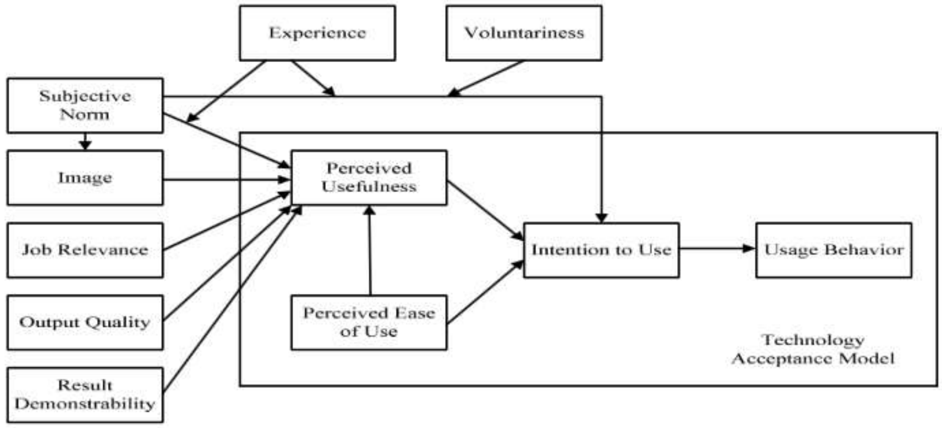


Figure 40 TAM2, [(Venkatesh & Davis 2000, December 2017]

It is possible to subdivide the items that constitute the TAM2 into two groups, in relation to the type of process by which they are characterized:

- Social influence
    - Subjective norm
    - Voluntariness
    - Image
    - Experience
- Cognitive instrumental
    - Job relevance
    - Output quality
    - Result demonstrability

In order to better understand the type of analysis conducted through the use of TAM2, a brief description of the items is presented (11).

Subjective norm: person's perception that most people who are important to him/her think he/she should or should not perform the behavior in questions.

Voluntariness: extent to which potential adopters perceive the adoption decision to be non-mandatory.

Image: the degree to which use of an innovation perceived to enhance one's status in one's social system.

Experience: Users' acceptance of an innovative device could vary with increase in their experiences.

Job relevance: is a key component of the matching process in which a potential user judges the effects of using a particular system on his/her job.

Output quality: the degree to which some individual judges the effect of a new system." In other words, it is the degree to which one thinks that a new system can perform required tasks.

Result demonstrability: tangibility of the results of using the innovation that will directly influence perceived usefulness.

For both TAM2 and Usability survey a Likert scale was used.

Likert scale, from the inventor Rensis Likert, is a scale based in order to measure the behavior of the people. It is a 7 points scale, by which the operators declare the agreement/disagreement with the items proposed. Through the analysis of the scores assigned to each item and of the sum of all the items it is possible to understand the behavior of the operator with respect to the device.

<u>Borg scale</u>

The Scale of Perceived Exertion (RPE), also called Scala RPE, or Borg Scale in reference to its inventor, Gunnar Borg, serves to evaluate the subjective perception of physical effort in relation to the entity or intensity of the same during an activity.

The RPE is often used to establish the intensity of the exercise by associating its perceptions and general responses according to the degree of fatigue. It has additional subjective indicators to help practitioners understand how to use this assessment more effectively. [Appendix 3]

<u>VAS scale</u>

The VAS Scale (Visual Analog Scale for Pain) is a unidimensional measure of perceived subjective pain intensity. It is used in order to analyze the rate of discomfort perceived by the operator when performing the task. The discomfort perceived is represented through the use of mannequins' representation.

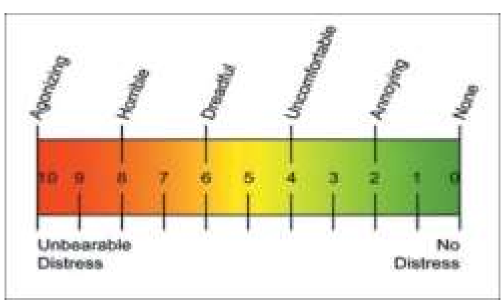


Figure 41 VAS scale representation

4.4.2. Avvocato Giovanni Agnelli Plant (AGAP) trials

The **Avvocato Giovanni Agnelli Plant** (AGAP) – named after former Chairman and grandson of Fiat's founder – is the production site for the **Maserati Ghibli** and **Maserati Quattroporte**.

Figure 42 AGAP plant [www.fcagroup.com, November 2017]

In 2009, FCA acquired the former Bertone assembly plant in Grugliasco near Turin, Italy. Through a clearly-defined and ambitious restructuring project, the Plant was transformed into an advanced production facility that makes **premium vehicles** for the **Maserati** brand.
The major challenge of the restructuring project was the ability to readapt an old factory into a modern one, with all the modern production needs. This result sometime in workstations with a very small and limited workspace.
With approximately 2,000 workers operating two shifts, the Plant currently produces around 140 cars a day. The cycle time is approximately 6 minutes, which is quite a long cycle time with respect to the usual cycle time of a car which is approximately one minute.
Four workstations were selected: three from assembly part and one from paint shop.

Table 17 Summary of the four workstations tested in AGAP and of the anthropometry of the volunteers

Unit	Workstation	UTE	M/F	Weight [Kg]	Height [cm]	Exo size
Paint shop	#1 Underbody sealing	1	Male	81	178	L
Assembly	#2 Fuel pipes	2	Male	65	179	L
Assembly	#3 Tunnel reinforcement bracket	2	Male	72	172	L
Assembly	#4 Cover underbody	3	Male	84	180	L

In order to understand the applicability of the exoskeleton to the selected workstations, as told before, a cognitive ergonomics analysis was done. The main drawbacks coming from the observation of the workers during their target activity (activity they do every day in the observed workstations) were collected and analyzed through the use of two interviews.

Workstation #1 (Paint shop): Underbody sealing

In this workstation, the worker must work all the time with arms at shoulder height. The task requires to seal some junction points between sheets, through the use of a gun with attached brush. The workstation is characterized by the car suspended through an overhead conveyor, a floor covered by a protection nylon and two rows of metal poles to protect the operator from accidental falls of the car.

Figure 43 workstation #1 (Paint shop): Underbody sealing [December 2017, FCA copyright]

Table 18 Summary of the real hours of trial for workstation #1

Unit	Workstation	Day1	Day2	Day3	Day4	Day5
Paint shop	#1 Underbody sealing	2h	4h	6h	6h	-

Considerations from the observation: the operator does not perceive support for the upper limb, instead he perceives a support for the lumbar part of the back. One of the major problem could derive from the size of the exoskeleton related to the protection poles, this is due to the fact that in some cases the operator has bumped against the poles. The rubbing of the suit on the upper arm due to the presence of the exoskeleton must be taken into account, because it could result in skin irritation.

Workstation #2 (Assembly): Fuel pipes

In this workstation, the worker works about 50% of the time with arms at shoulder height. The task is composed by many different subtasks, and it needs the attainment of kits out of the line and at a height different from the one of the workstation. The workstation is in a continuous line and the worker must interact with other workers in a narrow aisle with a declivity.

Figure 44 Workstation #2 (Assembly): Fuel pipes (Team Leader demonstration) [December 2017, FCA copyright]

Table 19 Summary of the real hours of trial for workstation #2

Unit	Workstation	Day1	Day2	Day3	Day4	Day5
Assembly	#2 Fuel pipes	40 min	-	-	-	-

Considerations from the observation: The workstation is definitely not suitable for the trial. The job is only for 50% of the cycle time at shoulder height. One of the main problem is the lack of space due to the overcrowding of that part of line. Moreover, it is difficult for the operator to reach the kit needed, also due to the gap between the kit and the line.

Another point to take into consideration is the part of the job task carried out inside the bonnet in the presence of hanging cables, this could inadvertently cause the exoskeleton coupling to the cables.

Workstation #3 (Assembly): Tunnel reinforcement bracket

In this workstation, the worker must work all the time with arms at shoulder height. The task requires to fix some parts, sometime by hands, sometime with the screwdriver. The worker must work under the car and must interact in the workstation with three other workers.

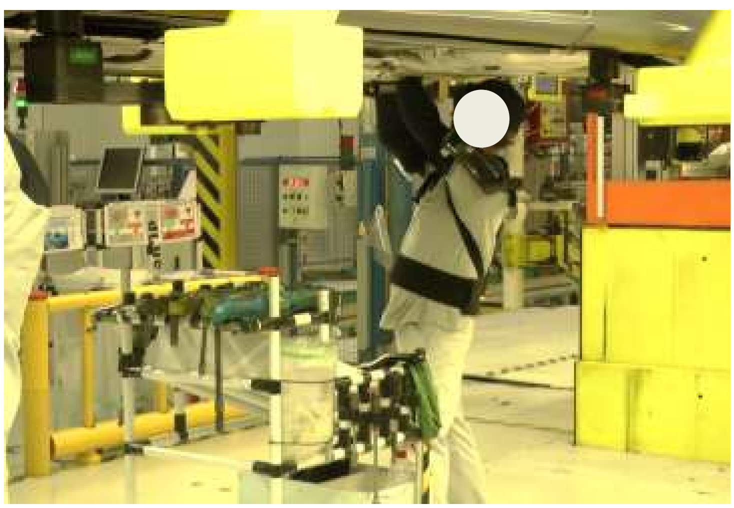


Figure 45 Workstation #3 (Assembly): Tunnel reinforcement bracket (Operator) [December 2017, FCA copyright]

Figure 46 Workstation #3 (Assembly): Tunnel reinforcement bracket (Team Leader) [December 2017, FCA copyright]

Table 20 Summary of the real hours of trial for workstation #3

Unit	**Workstation**	**Day1**	**Day2**	**Day3**	**Day4**	**Day5**
Assembly	#3 Tunnel reinforcement bracket	2h	4h	8h	8h	8h

Considerations from the observation: The workstation is particularly suitable for the trial. There is no presence of obstacles or limitations, also the interaction with the other operators (in term of encumbrance) is easy.

The operator has perceived arms support and less muscle strain. After the work-shift with the use of the exoskeleton, the worker claims to feel more rested. Arm support and less muscle strain are perceived.

Workstation #4 (Assembly): Cover underbody

In this workstation, the worker must work all the time with arms at shoulder height. The task requires to fit and fix some covers, at first with hands and then with the screwdriver. The worker must work under the car and must interact in the workstation with two other workers. In this case the workstation, even if fed by the continuous line, could be considered as a stop&go, the cycle time in this workstation could be neglected.

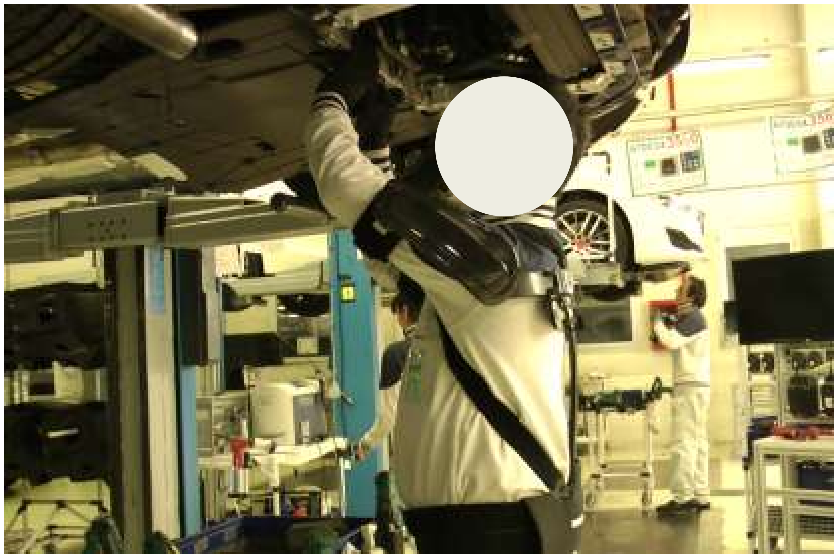


Figure 47 Workstation #4 (Assembly): Cover underbody [December 2017, FCA copyright]

Table 21 Summary of the real hours of trial for workstation #4

Unit	Workstation	Day1	Day2	Day3	Day4	Day5
Assembly	#4 Cover underbody	2h	2h	-	-	-

Considerations from the observation: The operator has perceived discomfort for the presence of the band of the exoskeleton, at the same time he has elbow pain. For these two reasons, it was decided to suspend the trial in this workstation in order not to affect the health of operator's muscles.

4.4.3. Mirafiori trials

Mirafiori assembly plant is the oldest FCA plant, it was one of the biggest Italian industrial site. Currently is only partially used and only two models are produced: Alfa Romeo Mito and Maserati Levante.

The trials were performed in the line dedicated to Maserati Levante due to interruption of Mito production from April 2018.

Two workstations were selected, both in the assembly part of the line.

Table 22 Summary of the four workstations tested in Mirafiori and of the anthropometry of the volunteers

Unit	Workstation	Male/Female	Weight [Kg]	Height [cm]	Exo size
Assembly	#1 Cruise fixing	Male	70	170	M
Assembly	#2 Cover underbody	Male (Op002) *	80	182	L
Assembly		Male (Op003) *	73	180	L

*() code assigned to identify the workers belonging to the same workstation

Workstation #1: Cruise fixing

The operator works all the cycle time with arms at shoulder’s height. The task is performed underbody and it is composed by two main sub-tasks: part fixing and check.
In the first sub-task, the operator fixes some parts with a screwdriver in the front and rear of the vehicle. Whereas in the second sub-task some checks are done on the underbody with a marker.

Figure 48 Workstation #1: Cruise fixing [December 2017, FCA copyright]

Table 23 Summary of the real hours of trial for workstation #1

Unit	Workstation	Day1	Day2	Day3	Day4	Day5
Assembly	#1 Cruise fixing	2h	4h	-	-	-

Considerations from the observation: the operator perceives support for the upper limb. The major problem derives from the rubbing of the jumpsuit in the frontal part of the shoulder due to the shape of braces of the exoskeleton, which results in skin irritation and slight swelling. Due to this factor, the worker has expressed the desire to stop the test. Another factor that must be taken into consideration is the reaction force given by the exoskeleton, while the operator is pushing down the telescopic arm in order to lock it.

Workstation #2: Cover underbody

In this workstation, the worker must work all the time with arms at shoulder height. The task requires to fit and fix some covers, at first with hands and then with the screwdriver. The worker must work under the car and must interact in the workstation with two other workers. In this case the workstation, even if fed by the continuous line, could be considered as a stop&go, the cycle time in this workstation could be neglected.

Figure 49 Workstation #2: Cover underbody [December 2017, FCA copyright]

Table 24 Summary of the real hours of trial for workstation #2

Unit	Workstation	Day1	Day2	Day3	Day4	Day5
Assembly	#2Cover underbody Op002	2h	4h	8h	8h	8h
Assembly	#2Cover underbody Op003	2h	4h	8h	8h	8h

Considerations from the observation: the two operators perceive support for the upper limb. The major problem derives, for operator 2, from the rubbing of the jumpsuit in the frontal part of the shoulder due to the shape of braces of the exoskeleton, which results in skin irritation. At the same time, an incorrect rotation of one of the cassettes of the exoskeleton was observed. During the test one of the braces of op002 exoskeleton has disassembled, this type of inconvenient can be easily related to the prototype nature of COMAU exoskeleton.

4.5.Results analysis

In order to analyze the engineering part of the results, starting from the usability surveys collected in plant during the trials, a possible subdivision of the items is developed.
Usability items can be subdivided into three main categories:

- Psychological items (items related to the psychological sphere of the human being):
    - It helps to make no mistakes
    - It helps me to do my job better
    - I am satisfied of the product
    - I like it
    - I felt at ease
    - I would use it in my job
    - I felt distressed
- Engineering items (items related to the behavior of the exoskeleton):
    - Movements freedom
    - It fits me
    - It is reliable
    - It is easy to use
    - Comfortable
    - I felt slowed
    - I had to learn how to use it
    - It is difficult to control
    - Unpredictable

- Workstation items (items strictly influenced by the type of workstation in which the device is tested):
    - It is consistent with the task
    - It is effective for my job
    - It is adequate for my job
    - It fits my job
    - It is compatible with my workstation
    - It would interfere with other working tools

During the trial each operator has assigned a score to each item through the use of a Likert scale (additive scale). For each operator, all scores were collected and summed up, in order to analyze the degree of usability of the device perceived by the operator. The same computation was also developed for each macro category, in order to identify the degree of usability perceived, with respect to the sphere to which they belong to.

Going deep in detail in the analysis, it is possible to state that:

- The number of items in the usability survey is 22, which means that the maximum score that could be reached is 154 (which is 22 multiplied by the maximum score that is 7 for the Likert scale adopted).
- The number of items related to the psychological sphere is 7, this means that in the usability survey the psychological sphere counts for the 31.8%. If we make the same analysis to the other two categories we find out that the engineering sphere counts for the 40.9%, whereas the workstation sphere influences the 27.3% of the final score of the survey.

To develop a more objective analysis of the device behavior, a purge of the data was done in order to exclude the aspect related to the psychological sphere.

Items scores, final Likert score and the purged one are reported in table.

The percentages reported in each category (e.g. psychological, engineering, workstation scores) are referred to scores normalized to the maximum one achievable in the category itself and not in the global usability survey, in order to better understand how much the goal is achieved in each group.

Due to the fact that Likert scale is not a scholastic scale, a conversion table between table percentages and Likert points is provided.

Likert score	Percentage
1	14.3%
2	28.6%
3	42.9%
4	57.1%
5	71.4%
6	85.7%
7	100%

Code	Plant	Workstation	day of trials	trial complete (Y/N)	USABILITY F/L day	Likert score	Device usability	Psychological scores		Engineering scores		Workstation scores		Likert score purged (no psycho sphere)	Device usability (purged)
OP001F	Mirafiori	Cruise fixing	2	N	F	102	66,2%	31,0	63,3%	41	65,1%	30,0	71,4%	71,0	67,6%
OP001L	Mirafiori	Cruise fixing	2	N	L	97	63,0%	33,0	67,3%	34	54,0%	30,0	71,4%	64,0	61,0%
OP002L	Mirafiori	Underbody cover	5	Y	L	80	51,9%	20,0	40,8%	26	41,3%	34,0	81,0%	60,0	57,1%
OP003L	Mirafiori	Underbody cover	5	Y	L	118,5	76,9%	35,0	71,4%	52	82,5%	31,5	75,0%	83,5	79,5%
OP004F	AGAP	Underbody sealing	4	N	F	79	51,3%	23,0	46,9%	34	54,0%	22,0	52,4%	56,0	53,3%
OP004L	AGAP	Underbody sealing	4	N	L	51	33,1%	14,0	28,6%	25	39,7%	12,0	28,6%	37,0	35,2%
OP005F	AGAP	Tunnel reinforcement bracket	5	Y	F	134	87,0%	41,0	83,7%	52	82,5%	41,0	97,6%	93,0	88,6%
OP005L	AGAP	Tunnel reinforcement bracket	5	Y	L	128,5	83,4%	39,5	80,6%	52	82,5%	37,0	88,1%	89,0	84,8%
OP006F	AGAP	Underbody cover	2	N	F	99	64,3%	31,0	63,3%	39	61,9%	29,0	69,0%	68,0	64,8%

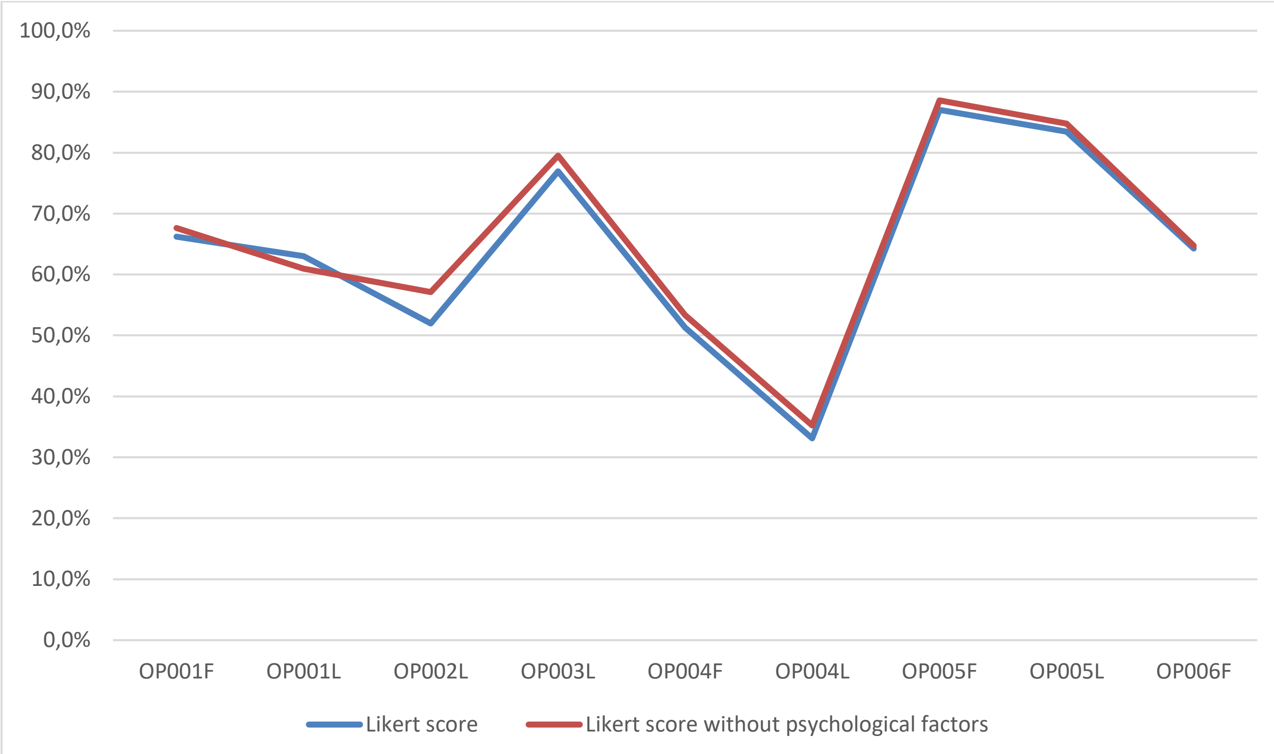


Figure 50 Likert score trend (complete and purged)

If we look at graph (Figure 50) it is possible to see that the discrepancy between the Likert score and the Likert score without the psychological sphere is very small. The presence of an outlier in Likert trend, related to last day of trial of OP001 (cruise fixing), could be easily justified by the high discrepancy between first day and last day of trials of the score related to one psychological item.

The discrepancy highlighted is probably caused by the change of operator that as provided the survey to the worker. Thus, from now going on, we can reasonably consider only the purged data in order to analyze the part of the project and of the prototype that could be improved, without taking any more into consideration the psychological part.

Analyzing only operators for whom usability surveys was collected both at the beginning and at the end of the trial, we see that the Likert total score (in %) is always decreasing. This decreasing trend could be easily justified by the initial enthusiasm of the operator in the first day of trials for the new device provided and for some problems related to the prototype itself.

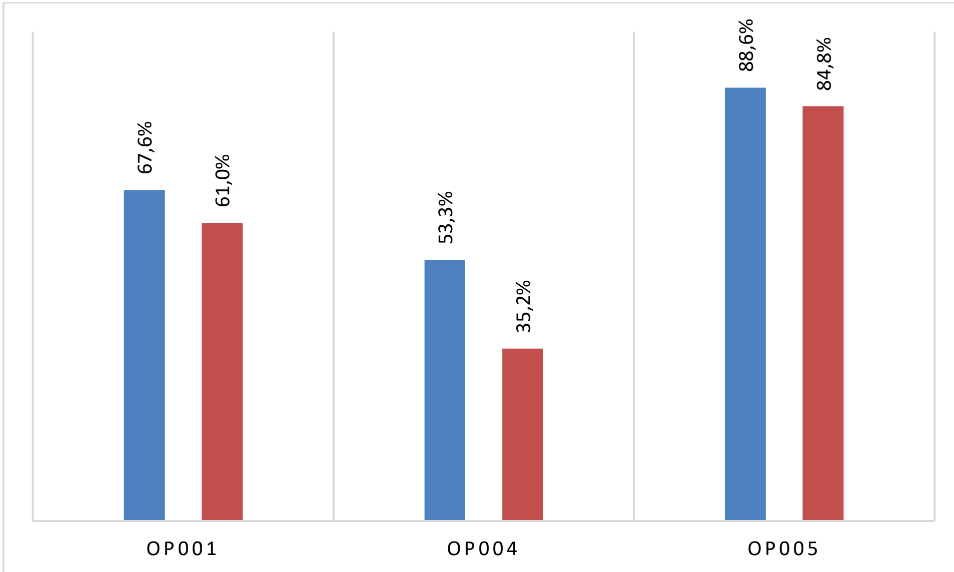


Figure 51 Likert score trend (purged one) First-Last day of trials

Analyzing the trend related to the workstation sphere it is possible to show that, except for OP004 (underbody sealing-AGAP), the evaluations done in the study phase related to the research of suitable workstations were correct. If we look at the Likert score provided by the operators to the items related to the workstation sphere, it is possible to see that the feedback is extremely positive. Taking into consideration that the choice of a suitable workstation influences the results of the trial for about 30% of the total score, it is possible to state that, in order to obtain truly scores related to the engineering sphere, we must at first carefully choose the workstations devoted to the trials.

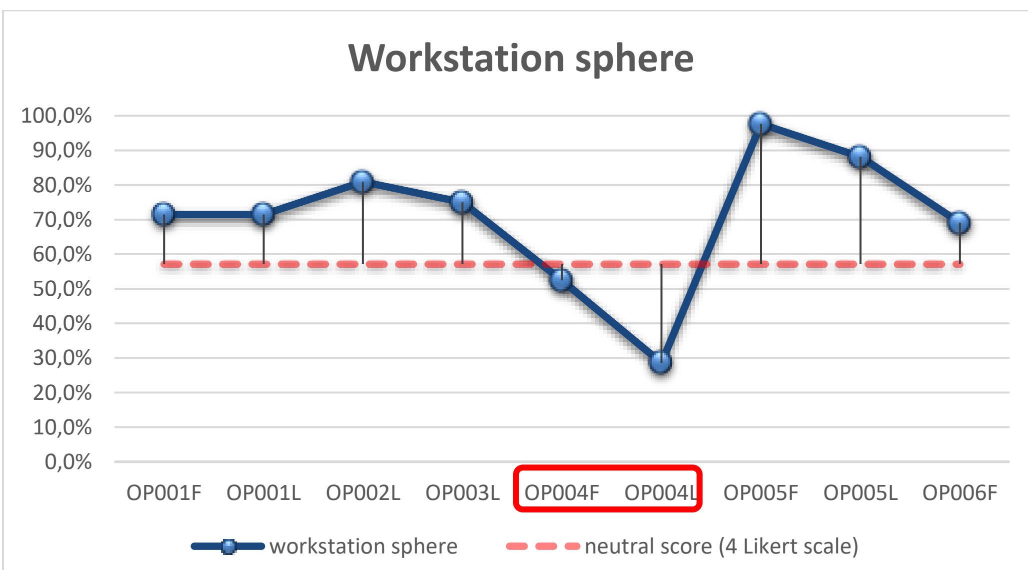


Figure 52 Trend of Likert score for the workstation sphere

As shown in Figure 52, scores below the neutral are the ones related to OP004 (Underbody sealing) in the first (OP004F) and last (OP004L) day of trials.

Negative points related to this workstation could be justify by the low scores assigned by the operator to the compatibility with the workstation (4F-2L) and to the high ones assigned to the interference with other working tools (6F-7L). As it is possible to notice from Figure 53, one of the main problems encountered was the interference between the encumbrance of the exoskeleton and the poles that protect the operator from chassis accidental falls.

Figure 53 Workstation underbody sealing (OP004) - AGAP trial

The low score obtained in the workstation sphere could also derive from the impossibility of the worker to perceive the support, thus the device was considered as a useless encumbrance.

Analyzing instead the engineering sphere, it is possible to see that only half of the scores are positive (above the neutral position), thus it is possible to state that, for what concern the engineering sphere, many evaluations must be done.

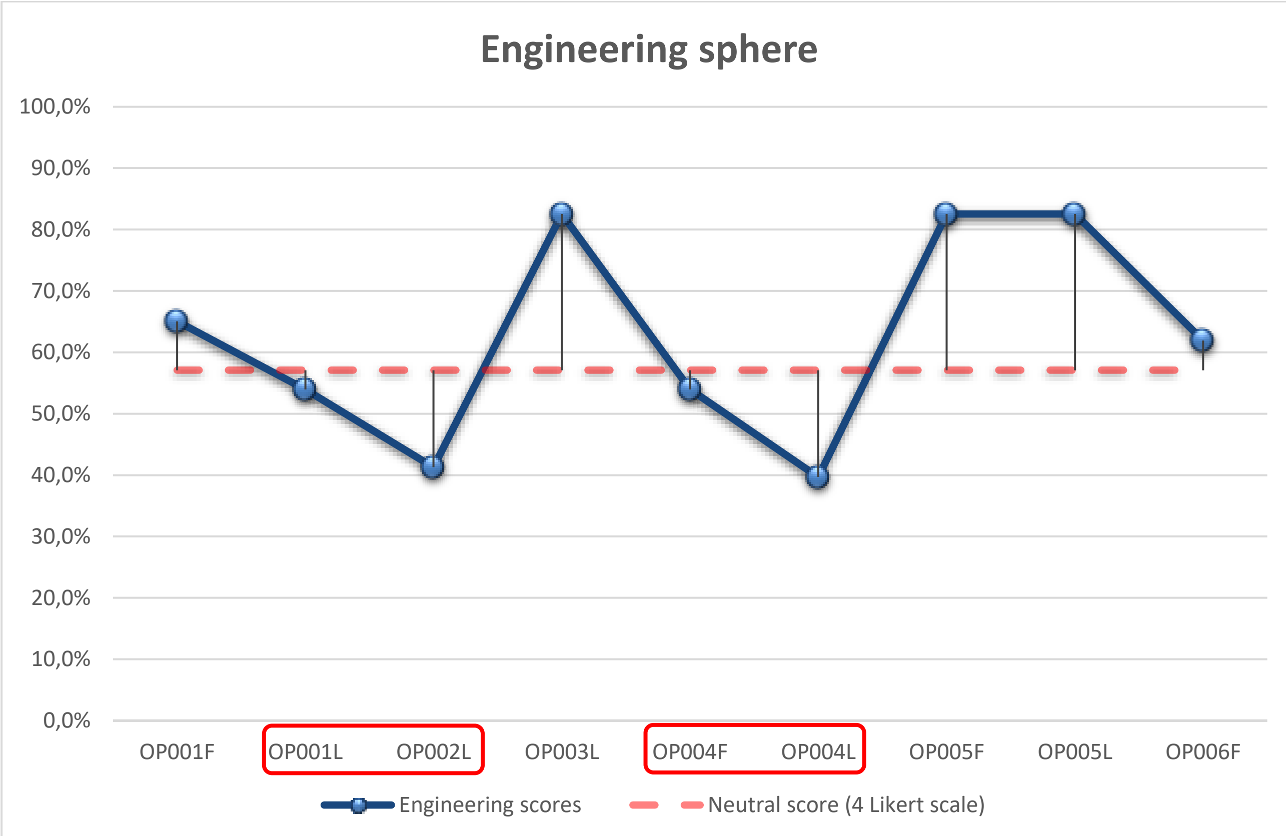


Figure 54 Trend of Likert score for the engineering sphere

Analyzing deep in detail the scores related to the operators that, for what concern the engineering sphere, are dissatisfied customers, it is possible to point out the problems related to the prototype and try to solve it in the mindset of pre-series production. For sake of simplicity we will consider only last day survey for the operator OP004, in order to take into account the same behavior for all the operators (survey at the end of the prolonged trial).

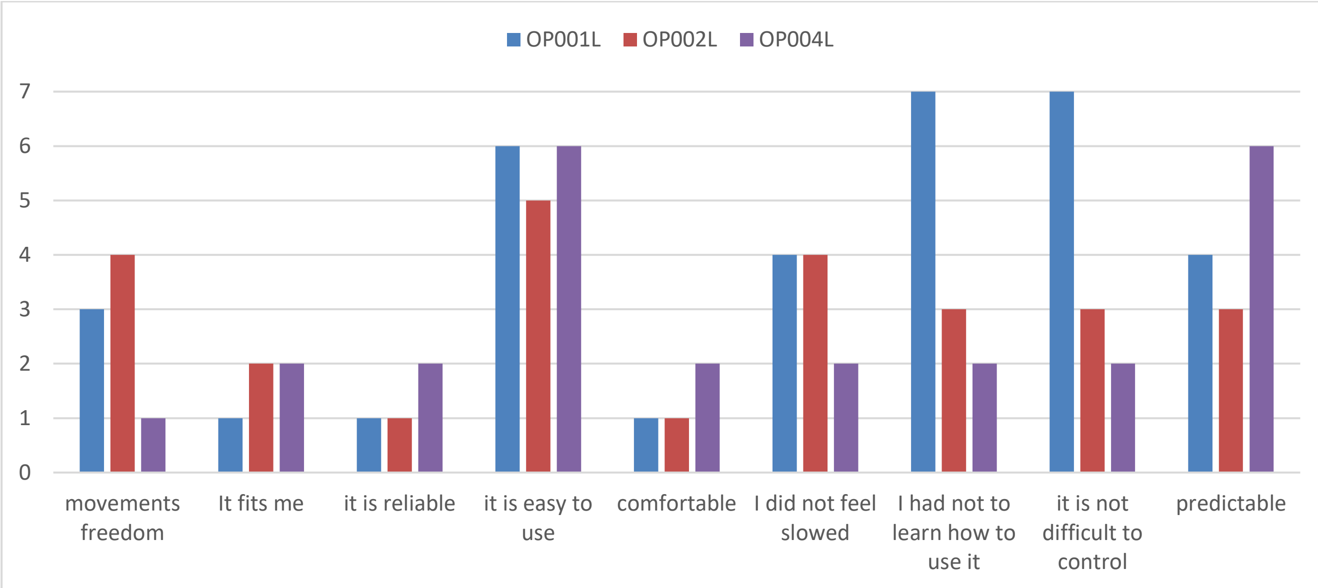


Figure 55 Engineering items trend for dissatisfied operators

As it is possible to see from Figure 55, the device is intuitive (it is easy to use). The main problems encountered are related to the fit of the device. At the same time operators do not perceive the reliability of the device and have some problems with the freedom related to the movements.

During trial phase, three main problems were pointed out by the dissatisfied operator, problems that could justify the low scores in the engineering items:

1. The presence of rubbing primarily related to the conformity of the brackets (material, shape, design) that create skin abrasion (low breathability)
2. The presence of vibrations at the shoulder's joint after some days of trials
3. The inability of the device to completely follow fast movements of the operators, thus resulting sometime in locking movements and sometime in the climbing over of the cassettes around the arms.

For what concern the first problem, which is mainly a design and material problem, COMAU and IUVO are already working on it, in order to find a suitable material to prevent rubbing and low breathability.

For what concern instead the second problem, it is related to the gap between the two indented wheels (that are part of shoulder mechanism). This gap sometime creates the vibration of the system when the operator was moving the arms.

The third problem is instead mainly related to size regulation of the prototype.

We must underline that the major problems that affect the engineering judge are primarily related to the prototype than to the product itself.

The problems encountered are mainly related to the fact that the prototypes developed by COMAU/IUVO are devoted to short trial and thus even the production company itself does not know the prototype behavior in case of long-usage.

All the problems highlighted were presented to COMAU, that is now working on the prototype drawbacks in order to provide a device able to face prolonged trials, in order to obtain results no more influenced by the misuse of the prototype.

Analyzing the trend of the engineering and workstation spheres related only to workers that have completed the trial (5 days of trial) we can see that the scores related to the workstation category are extremely high and almost similar, thus confirming that the selection of the right workstations may influence a lot the decision of the worker to continue or not the trial.

Figure 56 Engineering vs Workstation spheres after 5 days of trials

If, instead, we look at the scores related to the engineering category, we find out that OP002 (underbody cover Mirafiori) has a total score below the neutral one.

This extremely low score could mainly derive by some problems of the prototype encountered during the trial. In particular, the operator has perceived all the three problems highlighted in the analysis of Figure 55.

If we consider that the engineering sphere influences the overall score of the usability survey for the 40.9%, we thus conclude that we must take carefully into consideration the type of prototype used for the prolonged trials and, at first, evaluate if the prototype is developed to face prolonged trials without presenting defects.

5. Strategy and Business considerations

5.1.Strategy considerations

In order to implement the selection of the operators and workstations, to obtain more clear results without the need of a purged data, a more detailed analysis of categories trend was developed through the use of two matrices: BCG matrix and GE matrix.
In order to better understand the methodology applied, a brief introduction of the two matrices is proposed.

BCG matrix

The Boston Consulting Group Matrix is a model created in the seventies and is one of the tools used by management to define strategies and allocate resources / budgets for projects. The BCG Matrix can also be an excellent tool for the analysis of human resources.
Through BCG matrix it is possible to catalog workers in four main categories:

- Stars: they are the most promising products / services of the company. They are leaders in a rapidly developing market (good cash generation).
- Question marks: the products / services / markets on which we must ask ourselves whether it is better to invest or not. They are attractive because their target market is under development. However, since they have low market shares, they do not generate an immediate return on investment.
- Dogs: indicates those services / products with low cash generation. They are products / services with a low share in a mature market. Therefore, the company no longer invests on these products. It will therefore be necessary to adequately manage the decline phase.
- Cash Caw: they are the company's leading products / services (high cash generation, given the strong economies of scale and experience), in mature markets with very low growth rates where new competitors will hardly enter.

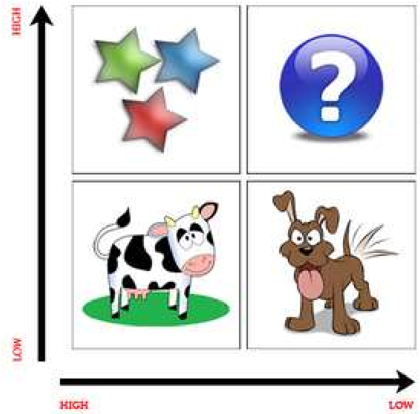


Figure 57 BCG matrix graphic representation

GE matrix

The General Electric Matrix, from the name of the company for which it was developed, is a business management portfolio tool, created by the consulting firm McKinsey
Unlike BCG matrix, created on the basis of simple variables, the GE matrix is constructed using aggregate variables that summarize the various factors underlying the competitiveness of the business and the attractiveness of the sector.
Strategies:

- investment and growth strategy (imposes the defense of the position acquired by investing to increase the level of the development rate and concentrating the efforts to maintain the strengths.)
- selective growth strategy (suggests the defense and / or growth of the acquired position by investing to support the actions of the competition and win over the customers.)
- selective strategy (suggests the defense of the acquired position by investing to concentrate investments where profitability is good and where risk is relatively low)
- harvesting or abandonment strategy (suggests minimizing further maintenance investments and planning the sale of the asset with greater financial benefit)

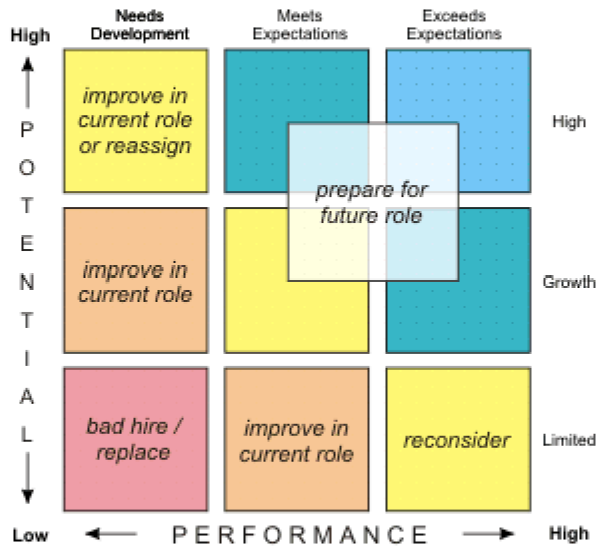


Figure 58 example of GE matrix representation

A third matrix, the relational matrix (Based on Fiocca's CPM assumptions), was used in order to analyze the psycological sphere.

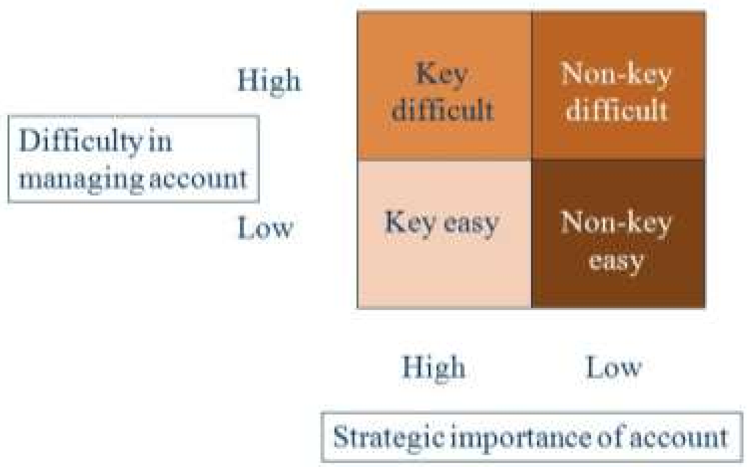


Figure 59 example of relational matrix representation

5.1.1. Analysis procedure

First of all, for each of the three categories highlighted in chapter 4.5, the most significative items were selected and the scores related to them were normalized to the maximum score (7).

Engineering analysis

The characteristics analyzed into this evaluation are the operator mindset (x axes) and the engineering aspects correlated (y axes)
Characteristics and items taken into considerations for each operator:

- Age (classified in terms of age higher or lower that 45 years old, which is in ergonomics terms the frontier between young and old people)
- Days of trial (maximum 5 days)
- Items from Usability:
  - It fits me
  - It is easy to use
  - I had to learn how to use it
  - It is difficult to control
  - It is unpredictable

For each operator a weighted average of the score was computed, considering the relative items importance as reported in Table 25 in order to evaluate the engineering aspects.

Table 25 engineering items relative importance

It is easy to use	25%
I had to learn how to use it	15%
It is difficult to control	30%
It is unpredictable	30%

For the operators that present scores for both first day and last day, the score is computed considering for 20% the influence of first day of trial and for 80% last day of trial. The final score regarding the engineering aspects is than averaged taking into consideration the number of days of trial with respect to the total one (5 days).
The item “it fits me” instead, was used in order to evaluate the operator mindset.

Operator mindset thus was computed as the product of the normalized item “it fits me” with the age of the operator normalized to 45 years old. Also in this case the final score was computed taking into consideration the different influence between first and last day of trials.

Table 26 Engineering aspects evaluation

code	age ><=45years	days of trial	It is easy to use	I had to learn how to use it	It is difficult to control	Unpredictable	I had not to learn how to use it	It is not difficult to control	Predictable	average	weighted average	weighted average related to first/last day	weighted average related to first/last day and to the number of days of trial
OP001F	53	2	0,86	0,43	0,29	0,29	0,71	0,86	0,86	0,82	0,84	0,84	**0,33**
OP001L	53	2	0,86	0,14	0,14	0,57	1,00	1,00	0,57	0,86	0,84		
OP002L	53	5	0,71	0,71	0,71	0,71	0,43	0,43	0,43	0,50	0,50	0,50	**0,50**
OP003L	53	5	0,86	0,14	0,14	0,14	1,00	1,00	1,00	0,96	0,96	0,96	**0,96**
OP004F	49	4	1,00	0,86	0,29	0,14	0,29	0,86	1,00	0,79	0,85	0,65	**0,52**
OP004L	49	4	0,86	0,86	0,86	0,29	0,29	0,29	0,86	0,57	0,60		
OP005F	44	5	1,00	0,86	0,14	0,14	0,29	1,00	1,00	0,82	0,89	0,94	**0,94**
OP005L	44	5	1,00	0,14	0,29	0,14	1,00	0,86	1,00	0,96	0,96		
OP006F	41	2	0,86	0,43	0,43	0,43	0,71	0,71	0,71	0,75	0,75	0,75	**0,30**

Table 27 Operator mindset evaluation

code	It fits me	operator mindset	operator mindset related to first/last day
OP001F	0,29	0,34	**0,20**
OP001L	0,14	0,17	
OP002L	0,29	0,34	**0,34**
OP003L	0,86	1,0	**1,0**
OP004F	0,29	0,31	**0,31**
OP004L	0,29	0,31	
OP005F	1,00	0,98	**0,87**
OP005L	0,86	0,84	
OP006F	0,43	0,39	**0,39**

The relation between the two characteristics is reported in Figure 60.

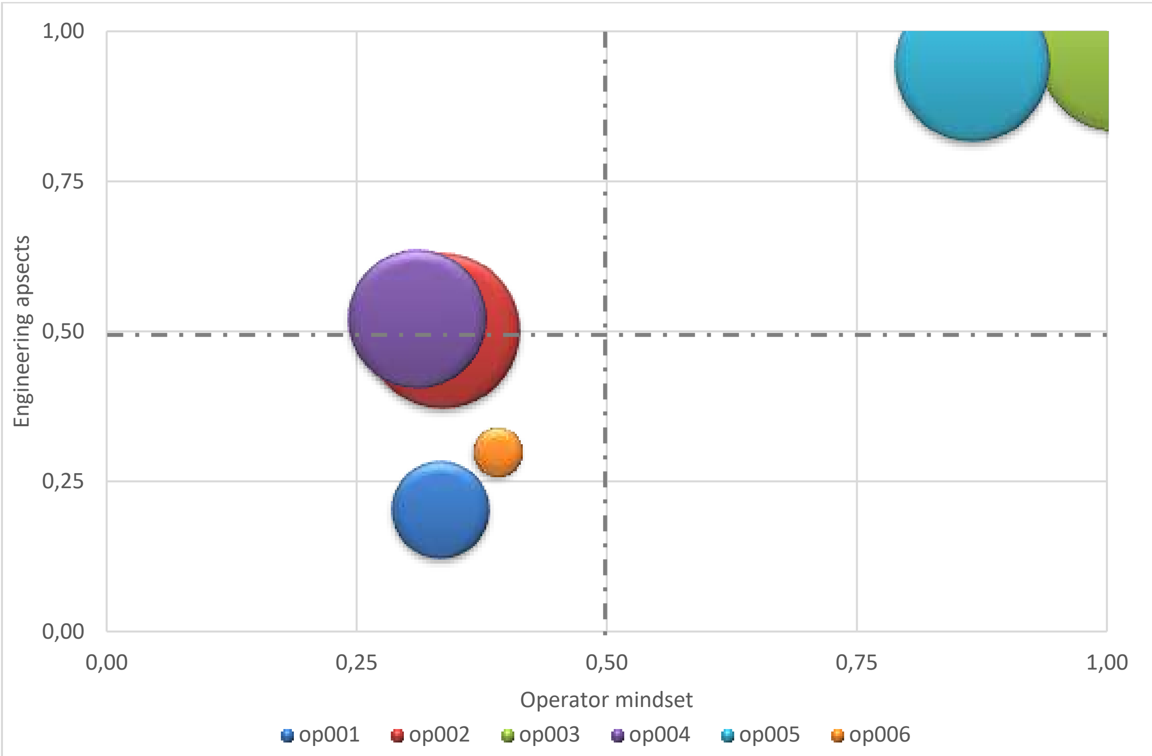


Figure 60 Engineering aspects - Operator mindset correlation

Workstation analysis

The characteristics analyzed into this evaluation are work relevance (x axes) and the correlated usability (y axes)

Characteristics and items taken into considerations for each operator:

- Days of trial (maximum 5 days)
- Items from Usability:
  - It fits me
  - It is easy to use
  - I had to learn how to use it
  - It is difficult to control
  - It is unpredictable
- Items from TAM2:
  - Work relevance

For each operator a weighted average of the score was computed, considering the relative items importance as reported in Table 28 in order to evaluate the workstation aspects.

Table 28 workstation items relative importance

It is consistent with the task	30%
It is compatible with my workstation	20%
It would interfere with other working tools	50%

As stated for the engineering analysis, for the operators that have the scores for both first day and last day, the score is computed considering for 20% the influence of first day of trial and for 80% last day of trial. The final score regarding the workstation aspects was than averaged taking into consideration the number of days of trial with respect to the total one (5 days).

The item "work relevance" instead, was used in order to evaluate the work relevance. Also in this case the final score was computed taking into consideration the different influence between first and last day of trials.

Table 29 Usability evaluation

code	days of trial	It is consistent with the task	It is compatible with my workstation	It would interfere with other working tools	It would not interfere with other working tools	average	weighted average	weighted average related to first/last day	weighted average related to first/last day and to the number of days of trial
OP001F	2	0,86	0,71	0,86	0,29	0,62	0,54	0,52	**0,21**
OP001L	2	0,86	0,57	0,86	0,29	0,57	0,51		
OP002L	5	1,00	0,86	0,86	0,29	0,71	0,61	0,61	**0,61**
OP003L	5	0,86	0,86	0,79	0,36	0,69	0,61	0,61	**0,61**
OP004F	4	0,86	0,57	0,86	0,29	0,57	0,51	0,41	**0,33**
OP004L	4	0,43	0,29	1,00	0,14	0,29	0,26		
OP005F	5	1,00	1,00	0,29	0,86	0,95	0,93	0,93	**0,93**
OP005L	5	0,93	0,93	0,29	0,86	0,90	0,89		
OP006F	2	0,71	0,71	0,29	0,86	0,76	0,79	0,79	**0,31**

Table 30 Workstation relevance evaluation

code	Work relevance (from TAM)	Work relevance (from TAM) related to first/last day
OP001F	0,86	**0,86**
OP001L	0,86	
OP002L	0,86	**0,86**
OP003L	0,79	**0,79**
OP004F	0,29	**0,29**
OP004L	0,29	
OP005F	1,00	**1,00**
OP005L	1,00	
OP006F	0,43	**0,43**

The relation between the two characteristics is reported in Figure 61.

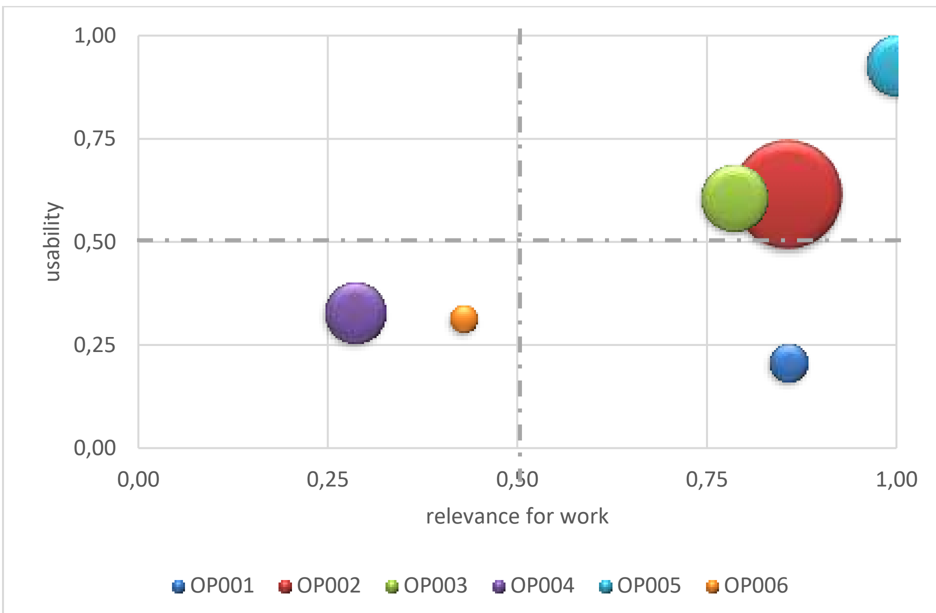


Figure 61 Usability- Relevance for work correlation

Psychological analysis

The characteristics analyzed into this evaluation are strategic relevance (x axes) and the correlated easy interaction (y axes)

Characteristics and items taken into considerations for each operator:

- Days of trial (maximum 5 days)
- Items from usability:
  - I am satisfied of the product
  - I like it

- I would use it in my job

- Items from TAM2:
    - Perceived usefulness
    - Intention to use

For each operator a weighted average of the score was computed, considering the relative items importance as reported in Table 31 in order to evaluate the workstation aspects.

Table 31 Psychological items relative importance

I am satisfied of the product	40%
I like it	20%
I would use it in my job	40%

As stated for the engineering analysis, for the operators that have the scores for both first day and last day, the score is computed considering for 20% the influence of first day of trial and for 80% last day of trial. The final score regarding the workstation aspects was than averaged taking into consideration the number of days of trial with respect to the total one (5 days).

The product between the items "perceived usefulness" and "Intention to use" instead, were used in order to evaluate the strategic relevance. Also in this case the final score was computed taking into consideration the different influence between first and last day of trials.

Table 32 Easy interaction evaluation

code	days of trial	I am satisfied of the product	I like it	I would use it in my job	average	weighted average	weighted average related to first/last day	weighted average related to first/last day and to the number of days of trial
OP001F	2	0,57	0,71	0,29	0,52	0,49	0,62	**0,25**
OP001L	2	0,57	0,43	0,86	0,62	0,66		
OP002L	5	0,71	0,71	0,71	0,71	0,71	0,71	**0,71**
OP003L	5	0,86	0,57	0,86	0,76	0,80	0,80	**0,80**
OP004F	4	0,43	0,57	0,43	0,48	0,46	0,32	**0,26**
OP004L	4	0,29	0,29	0,29	0,29	0,29		
OP005F	5	0,86	0,86	1,00	0,90	0,91	0,91	**0,91**
OP005L	5	0,86	0,86	1,00	0,90	0,91		
OP006F	2	0,71	0,71	0,71	0,71	0,71	0,71	**0,29**

Table 33 Strategic relevance evaluation

code	Perceived usefulness	Intention to use	strategic relevance	strategic relevance related to first/last day
OP001F	0,75	0,86	0,64	**0,64**
OP001L	0,75	0,86	0,64	
OP002L	0,32	0,86	0,28	**0,28**
OP003L	0,68	0,86	0,58	**0,58**
OP004F	0,29	0,29	0,08	**0,08**
OP004L	0,29	0,29	0,08	
OP005F	0,68	1,00	0,68	**0,68**
OP005L	0,68	1,00	0,68	
OP006F	0,29	0,50	0,14	**0,14**

The relation between the two characteristics is reported in Figure 62.

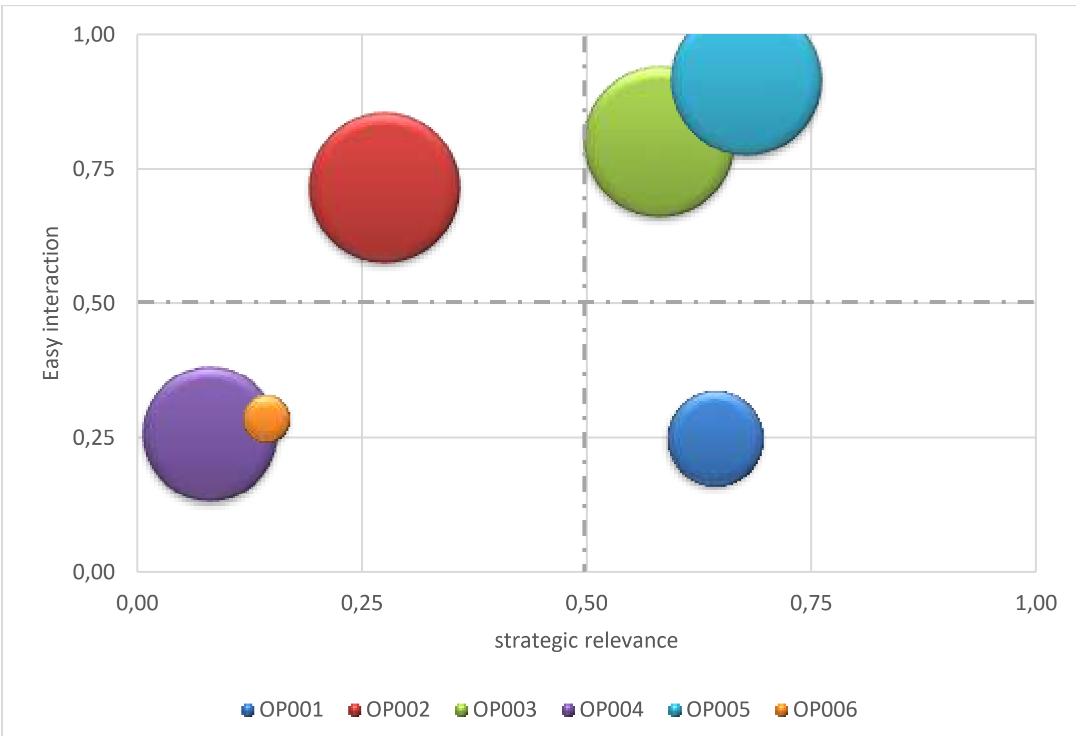


Figure 62 Easy interaction - Strategic relevance correlation

5.1.2. Strategic Analysis results

In order to catalogue the operators as a whole, the three matrices developed must be summarized and the interaction between the three categories must be evaluated.

Table 34 Matrices summary and McKinsey classification

Operator code	Body mass index	engineering matrix position	workstation matrix position	relational matrix position (psychological)	Mc Kinsey classification	Conclusion
OP001	24,22	Undesirable	cows	easy marginal	keep	strategic
OP002	24,15	Developed	stars	difficult marginal	keep	strategic
OP003	22,53	Attractive	stars	easy key	develop	star
OP004	25,56	Developed	Dogs	difficult key	leave	status
OP005	24,68	Attractive	stars	easy key	develop	star
OP006	25,93	Undesirable	Dogs	difficult key	leave	status

From Table 34 it is possible to highlight a correlation between McKinsey results and body characteristics, in particular with the evaluation of the body mass index (BMI>25 means overweight for OMS), meaning that the fit and comfort of the exoskeleton (which in this case mainly depend on the anthropometry of the worker) could be considered as one of the main factors that could affect the final result of the trial.

Another important aspect, emerged from the relational matrix, is the capability to find operators that are real volunteer for the trial and not strictly influenced by the opinion and decision of the Team Leader, as OP004 and OP006 are.

By the way, without taking into account the two operators that are not real volunteers, it is possible to state that one of the major factor that influence workstation matrix results and overall trial results, is the layout of the workstation itself, thus the possibility to have workstation in which there is low workers' interaction, a lot of free space without too many working tools and the risk to have working tools interference.

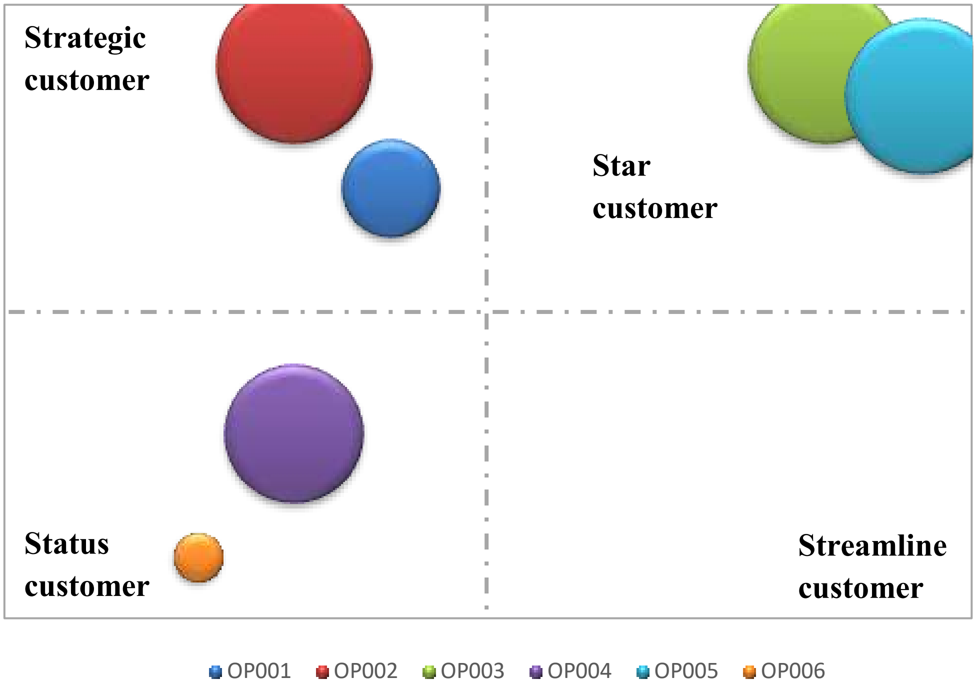


Figure 63 Graphical representation of operator and attractiveness vs workstation attractiveness

In Figure 63 a graphical summary of the results obtained is reported.

Through the use of McKinsey matrices, it was possible to catalogue the operators of the trials and obtain a sort of guideline useful to select future samples in order to obtain realistic results. A list of the principal characteristics that must be analyzed for the selection of the operator is reported.

Sample needed characteristics for the trial:

- BMI ≤ 25
- Workstation layout free of obstacle and with great maneuver margin without tool interference
- Real Voluntariness of the subject

Through the use of this guideline we can reasonably state that we are able to obtain realistic and accurate trial results.

5.2. Business considerations

COMAU exoskeleton project, in partnership with FCA ergonomics department, was developed in the mindset of industry 4.0.

From the point of view of COMAU, through the acquisition of IUVO, exoskeleton technology can be seen as a great business opportunity in order to diversify the market (apart from robot).

At this stage of the project, anyway, it is important to analyze the business from the point of view of FCA and, in particular, of FCA plants which are the final customers.

Going on, we will evaluate all benefits and costs from the point of view of FCA plants.

Background

Considering only the FCA plant in Italy, the number of underbody workstation with a biomechanical overload risk are 69. Considering 3 shifts, the number of positioned in these types of workstations are almost 191. For the purpose of this analysis, we can consider this number as the number of potential workers that can use COMAU exoskeleton.

In order to acquire one exoskeleton, the plant must pay to COMAU about 3000€.

If we consider the number of potential user and, at the same time, that each exoskeleton must be personal, the total investment of FCA plants is:

$$191\ workers\ \times 3k€ = 573\ k€ \rightarrow total\ investment\ required\ by\ FCA\ plants$$

Due to experimental phase of the project, it is possible only to make hypothesis about the Benefits derived from the application of these exoskeletons. In order to have a global vision of all the aspects of the project, the best case-worst case method is applied.

Best case

- Reduction of MSDs related to shoulder of 90%
- Reallocation of resources that are currently not allocable

Worst case

- Reduction of MSDs related to shoulder of 10%
- Reallocation of resources, that are currently not allocable, not feasible

MSDs general data

According to the analysis of INAIL data contained in INAIL statistical database, the number of MSDs related to osteomuscolar and soft tissues is the highest between the MSDs related to C29 category (according to INAIL C29 category is the one related to automotive assembly production).

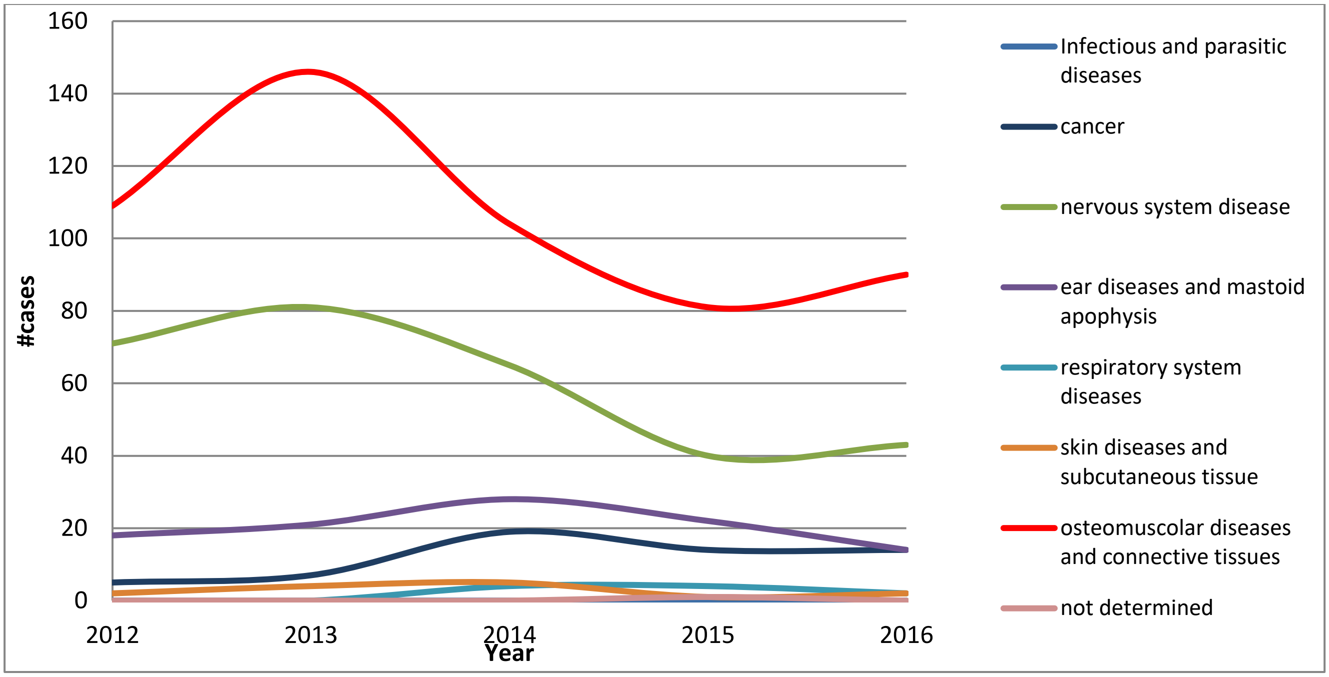


Figure 64 MSDs data from INAIL database, October 2017

In order to evaluate numerically the MSDs reduction for best/worst case we can consider the value of the last year of the survey (2016) which is 90 cases/year. We assume, for sake of simplicity all the cases attributed to the FCA group, although the statistics data concern all Car makers present on Italian soil (it is worth of notice that the number of recognized MSDs in 2016 in FCA is zero).

For what concern the cost related to MSDs, the consequences of accidents and occupational diseases increase costs of the company and decrease the profits. Cost effects could be computed immediately, whereas profits are affected in long term.

Costs increasing is due, in particular, to the loss of productivity of the company due to accidents and occupational diseases. We refer not only to the days of absence of the worker by illness, whose salaries are partially reimbursed by the insurance system, but also to action needed to reorganize the work and the replacement of the injured worker. The effects on the costs of the company include the following items: absence of the victim, interruption in production processes, reorganization of

work, first assistance, expenditure for recruitment of temporary staff, training of the worker who replaces the injured one, damages to the machinery, increase of the insurance premiums.
The effects on profits include: losses of production, loss of company image, job satisfaction. (12)
If considered for a single individual, a total of 3.3 days of work lost in the last year due to musculoskeletal pain may seem a limited number, but given the scale of the phenomenon, an important economic impact emerges at national level. (13)
In compliance with the Italian legislation and INAIL, some rules about "Daily allowance for absolute temporary incapacity" must be followed:

"The employer is obliged to pay to the injured worker the full remuneration for the day in which the accident occurred, and 60% of the salary itself for the subsequent 3 days." (14)

Considering that for the company the daily cost per worker is about 139.9€, the total cost after 4 days (included the one of "accident") is 391.6€. To this we have to sum the cost needed to substitute the operator with another operator which is 559.4€, the total cost for the company is thus 951€, with an increase of the costs of the 70% with respect to the normal cost.
Cost of each exoskeleton is 3k€, the cost related to each worker/yearly for the company is about 40k€.
In both cases we must consider tax relief and incentives coming from Italian legislation.

Tax relief and incentives for Industry 4.0 technologies

The 2017 Budget law [Legge di bilancio 2017] has extended tax relief and incentives related to the acquisition of capital goods for business.
Super-depreciation (140%) and Hyper-depreciation (250%-only for society business income [reddito di impresa]) support and incentive the companies that invest in new capital goods, in tangible and intangible assets (software and IT systems) functional to transformation technological and digital of production processes. (15)
In the 2017 budget law [part 1, section 1, article 1, comma 8-13, attachment 1] a list of all the industry 4.0 technologies, with the possibility to apply the Hyper-depreciation, is presented.
Exoskeleton technology is part of the category: "Dispositivi per l'interazione uomo macchina e per il miglioramento dell'ergonomia e della sicurezza del posto di lavoro in logica «4.0»", and therefore can be subjected, for the Italian legislation, to the Hyper-depreciation (250%).

Depreciation

Unitary exoskeleton cost [k€]	3
#exoskeletons FCA plant	191
Total investment [k€]	573
Super-depreciation	140%
Hyper-depreciation	250%
Tax savings	24%

DEPRECIATION EVALUATION	**Depreciation**		
	Ordinary	**Super**	**Hyper**
Deducible amount (IRES purpose) [k€]	573	802,2	1432,5
Tax savings (24% of the total deductible for IRES purposes) [k€]	137,52	192,53	343,8
Net investment cost (573k€ - tax savings) [k€]	435,48	380,47	229,2
Greater savings on the net cost of the investment [%]	-	9,6%	36,0%

Best case/Worst case evaluation

Best case **MSDs reduction 90% no reallocation**		**Worst case** **MSDs reduction 10% no reallocation**	
#cases prevented	81	#cases prevented	9
money saved/year [€]	31720,28	money saved/year [€]	3524,48
exoskeleton cost (191 workers) [€]	573000	exoskeleton cost (191 workers) [€]	573000
depreciation cost (5 years) [€]	343800	depreciation cost (5 years) [€]	343800
net investment [€]	229200	net investment [€]	229200
B/C (money saved/net investment)	0,14	B/C (money saved/net investment)	0,02

As it is possible to see from results, even if currently the cost related to MSDs in Italy for the society is very high, for what concern the cost related to carmaker, such as FCA, the money needed for the investment (even with a high depreciation) is huge with respect to the cost of MSDs. We can see that, even in the best-case evaluation, the B/C is below 1, which means that the costs are extremely high with respect to the benefits provided.

If, instead, we make an analysis considering the possibility to reallocate workers that actually are not allocable (estimation of 10% of MSD prevention cases), we can evaluate a cost saving of 40k€ per year per worker due to the possibility to allocate people that at the actual stage are not allocable due to limitation.

Io order to evaluate more exactly the business, a more detailed analysis of the investment and the money saved per year must be done.

The business evaluation conducted is based on 5 years in order to consider an intrinsic percentage of obsolescence of the product.

The model applied is like the one used for the Cash-flow evaluation, BUT due to the lack of cash-in (we can only estimate money saved) could not be considered a propriate Cash flow, it is possible to consider it anyway a sort of "saving flow".

Table 35 Best case "saving flow" (with reallocation of resources)

BEST CASE (5 years) [€]	Y0	Y1	Y2	Y3	Y4	Y5
Flow of money N-1		(573.000)	(510.720)	(448.439)	(386.159)	(323.878)
Exoskeleton cost	(573.000)					
depreciation cost		68.760	68.760	68.760	68.760	68.760
annual maintenance (estimated)		(38.200)	(38.200)	(38.200)	(38.200)	(38.200)
money saved for lack of injury		31.720	31.720	31.720	31.720	31.720
Flow of money (no reallocation)	**(573.000)**	**(510.720)**	**(448.439)**	**(386.159)**	**(323.878)**	**(261.598)**
Reallocation of people (about 10% of MSD cases prevented)		320.000	320.000	320.000	320.000	320.000
Flow of money with reallocation	**(573.000)**	**(190.720)**	**191.561**	**573.841**	**956.122**	**1.338.402**

Benefits (5 years) €	**2.102.400**	**B/C***	**2,75**
Costs (5 years) €	**764.000**		

*B/C (benefits/costs ratio) is intended as the money saved due to MSDs reduction and reallocation of people over the costs afforded due to maintenance and the initial investment.

It is possible to notice that the B/C is higher than 1, thus it could be considered a good investment. In order to have a clearer view of the B/C ration variation in relation to MSDs prevented and number of people reallocated a basic Matlab code was implemented and plotted.

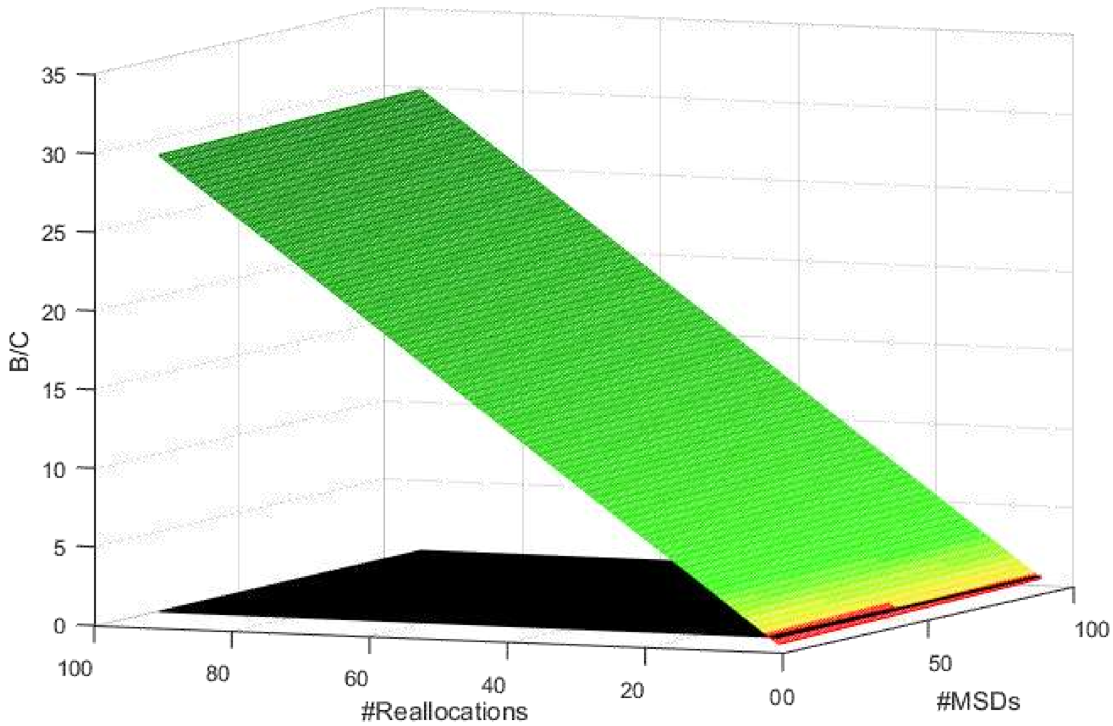


Figure 65 Graphic representation of the B/C implementation as function of reallocations and MSDs

As it is possible to see from the figure, the area in which B/C<1 is very small.

In particular, it is possible to find, through the evaluation of the data, the threshold B/C=1: it is possible to state that B/C>1 in case of 2 reallocation and 36 MSDs prevented; if the number of MSDs prevented is reduced, we need to reallocate at least 3 people in order to maintain a B/C>1.

Through the graph it is possible to see that, even if the initial costs are high, even with the reallocation of few people, the benefits overcome the costs related to the maintenance and acquisition of the device.

Every business evaluation conducted in this chapter is based on some assumptions, at the actual state of art nothing could be stated about the possibility of MSDs reduction and people with limitation code reallocation.

6. Final conclusions about the study

The study developed has highlighted the main criticalities related to the application of exoskeletons in a real environment as an automotive manufacturing plant is.

One of the main challenges of the study, as stated before, is related to the difficulty to find suitable workstations in which exoskeleton technology is applicable without interference, in safe condition, without affecting workers job behavior and without damaging the final product. The exoskeletons considered were developed in laboratory and thus tested on basic tasks, without considering the production field and all the constraints related to it, such as production line pace, space constraints and physical constraints.

In particular, one of the main aspects emerged from the observation of the operator during a working period is difficulty to find workstations in which the task required is composed only by movements and gestures for which the applied exoskeleton is studied.

If we think for example to the application of LAEVO exoskeleton, whose application requires workstations in which the task is characterized almost by the necessity to bend the back, without walking, which is quite difficult in a production line such as an Automotive production line in which the operator has a very short time to perform the task and, in many cases, has to follow the vehicle for a short piece of the line.

At the same time, through the use of virtual simulations in ChairlessChair application, it was highlighted the difficult interaction of workers with a device that completely change the way to perform their job and the possible benefits that could derive through the change in posture (only if in presence of adequate support).

Through the evaluation of COMAU prototype, instead, all the problems related to the development of a completely new type of device has emerged:

- The need of many trials in order to understand all the drawbacks and problems related to the design of the device.
- The limits related to the prolonged use of prototypes in a manufacturing field, that is characterized by efficiency, imposed pace and no possibility of errors.
- The impossibility to quantify the real health benefits for the workers.

- The need of enough space all around in the workstations selected in order to ensure that the operator could move freely and without bothering colleagues.

Through the strategic analysis and the use of McKinsey method, it was possible to define the characteristics of the ideal operator for future trials, in order to obtain as feedback clear and objectives results.

Finally, the business considerations developed, even with many simplifications and assumptions, were developed in order to try to analyze a problem that, nowadays, affects not only single companies but also all the major countries: the high number of costs related to MSDs that highly affect GDP.

EU-OSHA stated that worldwide work-related injury and illness results in in the loss of 3.9% of GDP, which means that roughly the annual cost is about 2680 Billion of €. By the away, it is extremely difficult at this point of the experimentation, evaluate benefits and cost saving for a product that is a prototype and for which the positive effects could be seen only in a long-range observation.

In order to have a clear view of this business, anyway, despite the economical assumption performed, a deeper analysis to investigate medical benefits (such as EMG) must be done.

Appendix 1 (Usability questionnaire)

All items were measured on a 7-point Likert scale, where 1 = strongly disagree, 2 = moderately disagree, 3 = somewhat disagree, 4 = neutral (neither disagree nor agree), 5 somewhat agree, 6 = moderately agree, and 7 = strongly agree.

I felt free	1	2	3	4	5	6	7
I felt slowed	1	2	3	4	5	6	7
I felt distressed	1	2	3	4	5	6	7
It is consistent with the task	1	2	3	4	5	6	7
I had to learn how to use it	1	2	3	4	5	6	7
It fits me	1	2	3	4	5	6	7
It is difficult to control	1	2	3	4	5	6	7
It is effective for my job	1	2	3	4	5	6	7
It helps to make no mistakes	1	2	3	4	5	6	7
It helps me to do my job better	1	2	3	4	5	6	7
It is adequate for my job	1	2	3	4	5	6	7
It is reliable	1	2	3	4	5	6	7
It is easy to use	1	2	3	4	5	6	7
It is comfortable	1	2	3	4	5	6	7
It is unpredictable	1	2	3	4	5	6	7
I am satisfied of the product	1	2	3	4	5	6	7
I like it	1	2	3	4	5	6	7
I felt at ease	1	2	3	4	5	6	7
It fits my job	1	2	3	4	5	6	7
I would use it in my job	1	2	3	4	5	6	7
It would interfere with other working tools	1	2	3	4	5	6	7
It is compatible with my workstation	1	2	3	4	5	6	7

Appendix 2 (Acceptability questionnaire)

All items were measured on a 7-point Likert scale, where 1 = strongly disagree and 7 = strongly agree. (11)

Intention to Use

Assuming I have access to it, I intend to use it. 1 2 3 4 5 6 7

Given that I have access to it,

I predict that I would use it. 1 2 3 4 5 6 7

Perceived Usefulness

Using it improves my performance in my job. 1 2 3 4 5 6 7

Using it in my job increases my productivity. 1 2 3 4 5 6 7

Using it enhances my effectiveness in my job. 1 2 3 4 5 6 7

I find the system to be useful in my job. 1 2 3 4 5 6 7

Perceived Ease of Use

My interaction with it is

clear and understandable. 1 2 3 4 5 6 7

Interacting with it does not require

a lot of my mental effort. 1 2 3 4 5 6 7

I find the system to be easy to use. 1 2 3 4 5 6 7

I find it easy to get the system to do

what I want it to do. 1 2 3 4 5 6 7

Subjective Norm

People who influence my behavior think

that I should use the system. 1 2 3 4 5 6 7

People who are important to me think that I should use the system.	1	2	3	4	5	6	7
Voluntariness							
My use of the system is voluntary.	1	2	3	4	5	6	7
My supervisor does not require me to use it.	1	2	3	4	5	6	7
Although it might be helpful, using the system is certainly not compulsory in my job.	1	2	3	4	5	6	7
Image							
People in my organization who use the system have more prestige than those who do not.	1	2	3	4	5	6	7
People in my organization who use the system have a high profile.	1	2	3	4	5	6	7
Having it is a status symbol in my organization.	1	2	3	4	5	6	7
Job Relevance							
In my job, usage of the system is important.	1	2	3	4	5	6	7
In my job, usage of the system is relevant.	1	2	3	4	5	6	7
Output Quality							
The quality of the output I get from it is high.	1	2	3	4	5	6	7
I have no problem with the quality of its output.	1	2	3	4	5	6	7

Result Demonstrability

I have no difficulty telling others about the results of using the system.	1	2	3	4	5	6	7
I believe I could communicate to others the consequences of using the system.	1	2	3	4	5	6	7
The results of using it are apparent to me.	1	2	3	4	5	6	7
I would have difficulty explaining why using the system may or may not be beneficial.	1	2	3	4	5	6	7

Appendix 3 (Borg scale)

Score	Verbal Anchor
0	Nothing at all
0.5	Extremely weak (just noticeable)
1	Very weak
2	Weak (light)
3	Moderate
4	
5	Strong (heavy)
6	
7	Very strong
8	
9	
10	Extremely strong (almost maximal)

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