POLITECNICO DI TORINO

Department of Mechanical and Aerospace engineering
Master of Science in Automotive Engineering

Final Dissertation

Human-centred approach in Industry 4.0:

Virtual validation of the design and application of an exoskeleton in the automotive industry

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“We celebrate our ability to create machines that move as man, yet we take for granted the miracle that is the human body.”

David Alejandro Fearnhead

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As this journey of my life comes to an end, I would like to thank the people that made it all possible.

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And everyone that made my life better.

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WMSDs	Work-related Musculoskeletal Disorders
CTS	Carpal tunnel syndrome
ISO	International Organization for Standardization
UNI	Ente nazionale Italiano di Unificazione
INAIL	Istituto Nazionale Assicurazione Infortuni sul Lavoro
BCG	Boston Consulting Group
3-D	Three-dimensional
MATE	Muscular Aiding Tech Exoskeleton
D. Lgs.	Legislative Decree
NIOSH	National Institute for Occupational Safety and Health
FCA	Fiat Chrysler Automobiles
IT	Information technology
IoT	Internet of Things
IIoT	Industrial Internet of Things
FsM	La Fabbrica si Misura
IEC	International Electrotechnical Commission
VR	Virtual Reality
CE	Conformité Européenne
HAL	Hybrid Assistive Limb
EMG	Electromyography
CV	Coefficient of Variation
CAD	Computer-aided Design

Abstract

In the present day, companies are constantly facing fresh challenges that they must overcome. Any company that fails to continuously improve itself will be left behind and eventually swallowed by the relentless advance of time. The biggest and most successful companies are restless, they never sleep, they never stop, and they never give up. These companies regularly challenge the norm and aim to change the status-quo, they expand their horizon and grab opportunities by the throat.

One of the many opportunities that companies are presented with is Industry 4.0 i.e. the fourth industrial revolution. Industry 4.0 brings new values and services for customers and for the company itself through the use of advanced technologies. The combination of advanced manufacturing and connected systems provides the company with a new tool to monitor its production processes and to fulfil its customers' needs and wants, enabling it to face new frontiers.

However, the advancement of technology does not mean the end of human presence in the industry. On the contrary, the importance of the human factor is clearer today than it was before. Robots can perform difficult repetitive tasks with precision, and have substituted manual labor in many production phases, but they lack the flexibility, dexterity and intelligence of humans. Therefore, Human-Robot Collaboration offers the advantages of both robots and humans, enabling workers to complete their jobs while being assisted by collaborative devices thus relieving them from ergonomically unfavorable conditions.

An example of Human-Robot Collaboration is the exoskeleton, a wearable device that interacts with the user to help them perform a task or to augment their capabilities. Nowadays, companies are looking for ways to develop and implement exoskeletons into their manufacturing processes, therefore creating the need for methodologies and approaches to achieve the expected results.

In light of this necessity, this thesis proposes a human-centred approach to the design and application of exoskeletons, shifting the centre of attention from the device itself to the ultimate beneficiary, i.e. the human being.

The first chapter puts into perspective the proposed approach, as it focuses on the ecosystem in which the exoskeletons exists, starting from ergonomics and its applications to the industrial sector all the way to Industry 4.0 and its technological innovations, thus giving a chronological overview of the evolution of the human-machine interface.

The second chapter is dedicated to an essential part of the approach i.e. exoskeletons. It gives a detailed view of what they are, their types, their many applications, and the key challenges that face them. An examination of some current available medical, military and industrial exoskeletons is also present in this chapter.

In the third chapter the core part of the approach is discussed: the human body. Its variability cannot be neglected and is therefore it is examined by undertaking a survey of various anthropometric measurements of 124 subjects using a 3-D Body Scanner. The project is outlined in this chapter and its results are discussed in detail.

The human-centred approach to the design and application of an exoskeleton is proposed in the fourth chapter. In this chapter, the above-mentioned approach is detailed step by step and is first applied on a commercial exoskeleton: the MATE by Comau. The approach serves as a tool to verify the wearability and movement of an exoskeleton, keeping in mind the final user and their variability and limits. The implementation of this approach in the design phase and its possible future developments are also discussed in this chapter.

The final chapter is dedicated to drawing conclusions from the study and reflecting on the obtained results.

1 Human-centric Smart Factories

The technological innovations in the field of industry 4.0 and the "ambient intelligence", offer new opportunities to bring humans to the center of the planning with the objective to create a comfortable working environment, adapted to their needs and wants. The adaptation of workstations, sensors and enabling technologies (collaborative robots and exoskeletons), offers a significant contribution to reducing the risks from biomechanical overloads and more generally for the reduction of the accident phenomenon.

The opportunities offered by ambient intelligence also require a thorough knowledge of the working population. At the present time, legislations on health and safety of workers, foresees that during the design phase of new machinery/industrial processes, ergonomic evaluations must consider the working population of interest. The use of anthropometric data is essential to design a safe, comfortable and productive work environment.

Although the perfect interaction between a workstation and a worker is not always possible, the integration of anthropometric data into ergonomic design ensures an improvement in the conditions of use or work, prevents the onset of musculoskeletal disorders, physical fatigue, psychological problems related to work while also helping to increase work performance and productivity.

The term coined to describe the integration of Industry 4.0 into the field of ergonomics is Ergonomics 4.0. It means experiencing the fourth industrial revolution combining the well-being of humans and the efficiency of systems, putting at the center of the grandiose commitment to designing the future, "man", with his limits and capabilities that modern technologies allow to develop more every day.

1.1 Ergonomics

According to the International Ergonomics Association: "*Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance*" [1].

The term Ergonomics, first coined by Wojciech Jastrzębowski in an article published in 1857, derives from two Greek words: *ergon*, which means work and *nomos*, which means laws, thus laws of work, or more precisely, the science of work.

Practitioners of ergonomics , i.e. ergonomists, contribute to the design and evaluation of tasks, jobs, products and systems in order to make them compatible with the needs, abilities and limitations of people [1].

There are two main branches of ergonomics, divided on the basis of the field of application: process and product ergonomics. Process ergonomics focuses on the interaction between the worker and his place of work: the workstations are designed in such a way to minimize the risks to the health of the worker and maximize his comfort. Product ergonomics investigates the best choices to be implemented on the product that a company wishes to commercialize.

Figure 1. Ergonomics: human centered design. [http://www.iea.cc - retrieved January 2019]

1.1.1 Disciplines

As mentioned before, process ergonomics primarily focuses on the design of workstations and workplaces. A bad organization of the workplace can cause physical harm to the worker. This is valid for any workplace, in any sector, be it industrial or else.

On one hand, underestimating the importance of the ergonomic aspect of design increases the risk of physical harm to the workers, which reflect directly on the performance of the worker and consequently on the final product. On the other hand, physical injury to a worker can be of varying importance and severity: a worst-case scenario is a work-related injury that causes disability. In such a case, the legal aspect also comes into play.

Process ergonomics means adapting the workstation to "man" and to ensure that the opposite is not true. Long gone are the days of specifically choosing a worker to perform a certain task. A workstation must be fit and adapted to human needs, ready to be used by whomever is working.

In addition, ergonomics not only relates to the adaptation of specific equipment work to the anthropometric and anatomical characteristics of the subject, but also takes into account the organization of the work, its content and the environment in which it takes place. Some of the environmental factors that are considered are: climate, light, heat, order/cleanliness, noise, vibration, harmful chemicals and radiations.

Ergonomics is a vast scientific field that interconnects different scientific disciplines, such as design, engineering, occupational medicine and psychology. Taking this into account, the domains of specialization within ergonomics are [1]:

- **Physical Ergonomics**: the field of ergonomics concerned with the human anatomical, anthropometric, physiological and biomechanical characteristics as they relate to physical activities. Simply put, it deals with the physical load on the human body;

- **Cognitive ergonomics**: concerned with the mental process, such as perception, memory, reasoning and motor responses. The purpose of cognitive ergonomics is to conceive simple systems which minimize the work load and the possibility of committing errors;

- **Organizational Ergonomics**: concerned with the optimization of sociotechnical systems, including their organizational structures, policies and processes.

It is also worth making a distinction in ergonomics with regards to the different phases of application. It can be divided to:

- **Preventive or Conception Ergonomics**: it is applied in the early stages of a product or process development, to reduce the production costs, improve results in terms of safety, and work quality [2].

  The advantage of this design process is that it minimizes the costs that would otherwise be necessary to make modifications later in the production stage.

- **Corrective Ergonomics**: it is applied in the production phase. It consists of an action or set of actions taken to eliminate the existing non-conformities, causes, defects or other undesired situations, to prevent their reoccurrence [2]. It is worth noting that a proper preventive approach limits the need for corrective actions therefore reducing costs and damage.

Figure 2 illustrates some of the subjects previously discussed in this part of the chapter.

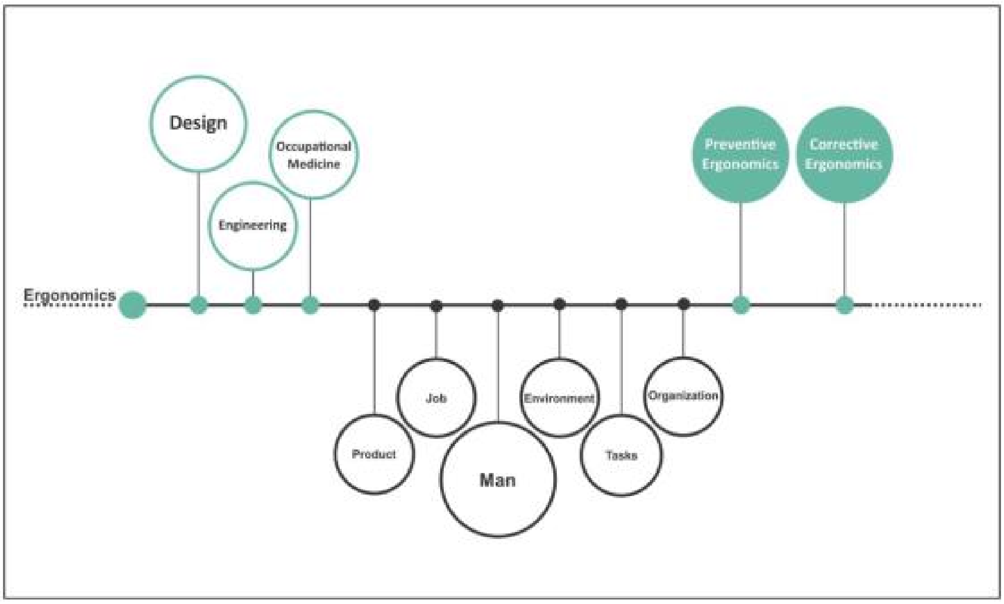


Figure 2. Ergonomics in product/process development [2]

1.1.2 Work-Related Musculoskeletal Disorders (WMSDs)

Musculoskeletal Disorders or MSDs are injuries and disorders that affect the human body movement or musculoskeletal system (i.e. muscles, tendons, ligaments, nerves, discs, blood vessels, etc.). WMSDs are Musculoskeletal Disorders related to, or caused by, the type of work performed.

When a muscle, tendon, nerve or joint is stressed and traumatized on a repeated basis for days, months or years, it eventually becomes damaged. This leads to a musculoskeletal disorder. WMSDs are also sometimes called repetitive strain injuries (RSIs), cumulative trauma disorders and overuse injuries [3].

Musculoskeletal disorders (MSDs) are widespread in many countries, with substantial costs and impact, on quality of life. MSDs are not uniquely caused by work, but they constitute a major proportion of all registered and/or compensable work-related diseases in many countries [4].

In the United States, MSDs are the single largest category of work-related illness, representing more than a third of all registered occupational diseases [5].

Common symptoms of MSDs are: swelling, as some tissues become irritated; pain; stiffness and loss of range of motion of surrounding joints; inability to work and function at home. The physical job features that are frequently cited as risk factors for MSDs include [4]:

- rapid work pace and repetitive motion patterns;
- insufficient recovery time;
- heavy lifting and forceful manual exertions;
- non-neutral body postures (either dynamic or static);
- mechanical pressure concentrations;
- vibrations;
- exposure to cold;
- combinations of the above.

Workers' health also has an economic impact on a wide scale, according to the World Health Organization: "Work-related health problems result in an economic loss of 4–6% of GDP for most countries. The basic health services to prevent occupational and work-related diseases cost on average between US$ 18 and US$ 60 (purchasing power parity) per worker."

Some of the most common Work-Related Musculoskeletal Disorders are briefly discussed in the following:

Carpal tunnel syndrome (CTS) is a type of MSD due to compression of the median nerve as it travels through the wrist at the carpal tunnel. It results in inflammation, pain, numbness, and tingling in the hand and arm. CTS makes it difficult for some people to perform ordinary tasks such as driving, holding a book and grasping small objects (Figure 3).

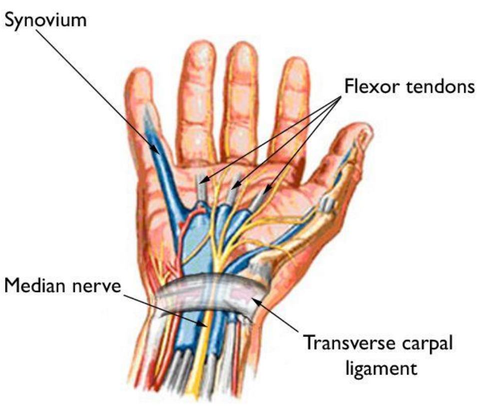


Figure 3. Carpal Tunnel Syndrome [https://orthoinfo.aaos.org - retrieved February 2019]

Carpal tunnel syndrome is often the result of a combination of factors that reduce the available space for the median nerve within the carpal tunnel [6].The work-related causes of CTS are forceful and repetitive work involving the same hand and wrist motions, and vibrations.

It is especially common in jobs where the hands are intensively used, such as assembly line work/manufacturing, sewing, finishing, cleaning, and meat, poultry, or fish packing [6]. Women are three times more likely than men to develop CTS. People with diabetes or other metabolic disorders also have a higher risk of developing CTS.

De quervain's tenosynovitis is a painful condition that affects tendons where they run through a tunnel on the thumb side of the wrist. It might impair thumb function. The cause of this syndrome has not yet been clearly determined, but it seems to be prevalent in workers who perform rapid repetitive activities involving the use of the thumb, such as fitting, pinching and grasping.
Other causes might be the frequent use of a mouse or trackball. The reason for this may lie in the postural requirements for mouse and trackball use in which the thumb is typically maintained abducted and extended [7].

In Italy, INAIL provides regular data on the of claims of WMSDs cases on the national level. Table 1 shows the number of claims in the industrial and service sectors in Italy between January and November 2017 and between January and November 2018.

Table 1. WMSDs claims filed in Italy in the industrial and service sectors (combined) 2017-2018 [8]

Sex	November 2017	November 2018	January-November 2017	January-November 2018
Male	3024	3286	31819	32796
Female	1030	1071	10926	10891
Total	**4054**	**4357**	**42745**	**43687**

1.1.3 Standards and Legislations

Ignoring the ergonomic aspect of workplace design not only has a detrimental effect on the health and well-being of workers in a single company but also extends to affect the whole country. For this reason, many countries have specific legislations and standards concerning worker health in the workplace.

The Italian Legislative Decree 81/08 is the primary reference in Italian law for protecting the health and safety of workers. It is important to highlight, in particular, the following articles[8]:

- **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";*

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

- **Article 22** - Obligations of designers: "*Designers of work places, workstations and plants must respect the general prevention principles in the field of occupational health and safety when they take design and technical decisions and must choose protective* *equipment, components and devices which conform to the* ***relevant legislative and regulatory standards****.*"

- **Article 23, Subsection 1** - Obligations of manufacturers and suppliers*: "The manufacturing, sales, rental or loan of working equipment, personal protection devices and systems which do not comply with* ***occupational health and safety legal requirements are forbidden.****"*

In articles, 22 and 23 reference is made to Decree 17/2010 [9] which implemented the European "New Machinery Directive" 2006/42/EC in Italy and compliance is thus mandatory.

The directive defines the minimum requirements that machinery and partially complete machinery must have to be placed on the market: "*so as not to endanger the health and safety of persons when properly installed and maintained and used for their intended purpose or under conditions which can reasonably be foreseen"* (Article 3, Subsection 1).

The D. Lgs. 17/2010 makes reference to four important risk factors:

1. Postures;
2. Forces;
3. Manual handling of loads;
4. Manual handling of low loads at high frequency;

It also defines the appropriate indications to for a correct ergonomic design.

The ergonomic principles, which must be respected, are those of Legislative Decree 17/2010 [9] §1.1.6 "Ergonomics", Annex I:

"Under the intended conditions of use, the discomfort, fatigue and physical and psychological stress faced by the operator must be reduced to the minimum possible, taking into account ergonomic principles such as:
- allowing for the variability of the physical dimensions, strength and stamina of the operator;
- providing enough space for movements of the parts of the body of the operator;
- avoiding a machine-determined work rate;
- avoiding monitoring that requires lengthy concentration;
- adapting the man/machinery interface to the foreseeable characteristics of the operators."

For what concerns international and European standards, in Annex XXXIII, the Legislative Decree 81/08 [8] makes specific reference to technical standards for risk evaluation. These standards are:

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 [10], 3-Recommended force limits for machinery operations [11], 4-Evaluation of working postures in relation to machinery [12], 5-Risk assessment for repetitive handling at high frequency);

ISO 11228 relates to manual handling (1-Lifting & carrying [13], 2-Pushing & pulling [14], 3-Handling of low loads at high frequencies [15]);

ISO 11226 relates to the evaluation of working postures.

1.1.4 Risk assessment

The objective of ergonomic analysis is to identify and quantify the risks on the health of the operators in order to eliminate them or reduce them to within acceptable thresholds. Methods and threshold values for different risks can be found in dedicated technical standards.

Table 2 summarizes the correlation between risk factors and the corresponding design and inspection standards.

Table 2.Dedicated standards for risk factors

RISK FACTORS	DESIGN STANDARD	TEST STANDARDS
Postures	UNI EN 1005-4 ISO 14738	ISO EN 11226
Forces	UNI EN 1005-3	-
Manual handling of loads	UNI EN 1005-2	ISO EN 11228-1 ISO EN 11228-2
Manual handling of low loads at high frequency	UNI EN 1005-5	ISO EN 11228-3

1.1.4.1 Postures

Workstations must be designed so that the operator may carry out the required tasks without assuming uncomfortable or awkward postures.

UNI EN 1005-4 [12] applies to all operators without distinction of gender or age because it considers the risk of postures as a function of the angles assumed by the main joint segments (neck, back, arms) and frequency. The risk assessment procedure includes:

1. Identifying the reference population;
2. Analyzing the task to be performed at the workstation and virtually simulating the position assumed by the operator (on drawing);

3. Evaluating whether the posture is static (permanence equal to or longer than 4 seconds) or dynamic;
4. In case of dynamic posture, evaluating the posture frequency, i.e. the number of times that the posture will be assumed per minute;
5. Comparing the angles assumed by the critical joint segments with the reference values in tables 1, 2, 3, 4, 5 and 6 of the standard;
6. Redesigning in case of non-acceptable postures,
7. Re-examining items from 1 to 6 using a physical prototype of the workstation and simulating the activity with the collaboration of an operator of suitable anthropometric characteristics.

Postures must all be acceptable in the foreseen work cycle conditions. Otherwise, re-design is needed to either eliminate or reduce the risks. Residual risks must be highlighted in order to take appropriate protection measures to eliminate them.

1.1.4.2 Forces

The use of muscular force causes a load on the musculoskeletal system which in unfavorable conditions may increase the risk of fatigue, discomfort and alterations of the musculoskeletal system itself. Risks in designing a machine, a tool or a device requiring the use of muscular force by the operator may be controlled by optimizing the required forces.

UNI EN 1005-3 [11] provides the acceptable force limits for reducing health-related risks according to the exerted force type and the expected user population. It is applied to assess the tasks in which muscular force is applied without movement of loads. Thus, it does not apply to the lifting and carrying of loads, pushing and pulling for distances greater than 2 m.
The method consists of three steps:

1. Step A: determination of maximal isometric force (FB), for specified actions, with consideration to intended user population.

2. Step B: determination of reduced maximal force (FBr) taking into consideration velocity, frequency and duration of action.
3. Step C: determination of risk tolerability.

Forces acting on the hands are an example of use of this method (Figure 4). The maximum applicable force limits depend on the joint segment used:

- Segment A: force is exerted by the pressure of fingers only (thumb, forefinger or pinching thumb opposed to one, two, three fingers).
- Segment B: force is applied mainly with the palm of the hand or with all fingers.
- Segment C: power grip force is exerted - power or contact.

The limits suggested in Figure 4 indicated by “OK” in the “Force assessment” column for designing components, equipment and control levers requiring application of force with the hands must be complied with.

SEGMENT		Limit	Force assessment
A	thumb - forefinger side, forefinger, thumb - 2 fingers	< 25 N	OK
		> 25 N	KO
B	ball of the thumb, thumb - 4 fingers, thumb - 4 fingers	< 45 N	OK
		> 45 N	KO
C	power grip, pliers (OW = 70%)	< 75N	OK
		> 75N	KO

Figure 4. Limits of acceptable forces applied on the hand [FCA]

The forces calculated in design must be within the foreseen limits of the recommended zone. Otherwise, redesign is needed to either eliminate or reduce the risks. Residual risks must be highlighted in order to take appropriate protection measures to eliminate them.

1.1.4.3 Manual handling of loads

With regards to manual handling of loads, Section VI of the D.Lgs 81/08 defines the obligation of the employer to eliminate or at least reduce musculoskeletal disorders caused by activities which are not carried out in ergonomically favorable conditions (Articles 167 and 168). These activities include lifting, lowering, pushing, pulling or carrying loads and the technical standards to which reference shall be made to evaluate the risks are those of the ISO 11228 series.

Four factors predominantly influence the evaluation the activities of manual handling of a load:

1. Load characteristics: weight, size, stability, etc.;
2. Posture in transport/lifting: flexion of the back, twisting of the trunk and an excessive distance from the load to the trunk are factors that, other than the weight lifted, aggravate the risk related to the movement;
3. The amount of physical effort: the value of the frequency of the liftings as well as the duration of such activities;
4. Characteristics of the work environment: equal attention should be placed also in the control the presence of different levels (stairs, steps, blocks, etc) and to the state of the pavements.

The risk assessment method for lifting activities consists in calculating the lifting index, or NIOSH index, according to Method 3 of UNI EN 1005-2 [10]. The NIOSH method is aimed at the assessment of the actions of manual lifting of loads. For each lifting action, the method is able to determine the so-called recommended weight limit (RWL) through an equation that,

starting from a maximum weight lifted in ideal conditions, considers the possible existence of adverse elements and consequently takes them into account using multiplication factors.
The conditions for the applicability of the method are shown in Table 3.

Table 3. Applicability of the NIOSH method

APPLICABLE	NOT APPLICABLE
Mass of lifted object ≥ 3 kg	The method applies to masses < 3 kg but is not mandatory
Distance < 2 m	Carrying by walking for more than 2 m
Vertical action forces	Pulling and pushing
Work shift ≤ 8 h	Work shift > 8 h
Standing posture	Sitting or kneeling posture
Smooth lifting, without sudden accelerations (action speed < 0.8 m/s)	Action speed > 0.8 m/s
Manual lifting only without external aids	Use of spade or wheelbarrow
Good coupling between the feet and floor (foot-ground friction coefficient > 0.4)	Slippery surfaces (foot-ground friction coefficient < 0.4)
The objects to be lifted are not very cold, hot or contaminated	The objects to be lifted are very cold, hot or contaminated
Stable objects	Liquids, objects with unstable centre of gravity
Moderate thermal environment (temperature = 19 °C-26 °C; humidity= 33-50%)	Ambient temperature out of the range 19 °C-26 °C humidity out of the range 33-50%
Comfortable work spaces	Narrow work spaces

If the conditions of applicability are met, the Lifting Index (LI) can be calculated. It is the ratio between mass of object to be lifted and the recommended weight limit (RWL):

$$Lifting\ index = \frac{Mass\ of\ object\ to\ be\ lifted}{Recommended\ weight\ limit}$$

The recommended weight limit is obtained by multiplying the maximum weight limit (the reference mass MR) by the reduction factors which take the lifting conditions risks into account. These factors are presented in Table 4.

Table 4.Reduction factors for the calculation of the NIOSH lifting index

LIFTING CONDITION	REDUCTION FACTOR	
vertical position at beginning of lifting	V_m	HEIGHT factor
vertical displacement	D_m	DISTANCE factor
horizontal distance	H_m	HORIZONTAL factor
asymmetry angle	A_m	ANGULAR factor
grip	C_m	GRIP factor
frequency	F_m	FREQUENCY factor
limbs used	O_m	additional factors
No. of operators	P_m	

The recommended weight limit is then calculated using the following formula:

$$RWL = MR \times V_m \times D_m \times H_m \times A_m \times C_m \times F_m \times O_m \times P_m$$

The reference mass MR is taken as: 25 kg for men and 20 kg for women.

The Lifting Index is then compared to the values provided in Table 5 to determine the appropriate measures to be taken.

Table 5. Lift Index ranges

LIFTING INDEX	RANGE	RISK
$LI \leq 0.85$	green	zero or negligible
$0.86 < LI < 0.99$	yellow	significant (attention needed)
$LI \geq 1$	red	present

Green range: presence of zero or negligible risk, no corrective actions needed.
Yellow range: presence of significant risk, redesign is needed to lower the risk by operating on risk factors or further analysis needed to ascertain whether the risk is acceptable.
Red range: presence of risk, lifting conditions are not acceptable, redesign is needed.

In case of risk (yellow or red range), the single factors will need to be assessed to improve lifting conditions. Workstations requiring manual lifting must be within the green range otherwise mechanical aids are needed.

1.2 Ergonomics in FCA

Process Ergonomics has many important applications in the industrial sector and especially in the automotive sector and, in particular, in a company like FCA. In FCA there are many activities that require the attention of the ergonomist.

The company has matured the idea that true prevention starts at the beginning of the project, before harmful events start to poster, by developing appropriate methodologies for revision. From the first moment of the design of a production line, it is essential to take into account the contribution of ergonomics, which entails taking into account the interaction between "man" and the tools used, the machinery and the plant.

In a business context, each choice must also be discussed and evaluated on the economic basis, then, it is important to examine how the ergonomic design affects the overall cost of the development of the whole project. Figure 5 expresses the feasibility of the ergonomic interventions and the incidence of the costs necessary for modifications to the project as a function of time.

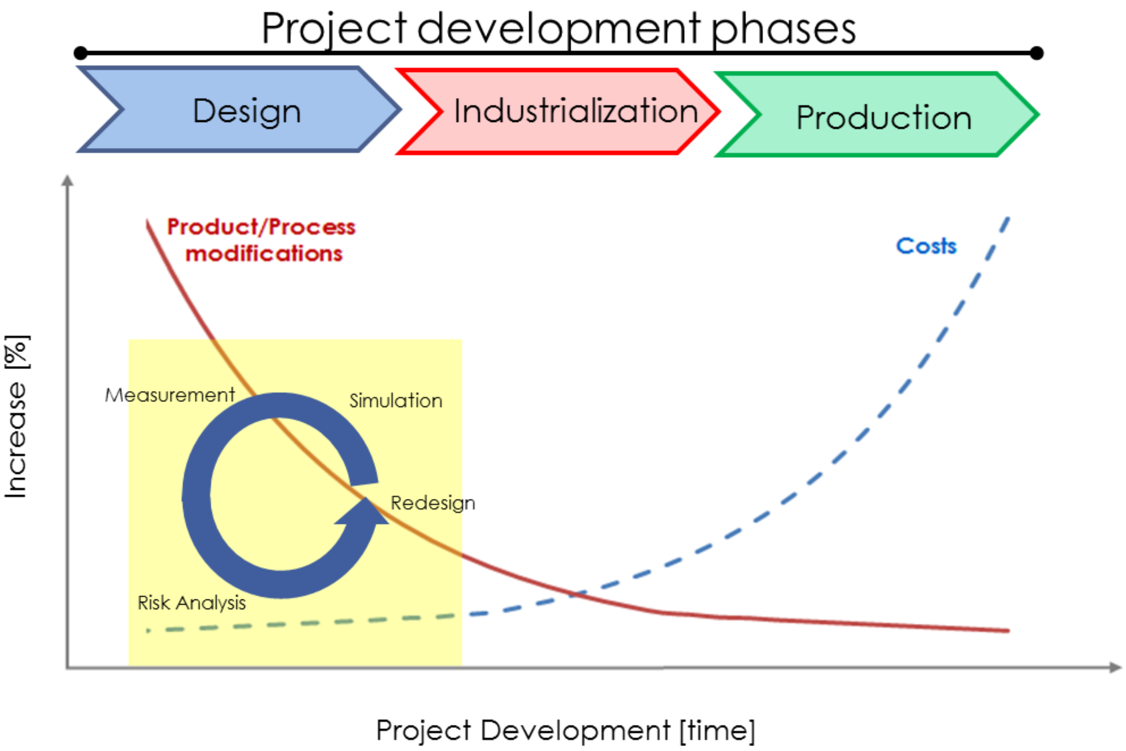


Figure 5. Feasibility of ergonomic modifications with respect to project development phases [FCA]

As notable in the figure, the feasibility of changes and the related costs have inversely correlated trends. The feasibility of the design changes for ergonomic needs is high in the design phase of the project and becomes lower as a result of simulations and redesigns in the final phase of industrialization.

On the other hand, the costs are substantial in the production phase. It follows that the best method is to integrate the design according to the principles of ergonomics in the starting phases of the project, which is what FCA has decided to do, by integrating the ergonomic design in WorkPlace Integration (WPI). As previously mentioned, this method is called preventive ergonomics.

Thanks to the techniques of Digital Manufacturing and Virtual Ergonomics, it is possible, through 3D modeling, to view the assembly line to be realized, to check the feasibility of the assembly operations, as well as the reachability of certain points. It is also possible to check the compatibility of the presence of the worker with the dimensions of the car while verifying the application of the ergonomic standards and legislations. The advantage of this system lies in the fact of being able to note any ergonomic problems and make appropriate proposals for improvement in an early phase of the project thus avoiding higher future costs.

Figure 6 shows the way in which the ergonomic principles are applied in the various stages of a project in the company, from design to production. In the design phase, ergonomists analyze the job to be done to identify any critical ergonomic problems following the technical standards of the UNI EN 1005.1/2/3/4/5, thus obtaining a correct design of the workplace and process. In the initial stage of industrialization, the aim is risk prevention/reduction; for this phase, there is no specific reference, but FCA has chosen to apply the ERGO - UAS system, which consists of the application of MTM-UAS, the ergonomic evaluation using the EAWS (European Assembly Work-Sheet) and the assignment of the Rest Factor. Finally, during the production phase, the optimization of the workplace is performed, referring to the D. LGS 81/08 and to the ISO 11228.1/2/3 standards.

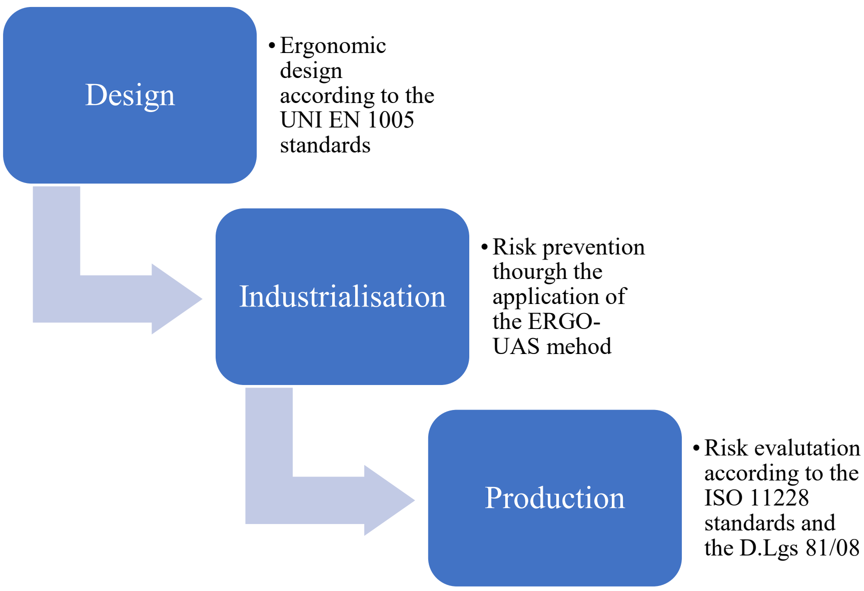


Figure 6. The phases of process ergonomics in FCA [FCA]

1.3 Industry 4.0: Smart Factories

Companies are always looking for new methods and technologies to improve their production process. A company which fails to cope with technological challenges also faces the challenge of introducing new products/services, innovation, and business models [16].

Industry 4.0 is one of 10 "Future Projects" that was identified, in 2011, by the German government as part of its High-Tech Strategy 2020 Action Plan. The INDUSTRIE 4.0 project represents a major opportunity for Germany to establish itself as an integrated industry lead market and provider (Dr. Benno Bunse) [17].

Different terminologies are used to describe this relatively new concept, such as **Industry 4.0**, **Industrial Internet of Things** (IIoT), **Smart Factory** and **Smart Manufacturing** [18]**.**

The term "4.0" is used to indicate that this is considered as the fourth industrial revolution. The first revolution was the use of mechanization and steam power in the 18th century. The second revolution was the advent of mass production and the use of electricity that came about in the end of the 19th century and the start of the 20th century. While the third industrial revolution started in the 1970s and is characterized by the use of computers and automation (Figure 7).

The basis of Industry 4.0 is modularity and decentralization. A decentralized production has the advantage of having an independent process management, where the real and virtual worlds interact to provide a crucial new aspect of the manufacturing and production process [17].

Industry 4.0 can be defined as a revolution enabled by application of advanced technologies at the production level to bring new values and services for customers and for the organization itself [16].

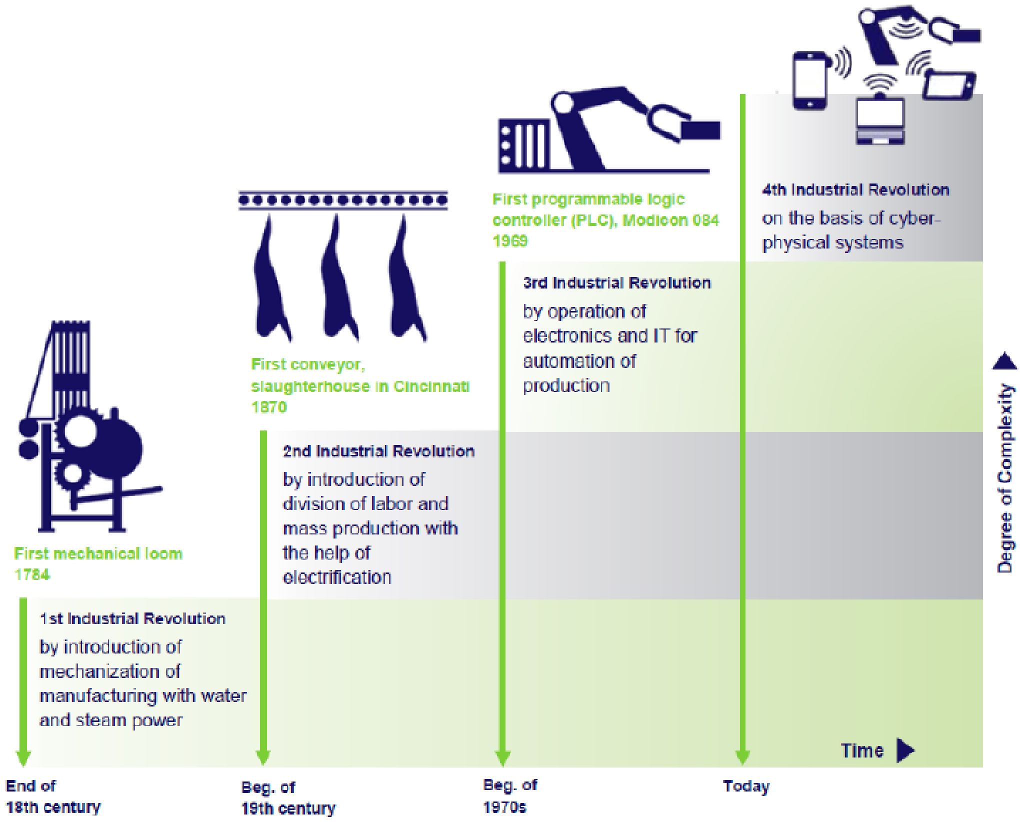


Figure 7. The four industrial revolutions - (Kagermann, Wahlster, & Helbig, 2013)

Industry 4.0 is powered by nine foundational technology advances, they are referred to as the nine pillars of Industry 4.0 [19]:

1. **Big Data and Analytics:** it is the collection and comprehensive evaluation of large data sets from different sources with the aim of optimizing production quality, saving energy and improving equipment service through real-time decision making.
2. **Autonomous Robots:** robots are becoming more autonomous, flexible and cooperative. The goal is to allow robots to interact with one another and to interact safely with humans, thus giving these robots the ability to learn from humans.
3. **Simulation:** in the future, 3-D simulations of plant operations will be used more extensively. This will allow the virtual testing and optimization of the machine settings

for the next product in line, thereby lowering machine setup times and increasing quality.

4. **Horizontal and Vertical System Integration:** today, IT systems are not fully integrated. The link between companies, suppliers and customers and even the link between different departments inside a company (such as engineering, production and services) is weak. With Industry 4.0, organizations will be interconnected within a cross-company, universal data-integration network.
5. **The Industrial Internet of Things:** the Internet of Things (IoT) is simply defined as a network of internet connected objects able to collect and exchange data. An industrial IoT would allow devices to communicate and interact with one another and with controllers, enabling decentralized decision making and real-time control.
6. **Cybersecurity:** as more and more devices and machines are interconnected and use standard communication protocols, the need for a secure, safe and reliable communication as well as sophisticated identity and access management, are essential.
7. **The Cloud:** the production-related processes of Industry 4.0 will require an increase in data sharing across sites and companies. While at the same time, the performance of cloud technologies is expected to improve, achieving response times of some milliseconds.
8. **Additive Manufacturing:** some methods, such as 3-D printing, are used today for prototyping and producing individual components. With Industry 4.0, these methods will be used to produce batches of customized products. Decentralized additive manufacturing systems will reduce transport and stock costs.
9. **Augmented Reality:** augmented-reality-based systems will provide workers with real-time information, such as repair instructions, which would improve decision making and simplify work procedures.

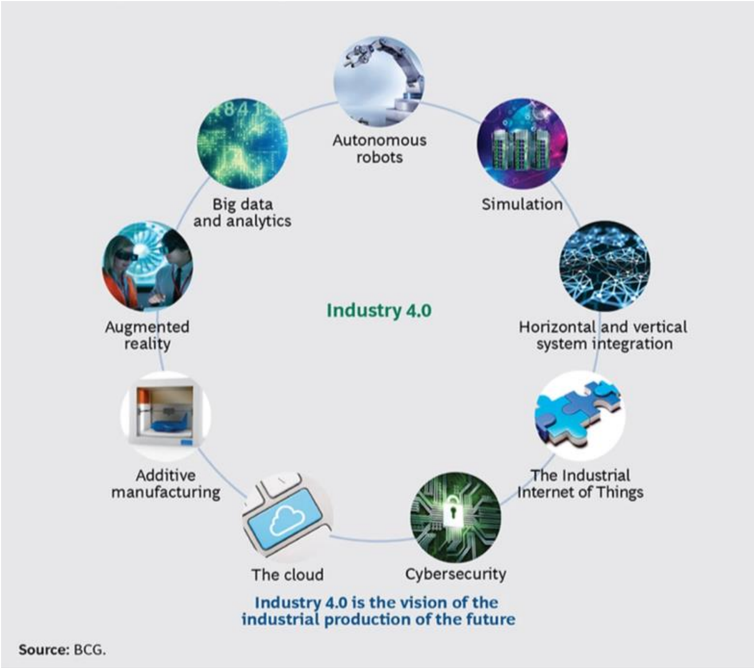


Figure 8. The nine pillars of Industry 4.0 [19]

Industry 4.0 is a social and economic challenge that requires rethinking factories trough digitalization, how to design objects, create prototypes and monitor the production lines in real time [2].

The center of attention here is the human being and his interaction with the machines, robots and tools at his disposal. One must not underestimate the importance of humans in the workplace, robots can solve many issues, but they cannot fully replace human beings.

Among the different technologies developed in Industry 4.0, simulation and VR are interesting areas in which the technological advances will certainly introduce a change in the production paradigm.

Engineers and designers of production systems would be able to fully immerse themselves in the virtual world and experience the production process in the most realistic way. This would allow them to reduce time and costs for inspections related to the product itself or to the manufacturing process [2] (Figure 9).

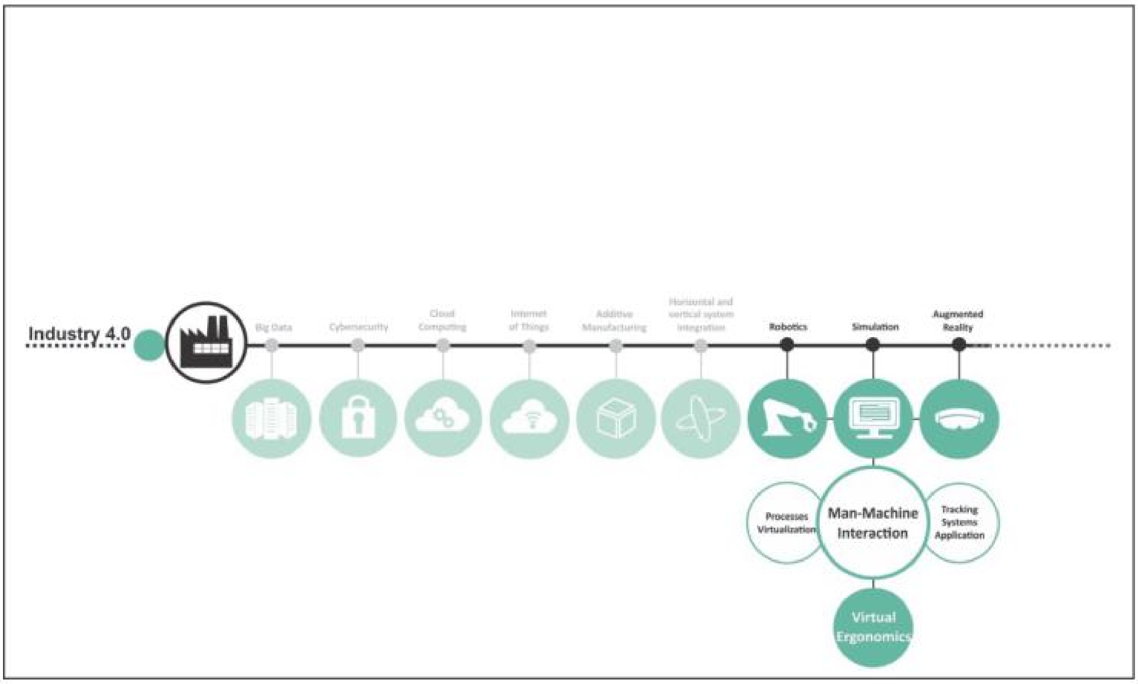


Figure 9. Simulation and virtual realities in Industry 4.0.[2]

1.4 Ergonomic Design: a Human-Centred Design

As already highlighted in the previous paragraphs, the goals of ergonomic design are to prevent or reduce the occurrence of occupational diseases and the general improvement of the working conditions.

The ISO standard 9241-210:2010 [20] describes human-centred design as an "*approach to systems design and development that aims to make interactive systems more usable by focusing on the use of the system and applying human factors/ergonomics and usability knowledge and techniques.*"

This means that, by definition, ergonomic design is equivalent to human-centred design, as they both focus on applying human factors and ergonomics principles in the design of a product or process, keeping in mind that humans are the centre of attention and working towards the continuous improvement of the products and processes they use.

Furthermore, according to the ISO standard 9241-210:2010 [20], *"This approach enhances effectiveness and efficiency, improves human well-being, user satisfaction, accessibility and sustainability; and counteracts possible adverse effects of use on human health, safety and performance."*

As previously mentioned, Virtual Ergonomics (VE) and Digital Manufacturing (DM) are combined, in the context of a "Virtual Factory", in order to note any ergonomic problems and make appropriate proposals for improvement in an early phase of the project. Virtual Ergonomics uses virtual simulation to analyze manual operations and to determine, with considerable anticipation, possible criticalities of an ergonomic nature. In VE, virtual manikins interact with digital models of components, equipment and containers. By simulating the activities, working conditions can be improved in terms of ergonomics, safety and work organization, while also guaranteeing the quality of the final product and reducing overall production costs (Figure 10).

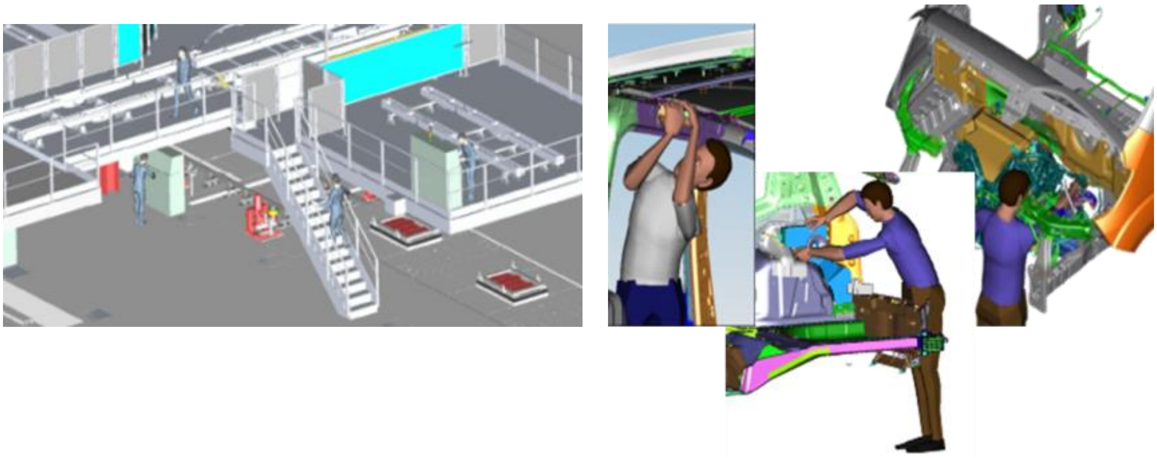


Figure 10. Virtual Factory and Digital Human Modelling [FCA]

Digital Manufacturing is the simulation in detail of all the assembly operations of a new product in order to optimize the production processes and the design of the new lines. In FCA for example, the expert ergonomists of Virtual Ergonomics analyze in virtual 100% of all the manual operations of assembly lines, and all the critical operations for the veneering and painting. They then proceed with the validations on physical prototypes of solutions determined in the virtual environment (Figure 11).

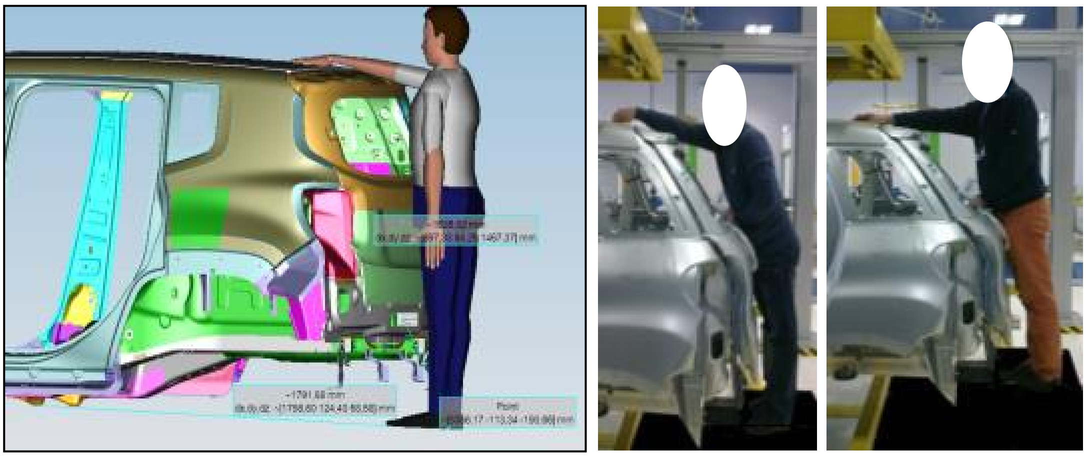


Figure 11. Virtual Simulation and validation on physical prototypes [FCA]

In addition to the techniques mentioned above, Immersive Virtual Reality is also used to simulate the assembly operations with true perception of dimensions and spaces and to highlight critical issues related to visibility and reachability of the work point.

Figure 12. Immersive Virtual Reality applied to the automotive industry [https://www.optis-world.com]

2 Exoskeletons

In engineering, an exoskeleton is most commonly defined as a wearable device, external to the body, that is used to support or enhance human movements. Exoskeletons are made up of segments and joints that should correspond, to a certain extent, to the ones of the human anatomy. The exoskeleton works in symbiosis with the movements of the wearer.

In biology, however, exoskeletons are a kind of external covering for an animal, usually for protection or support [21]. Figure 13 Shows an analogy between exoskeletons in the two fields.

	The Biological Exoskeleton		Exoskeleton in the Engineering Field	
Function		**Example**		**Application/Example**
Support	Supporting the body of the invertebrates	• Because molluscs have a soft body, they are more fragile • It is also more difficult for them to support their body in terrestrial environments or to attach to substrates in aquatic habitats	Supporting physically disabled patient or walking assistance	• Rehabilitation engineering for the human motor system
Enhancement	Enhancing the power of animals	• Ingrowths of the arthropod exoskeleton known as apodemes serve as attachment sites for muscles • Similar to tendons, apodemes can stretch to store elastic energy for jumping, notably in locusts	Strengthening the human operator	• Power amplification
Protection	Protecting the animal's body	• The shell of a crab	Protecting the human operator	• External armor for soldier, rescue devices, safe manipulation in risky environments
Sensing	Obtaining the information, sensorium	• The spider's rigid exoskeleton readily conducts vibrations, transmits mechanical stress that may be caused by substance vibrations, by gravity, or by the spiders's own movement	Interface of human operator and the environment to acquire information	• Telemanipulation • Virtual reality • Entertainment

Figure 13. Analogy between the biological exoskeletons and exoskeletons in the engineering field [21]

2.1 Classifications

There exist many different ways to classify exoskeletons. A major division of exoskeletons is according to the principle of action, therefore dividing them in active or passive exoskeletons.

Active exoskeletons are essentially wearable robots, as the contain motors, actuator, batteries, computerized control systems and sensors. The actuators help the actuation of the human joints and augment the power of the wearer [22]. These are usually electrically powered, either directly or by rechargeable batteries.

Active exoskeletons have a potential for development as they offer an augmentation of the capacity of the wearer. The current lack of standards and the requirements of the industrial environment determine that their introduction to the automotive production lines is likely to ensue in the years to come [23].

On the other hand, **passive exoskeletons** are not powered by motors; they rely on kinetic energy accumulation using components such as springs and dampers, and weight redistribution to assist the wearer and sustain his/her movements.

They are potentially less effective than active exoskeletons but are easier to introduce in the assembly line of a factory, since they are lighter, require no control and there is no bottleneck of standards [23]. In the medical field, however, active exoskeletons are more diffused.

Exoskeletons can also be distinguished by the body part or parts that they support or provide power to. An upper body exoskeleton is designed to assist the upper limbs (shoulder, elbow, wrist) while guaranteeing ease of movement. A lower body exoskeleton assists the lower limbs of the human body, for such an exoskeleton, careful attention has to be given to ability of the system to support the weight of the wearer during walking. A lower back exoskeleton supports the lumbar region of the back, thus reducing the stress on the back during manual handling of loads. There exist also full body exoskeletons.

Another way to classify exoskeletons would be by how much they resemble the human anatomy. Anthropomorphic exoskeletons have the rotational axes of their joints aligned with the rotational axes of the human body, while that is not true for non-anthropomorphic exoskeletons [22].

2.2 Applications

Exoskeleton application can be categorized within two macro areas: medical and nonmedical [21] [24]. This distinction is based on the end user, i.e. the wearer and it takes into account many differences between medical and non-medical exoskeletons.

Medical exoskeletons are designed to help the motion of a patient in some specific manner, these exoskeletons would help the patient regain mobility and strength [24]. While non-medical exoskeletons are physical assistant robots falling under the category of personal care robots. Non-medical exoskeletons can be further split into 4 categories industrial, military, healthy people and general purpose.

The key differences between medical and non-medical exoskeletons are the following [24]:

- Patients cannot make the required movements to provide the motion trajectories for the exoskeletons, whereas healthy people can. Thus interfaces, control strategies, mechanical interfaces and so on need to be designed specifically for the needs of the patient/wearer. Medical exoskeletons often require specialist medical professionals to deploy and use them, so that the patient can be given the maximum clinical benefit and be safely operating the exoskeleton;

- In non-medical applications, the movement user must be replicated correctly and precisely to ensure a natural movement as much as possible. The users must be able to don, operate and doff the exoskeletons quickly, easily and autonomously;

- The international safety regulatory requirements (ISO/IEC) are different for medical and nonmedical exoskeletons and must be complied with for successful commercialization.

2.2.1 Medical Exoskeletons

Rehabilitation and functional compensation represent two important potential applications of medical exoskeletons [21]. An estimated 185 million people worldwide use wheelchairs or other functional assistance devices daily [21].

Medical exoskeletons will be a key part in the rehabilitation of the upper and lower limbs of patients, be they old or young, as they allow the patient to replicate a certain rehabilitation exercise as much as they need. Thus, enabling them to enhance their performance gradually within the safe and controlled environment that the exoskeleton provides.

By the end of 60s and beginning of 70s of the past century, active exoskeletons for paraplegic people were being developed in Belgrade at the Mihajlo Pupin Institute [25].

There exist also exoskeletons to be used by the people administrating medical help, such as nurses for example. A full body exoskeleton for augmenting the power of a nurse to take care of patients has been developed by the Kanazawa Institute of Technology [26].

It is worth noting that, in some medical applications, stationary exoskeletons can be used, while that is not the case in an industrial application for example. In a rehabilitation center, space occupancy is not an issue. On the other hand, if the rehabilitation is to be done at home then a mobile, compact and lightweight exoskeleton that can offer mobility assistance is preferred.
Some examples of current medical exoskeletons are:

Lokomat by Hocoma: a stationary lower body exoskeleton that provides highly repetitive physiological gait training. A study was conducted [27] with the aim of comparing conventional physiotherapy (CP) with robotic training (RT) (using the Lokomat) combined with CP and to measure the effects on gait, balance, functional status, cognitive function, and quality of life in patient with stroke. The study concluded that RT with CP is more effective than CP alone.

Figure 14. Lokomat by Hocoma - [https://www.hocoma.com - retrieved January 2019]

HAL for medical use by Cyberdyne: a lower limb exoskeleton for use by people who have disorders in their lower limbs and whose legs are weakening. When a person moves the body, various signals are sent from the brain to the muscles through nerves. Those Signals leak on the skin surface as “bio-electric signals (BES)”. HAL reads the BES, and accordingly compensates muscle power of lower limbs and assists the wearer in walking, standing-up and sitting-down. It has obtained the CE marking and has been certified for use as a medical device in the EU [28].

Figure 15. HAL for medical use by Cyberdyne [www.cyberdyne.jp – retrieved January 2019]

MyoPro® Motion E by Myomo: a myoelectric elbow orthosis that provides a powered movement to the arm while keeping the hand and wrist in a fixed position. When the user tries to bend their arm, sensors in the brace detect the weak muscle signal, which activates the motor to move the arm in the desired direction. It is engineered for paralyzed individuals, such as ones who have suffered a brachial plexus injury, stroke or other neuromuscular disorder [29];

Figure 16. MyoPro Motion E, [https://myomo.com, retrieved January 2019]

Hand of Hope (HOH) by Rehab-Robotics: a rehabilitation device for the hand and forearm that may help patients regain hand mobility through motor relearning. The HOH uses surface electromyography (sEMG) sensors to detect muscle signals and move the hand accordingly. It can be used by patients that have decreased muscular activity after stroke, spinal cord injury or hand/finger injury [30].

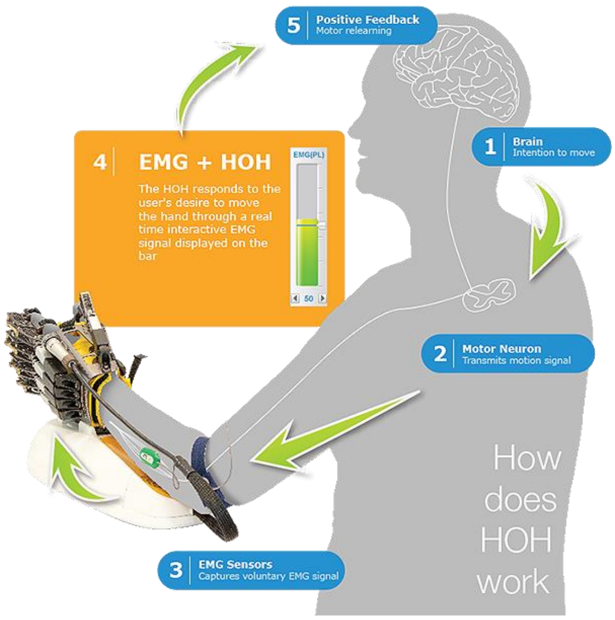


Figure 17.Hand of Hope by Rehab-Robotics - [http://www.rehab-robotics.com, retrieved January 2019]

2.2.2 Military Exoskeletons

Exoskeletons would be helpful for soldiers that are required to carry on their gear, backpacks and ammunitions, travel for long distances and perform combat missions when they reach their destination.

During the 1960s, the General Electric Company developed the “Hardiman”, a two-armed master–slave manipulator used for handling radioactive equipment. The master exoskeleton was worn by the operator and its motion was reproduced by the two-arm slave unit. When radioactive material is handled, a concrete barrier was used to separate the master station and the slave. The master and the slave were only connected electrically [31].

A more recent example of a military exoskeleton is HULC (Human Universal Load Carrier) by Ekso Bionics and Lockheed Martin. The HULC is a hydraulically powered exoskeleton that enables soldiers to carry loads up to 200lb (91kg). The weight of the load gets transferred to the ground through the exoskeleton [32].

Figure 18. A soldier wearing the HULC exoskeleton - [https://www.army-technology.com, retrieved January 2019]

Military exoskeletons are practically useful only if they reduce the metabolic cost significantly while augmenting the load carrying capacity of soldiers [24]. An exoskeleton that can demonstrate a reduction of the metabolic cost, of a loaded with equipment infantry, means a soldier that can cover more ground, have more supplies, become more independent and have additional armor [33].

The challenges faced by military exoskeletons can be simply summarized as follows: they must be comfortable to wear for a prolonged period of time and integrate with already established equipment and standards.

For military active exoskeletons, a challenge that needs to be surpassed is that the actuators and torque generators require bigger and longer-lasting batteries to ensure long operational times. Bigger batteries mean more weight, which means more power needed to support it, which in turn means larger batteries, thus risking the fall into an infinite loop.

Military exoskeletons must be universal and fully integrated with the soldier while not getting in the way of weapons or the ability to take cover. Furthermore, the must be reliable and durable so as not to become a liability and in real combat situations [33]. Other than the use of exoskeletons for the human motor performance of soldiers, the military are looking to build VR simulators for troop training [21].

2.2.3 Exoskeletons for the elderly

In the coming years, a sector that is likely to grow in importance is the sector of wearable robots can provide help to elderly persons [24].

According to the United Nations: In 2017, there were an estimated 962 million people aged 60 or over in the world, with Europe having the greatest percentage of population aged 60 or over (25 percent). The number of people aged 60 or above worldwide, is expected to rise to 1.4 billion in 2030, 2.1 billion in 2050, and to 3.1 billion in 2100 (Figure 19).

Globally, the number of people aged 80 or over is projected to triple by 2050, from 137 million in 2017 to 425 million in 2050. Estimates indicate it will reach 909 million people in 2100, nearly seven times its value in 2017.

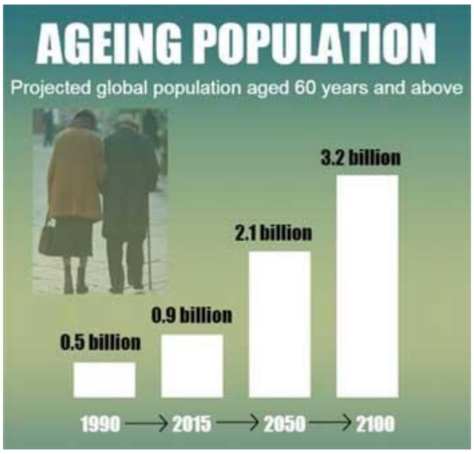


Figure 19. Projected global population aged 60 years and above- [http://www.un.org, retrieved January 2019]

Healthy elderly persons have no serious disability or disease as such, which demands the intervention of medical personnel. Elderly people are simply less mobile than they were younger, they get tired more quickly by doing activities which require significant physical effort.

Only a few multipurpose exoskeletons have been developed which can be used by elderly people and no commercial exoskeleton is available to date [24].

2.2.4 General purpose exoskeletons

These are exoskeletons designed with no specific target application in mind. They can be used for entertainment or sports to name a few applications. In the gaming industry, AxonVR aims to develop a full exoskeleton that is suspended in the air and provide the appropriate resistance to make the user feel they are walking, swimming, or interacting with objects [21] [34]. At the moment, gaming exoskeletons do not aim to simulate entire objects but just their effects. A power glove can be used to provide resistance when touching a virtual object [34].

Gaming exoskeletons are at an intersection point between virtual reality and exoskeleton technology. On one hand, VR technology is mostly open sourced and is expected to have numerous applications in the next two years. On the other hand, game developers are now looking for exoskeleton devices to further immerse players in the gaming experience and exoskeleton developers can benefit from gaming to provide a more immersive experience for their users [34].

2.2.5 Exoskeletons for the industry

In the industrial environment, robots are used to perform tasks that require large forces; these robots, however, do not possess many abilities, which human beings do, such as: manipulation ability, dexterity, flexibility, problem-solving skills and quality [23].

A perfect example is the environment of storage and dynamic manufacturing in which the variety of the production mix is very high. In this case, total automation would be excessively expensive, due to the high costs of programming and the greater spaces required. In addition, the human capacity to observe and make decisions based on assessments dictated by experience, as well as the ability to vary the production activities according to the needs, several times during a shift, makes the presence of the human figure essential.

Therefore, workers are still required to perform some manual tasks. Proper measures need to be applied to ensure that these tasks respect the ergonomic principles. Many different materials-handling equipment are used to carry and move physical loads, like cranes and partners. Nevertheless, they are seen by workers as time and space consuming, so they are sometimes unused. This fact becomes particularly important when the operator works for years stressing the joints and creating the risk of developing work-related musculoskeletal disorders.

Hence, the need for an assistive device that works in tandem with the user, helping them perform their usual tasks is a step ahead in the right direction. Exoskeletons are an example of the advancement of Human-Robot Collaboration technologies.

It is important therefore to recall the different typologies of exoskeletons depending on the body part they support and their potential application in an industrial environment. An upper body exoskeleton is designed to assist the upper limbs, in an industrial setting, more specifically the automotive sector, it can be used to help the worker in tasks such as: assembly, packaging, stock management, underbody and finishing operations, gluing, painting, etc.

A lower body exoskeleton assists the lower limbs of the worker, this device would reduce the stress on the lower limbs and fatigue in general. Some lower limb exoskeletons function as a "chair" that is connected to the body, it allows the worker to alternate between sitting, standing and walking. A lower back exoskeleton supports the lumbar region of the back, thus reducing the stress on the back during manual handling of loads and helps the worker with lifting and lowering activities.

In literature, many exoskeletons for industrial use have been studied or designed, their challenges and their control strategies have also been discussed [22] [23] [35] [36] [37] [38] [39]. In the following, some of the most current relevant exoskeletons are briefly explained and corresponding notable studies are examined.

The Levitate AIRFRAME is a wearable, lightweight technology engineered to improve upper extremity musculoskeletal health in workers who engage in repetitive arm motion and/or static elevation of the arms. It consists of a metallic frame core and two armrests for the upper arms. Mechanical passive elements are present along the upper arms to partially relieve upper limb muscles and shoulder joints by transferring the weight of the arms from the shoulders, neck and upper back to the core body (Figure 20). The mechanical support is null when the arms are at rest and it progressively increases when the arms are raised. The exoskeleton comes with different sets of mechanical passive elements, the appropriate set is chosen depending on the arm weight and the task to be performed [40].

Figure 20. Levitate AIRFRAME - [https://www.levitatetech.com, retrieved February 2019]

The Levitate AIRFRAME passive exoskeleton was the subject of a study [23]. The device is engineered to support the arm of the wearer when the arm is raised in static or quasi-static postures so the aim of the study was to test the effectiveness of the exoskeleton in assisting automotive workers in tasks that involve postures with elevated arms or require repeated arm motion.

The study started from the hypothesis that the use of the Levitate exoskeleton is effective to: (i) increase the endurance time of static postures with elevated arms and (ii) assist in repeated manual handling tasks of small loads. User acceptance, implementation of exoskeletons in the automotive industry and risk assessment of the biomechanical workload in the design phase were also discussed. 29 healthy males participated voluntarily in the study. Workers were identified based on their anthropometry (height in the range 170 – 180 cm), in order to fit the specifications of the exoskeleton. For reasons of homogeneity, other inclusion factors were an age between 45 and 65 years and no limitation in strength or musculoskeletal disorders in the upper limbs.

The tests were conducted in ergonomics laboratory of FCA. Three different tasks were performed with and without the exoskeleton: (1) a static task, (2) a repeated manual material handling task and (3) a precision task. At the end of each task, both with and without the exoskeleton, a cognitive ergonomist held a semi-structured interview with the worker, aimed at understanding the quality of the interaction with the device.

Concerning the static task, the operators maintained the static posture for a mean time of 183.9 s and 246.2 s without and with the exoskeleton respectively, which is a 31.1% relative increase in time length in the second case.

For the manual material handling task, most of the operators remarked that, when wearing the exoskeleton, part of the force they had to exert was aimed to maintain the adducted position against the device. Although, they declared the device was helpful in raising the object.

While for the precision task, the operators were unanimous to assess that in this task the presence of the exoskeleton was beneficial both for the perceived fatigue and for the precision of the execution.

In the study, workers increased their performance (average improvement 30%) when wearing the exoskeleton and perceived less fatigue. Cognitive assessment showed that the participants perceived the exoskeleton positively; describing it with positive qualities such as efficient and useful but affirmed that the use of the exoskeleton should be on a voluntary basis.

The study affirms the need for further information on acceptance of the device by the operators and long-term use in the real automotive environment. It highlights the requirement of a deeper understanding of the biomechanical workload in exoskeleton-assisted work tasks and of the potential repercussions in the work methods already in design or industrialization phase.

Recently, Toyota has made the AIRFRAME mandatory personal protective equipment (PPE), in two of its plants in the US. In its Woodstock plant, 24 workers were required to use the exoskeleton as of November 2018, while in its Princeton plant almost 200 of the 7,369 workers will be required to use the devices as of March 2019 [41].

The **HAL-LB03** Lumbar Type for Labor Support (Figure 21), is an active exoskeleton by Cyberdine Inc.; a spin-off from the Tsukuba University in Japan. HAL mitigates risks of back pain when he/she lifts heavy goods, by reducing the stress applied on the back [28].

According to Cyberdyne, HAL reads the bio-electric signals coming from the brain to the muscles and assists the movement of the user according to their intention (lifting or carrying). The exoskeleton assists lifting or carrying by powering the hip joint directly with the use of a DC motor and a harmonic gear drive.

HAL weighs 3 kg, including the battery, which is a considerably low weight for an active exoskeleton when compared with other similar exoskeletons. The battery has a drive time of ca. 4.5 hours and has a charging time of ca. 2 hours.

Figure 21. HAL lumbar type for labor support [www.cyberdyne.jp - retrieved February 2019]

HAL-LB03 is classified as IEC liquid ingress protection level 4 (splashing of water), and IEC solid particle protection level 5 (dust protected) and dust proof, enabling its use in outdoor settings. It is also compliant with the ISO13482 standard, the international safety standard for personal care robots and the European Machinery Directive (CE certified).

The **backX**, by University of California at Berkeley and suitX, is a passive lower-back exoskeleton that reduces the forces and torques on the lower back region (L5/S1 disc) by an average of 60% while the wearer is stooping, lifting objects, bending or reaching [42] [43].

The exoskeleton does not impede natural movements, the wearer can walk, ascend and descend stairs and ladders, and drive automobiles. It uses a system of passive torque generators to counter the torque acting on the lumbar region. It is also compatible with standard safety harnesses and tool belts.

Figure 22. backX worn by an operator [www.suitx.com/backx - retrieved February 2019]

The Model AC of the exoskeleton has a hardware that weighs 3.4 kg and it is worn with an Exoskeleton Harness that weighs 1.1 kg. It is a modular exoskeleton that combined with both legX and shoulderX becomes MAX; a full-body exoskeleton.

Model AC frame is load-bearing: it will transfer the weight of attached loads directly to the hips or to the ground if legX is attached.

The **FORTIS**, by Lockheed Martin, is a passive exoskeleton for the industry that allows operators to lift tools weighting up to 16.3 kg with the use of a Tool Arm. Lockheed Martin claims that muscle fatigue of the wearer is reduced by 300 percent [44].

The frame of the exoskeleton is made up of a series of segments and joints, that are connected at a central belt at waist level. The Tool Arm is connected to this belt and its weight is transferred to the ground via the frame. The counterweights for the tool are connected to the back of the belt (Figure 23).

Figure 23. FORTIS with the operator in a kneeling posture [https://www.lockheedmartin.com - retrieved February 2019]

According to Lockheed Martin, the precision of the worker while working with the exoskeleton is augmented, due to the fact of the reduced muscular effort required to perform the task. Tests showed that FORTIS helps the user to hold a tool weighting 7.2 kg for 30 minutes without fatigue. The same user was able to hold the tool for only 3 minutes without the exoskeleton.

It is worth noting that at the time of writing the FORTIS is still a prototype, therefore further trials are expected, but it is commercially available.

The **ATOUN Model Y**, by ATOUN Inc. is an active lower-back exoskeleton that alleviates burden when lifting heavy objects, through motors as well as sensors that detect the movements of the waist [45].

The ATOUN has 3 working modes, it switches automatically between them depending on information from sensors that detect the movements of the wearer. These modes are:

- Assist Mode: Assists the wearer to lift an object by pulling the body as if stretching the waist;
- Walk Mode: The motors are turned off when the wearer starts walking;
- Brake Mode: Supports the body while lowering the object.

The exoskeleton has 2 motors, one for each side, that work independently to enable natural support of a maximum of 10 kgf. It weighs 4.5 kg; including the battery, that lasts 4 hours on average. It is also IP55 certified.

Figure 24. ATOUN Model Y [http://atoun.co.jp/products/atoun-model-y - retrieved February 2019]

The **Cray X**, by German Bionic is an active exoskeleton that supports the lower back of the wearer when lifting heavy loads, it has been specially designed for people manually handling goods and tools, to reduce compression pressure in the lower back area [46].

The exoskeleton weighs 8.5 kg, including a battery that lasts up to 8 hours. It provides active-assistance through two servomotors (right and left); the user initiates the motion and the exoskeleton only helps. The motors generate a maximum moment of 100 Nm, with the forces applied on the back of the thighs and behind the shoulders to return a person to their initial position.

Cray X is designed to fit workers with heights between 1.6 m and 1.95 m. It is envisioned to be shared by multiple workers; a worker can wear it when performing a lifting task and then give it to another worker when they are finished. On the first trial, a representative from the company would help the user to wear and regulate the exoskeleton. Subsequently, in the work environment each user can don and doff the exoskeleton on their own.

The exoskeleton is equipped with position sensors for controlling the engines that allow a good freedom of movement in the walking stages and in the torsion of the trunk. Amongst its features is the use of Makita batteries that are already in use in power tools such as screwdriver. These batteries offer a reduction in size and weight with respect to alternatives while also being easily replaceable. Additionally, the Cray X has obtained the CE certification.

Subject that participated in tests of the exoskeleton (lifting and postural maintenance) appreciated on one hand its versatility due to the ease of adjustment of the motors and their effectiveness but on the other hand have perceived a significant discomfort due to the overall weight of the structure.

The Cray X is equipped with a display screen the user to change the control parameters: turn the support on/off, change the level of assistance (max. 15 kg), modify the reaction time, the sensitivity and the counter-force (force countering the descent).

According to German Bionic, future improvements of the exoskeleton include the connection of the exoskeleton to the cloud (through Wi-Fi and LTE) to enable the makers to push updates remotely and to diagnose any faults/problems so as to provide immediate assistance. The company also plans to reduce the weight of Cray X.

Figure 25. Cray X, standing posture

Table 6 summarizes the key specifications of some of the previously mentioned exoskeletons.

Table 6. Key specifications of some current exoskeletons

Name	Company/Entity	Support Region	Type	Weight	Autonomy	Key Specifications
HAL-LB03	Tsukuba University-Cyberdyne Inc.	Lower Back	A	3 kg (incl. Battery)	Yes, battery life of ca. 4.5 h	Reads bio-electric signals, assists lifting and carrying by powering the hip joint directly via a DC motor and a harmonic drive gear
backX	University of California at Berkeley and suitX	Lower Back	P	Model AC: 3.4 kg hardware, 1.1 kg harness	Yes	Reduces compression on the spine at L5/S1 disc by an average of 60%. Transfers the weight of attached loads directly to the hips or to the ground if legX is attached. Connects to shoulderX and legX to become MAX
FORTIS	Lockheed Martin	Back and Legs	P	N/A	Yes	Transfers loads through the exoskeleton to the ground in standing or kneeling positions, supports weights of tools up to 16,3 kg, reduces muscle fatigue by 300%
Atoun Model Y	Atoun Inc.	Lower Back	A	4.5 kg (incl. Battery)	Yes, average battery life of 4h	Motorised support with a maximum assisting force of 10 kgf
Cray X	German Bionic	Lower Back	A	8.5 kg	Yes, battery life up to 8 h	Provides support while lifting heavy objects (maximum 15 kg) to relief stress off the lower back

2.3 Actual industrial exoskeletons challenges

Despite the many advantages of the use of exoskeletons, such as the reduction of the L4/L5 compression [47] [22] the decrease in muscle work measured through EMG [22], improvement in quality of tasks performed [23] and the reduction of fatigue in general, exoskeleton application in industrial environments still faces many challenges.

The challenges faced depend on the type of exoskeleton, the application and the technology. For passive and active exoskeletons, key challenges are as follows:

- **Comfort**: after a certain period of gradual use, a worker would ideally wear the exoskeleton for the full work shift (8 hours). Thus, comfort is a key issue in the acceptance and the usability of exoskeletons [23];

- **Weight**: the weight of an exoskeleton depends mainly on its components and the function it is intended to perform. An upper-body exoskeleton would usually weigh less than a full-body exoskeleton. The long-term effects of the weight of an exoskeleton on the human body (especially the lumbar region) are yet to be studied. Legally speaking, exoskeletons weighting more than 3 kg could be subject to ergonomic analysis similar to that of the previously discussed NIOSH, but at the moment, no such analysis is required by law;

- **Safety**: as for any equipment used in industrial settings, worker safety is the first priority. It is thus imperative to have safety standards already in place; the ISO 13482:2014 [48] standard, defines the safe design, protective measures, and information for use of personal care robots. However, to date, international safety standards and legislations for industrial application of exoskeletons do not yet exist, significantly hampering their adoption. Active exoskeletons, for example, can’t be used in Italian factories at the moment because of the lack of standards/ legislations;

- **Materials/Technology**: the choice of materials strongly influences the ability of the exoskeleton to help the wearer perform the tasks required. Cost, weight and manufacturing ease are three main factors guiding this choice. Considering the same piece, steel is heavier than aluminum but has better resistance to fatigue. Lighter materials such as carbon fibers and titanium are more expensive;

- **Adaptability**: human anthropometric variability is very large and often impossible to, completely, account for. Being wearable devices, exoskeletons must be designed with human anthropometry in mind. Commercial exoskeletons are usually available in different sizes that are further adaptable to each user. Adaptability is a key issue that influences the perception of comfort of the wearer and the correct functioning of the exoskeleton**;**

- **Price:** as for any product, price is an important driver behind its adoption and diffusion. In modern day business settings, the price of a product is no longer determined by the simple sum Price = Cost + Profit. Today on the other hand, the applied logic behind pricing strategies is Profit = Price - Cost, the price is determined by market factors, while the cost of any product depends of course on the materials and the technologies used to produce it, therefore a company must carefully balance both to reach its profit targets. Pricing strategies differ for active and passive exoskeletons, as some companies view active exoskeletons as a competitor to assistive lifting devices and choose their prices accordingly. Therefore, active exoskeletons are generally more expensive than passive exoskeletons. Similarly, pricing strategies naturally differ for different types and applications exoskeletons, a lower body exoskeleton would have a different price to an upper body exoskeleton.

In addition, for active exoskeletons, the following challenges also apply:

- **Increased Weight**: due to the additional components of an active exoskeleton (battery, actuators, motors, sensors…) it usually weighs more than a passive exoskeleton.

Heavier exoskeletons require more powerful and longer-lasting batteries. Such batteries are usually large and heavy. Which would make the exoskeleton even heavier, thus risking the fall into a closed loop. Improvements in battery technology is therefore required to make the next step forward;

- **Actuators/Motors**: there exist different types of actuation for the movement of active exoskeletons. Some common examples include pneumatic artificial muscle (PAM), DC motor, servomotor or hybrid technologies [49];

- **Human Joint Simulation**: anthropomorphic active exoskeletons must reflect the human anatomy, kinematics and kinetics to enable natural and comfortable movements. Human anatomy is again at the center of the problem; the shoulder, for example, is a complex joint to incorporate in exoskeletons, as it comprises three orthogonal axes of rotation plus transversal sliding of the center of rotation [22];

- **Control**: the electronic control unit (ECU) analyzes data from the sensors and commands the actions of the actuators accordingly. Correct control requires the detection of movements and the differentiation between intended and unintended movements. Such a task is problematic and obligates the use of multiple sensors and complex signal processing. There exist two typologies of control: On-Board ECU in which the control unit is part of the exoskeleton or Remote Control (i.e. Cloud Computing) in which the data from the sensors are relayed to a remote-control unit that acts upon the actuators;

- **Additional Safety Requirements**: such as battery explosion or fire precautions, detection and prevention of sudden/unsafe motions that can cause injury to the user and the detection and storage of failures/errors.

3 Extraction of anthropometric measurements using a 3-D whole-body scanner

As highlighted previously, the use of anthropometric data is essential to design a safe, comfortable and productive work environment. Anthropometric measurements can be gathered using a variety of instruments. Traditionally, these measurements are gathered using instruments such as an anthropometer, tape measures and calipers. A relatively new application to anthropometry is the three-dimensional (3-D) scanner.

3-D scanners generate a 3-D point cloud of the outside of the human body that can be used for many applications. There are currently no standardized methods for using 3-D point clouds in the design process. Consequently, many users extract one-dimensional (1-D) data from 3-D point clouds. The ISO 20685-1:2018 [50] standard concerns the application of 3-D scanners to the collection of one-dimensional anthropometric data for use in design.

The human body is difficult to measure, and traditional measurement methods have to be performed by a skilled anthropometrist, resulting in a slow measurement process. On the other hand, the 3-D scanner allows for a fast and accurate acquisition of a greater number of measurements with respect to the traditional method. A person can be scanned at any time and then measured later. The person can also be measured multiple times, by different people, to minimize the observer and measurer errors.

Fiat Chrysler Automobiles (FCA) in collaboration with Politecnico di Torino, Università di Torino and Università degli Studi della Campania "Luigi Vanvitelli", decided to extract several anthropometric measurements using a 3-D Body Scanner, within the scope of the “La Fabbrica si Misura” project.

3.1 La Fabbrica si Misura

The "La Fabbrica si Misura" (The Factory Measures Itself) project, through an extensive measurement campaign, aimed to estimate the anthropometric measurements of the Italian working population in order to provide support for the design of the work environment. The project was born from the collaboration between Fiat Chrysler Automobiles (FCA), Politecnico di Torino and the National Institute for Accident Insurance at Work (INAIL). It oversaw the acquisition of anthropometric data of more than 6000 subjects (at least 3000 per sex) belonging to the working population (i.e. having an age between 18 and 65 years) of FCA plants distributed throughout Italy, estimated in percentage of the distribution of the plant compared to the total population.

At the time of the start of the project, there were no complete anthropometric databases of the Italian working population or more specifically of the manufacturing sector and the databases available in the literature (even at the European level) were not updated or exhaustive. The current international reference for anthropometric data is ISO 7250-1/2 [51] [52] which collects statistical analyses on anthropometric measurements carried out in different countries. For Italy, the reference is the "Italia si Misura" survey campaign carried out on Italian beaches, in the cities of Ancona and Naples in the years 1990-1991.

The objective of the project was the creation of an anthropometric database of workers in the vehicle and mechanical production factories that is representative of the Italian population, sampled from the FCA plants, in order to allow the design and construction of more comfortable workplaces and workstations that are explicitly designed for the FCA population. In particular, data collection was aimed at the body measurements that are crucial for the creation of virtual manikins to be used in Digital Human Models for early evaluation of the manufacturing workplaces and the design of protective/auxiliary devices such as exoskeletons. For this reason, the choice of the anthropometric measurements includes body dimensions that are not present in the current reference standard [53].

3.2 Project Scope and Timeline

The 3-D body scanner project as part of the “La Fabbrica si Misura” project, aims to integrate and validate anthropometric measurements of the Italian working population. As stated above, the project stakeholders are: Fiat Chrysler Automobiles (FCA), Politecnico di Torino, Università di Torino and Università degli Studi della Campania "Luigi Vanvitelli".

As an outcome, the project serves as a completion and continuation of FsM, and its results will be integrated within the results of the FsM, thus allowing the creation of better workstations, up-to-date virtual manikins and more adaptable exoskeletons.

The project started on September 2018 with the target of scanning and measuring 100 people, 50 males and 50 females, with an age between 18 and 65 years. At the beginning, all project stakeholders participated in a course on the use of the body scanner and the scanning software, which was followed by the definition of the measurements to be taken and the creation of a scanning protocol.

The scanning and measurement processes started in October 2018 and lasted till the end of December 2018. At the same time, a database of the measurements taken was created and regularly updated as the project advanced. An analysis of the results of the project and of the measurements taken began in January 2019 (Figure 26).

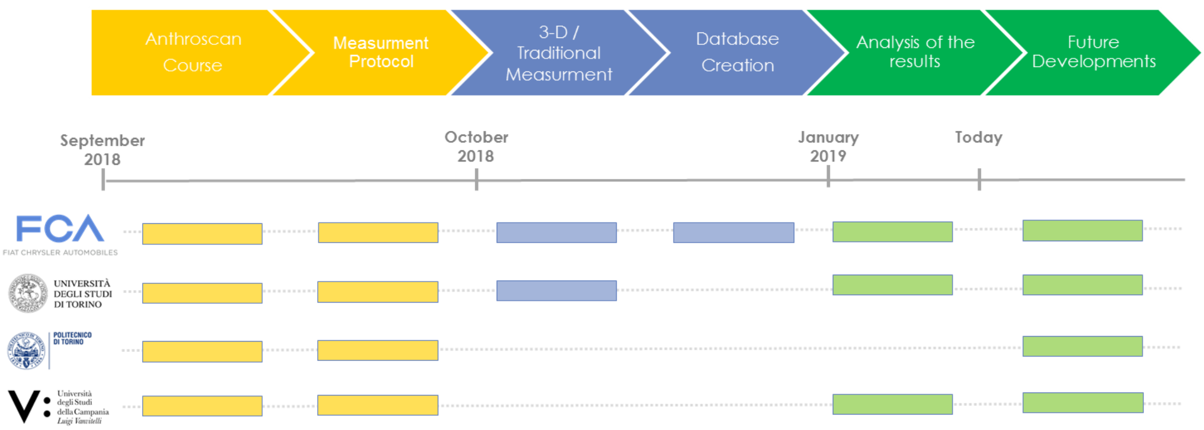


Figure 26. 3-D body scanner project timeline

3.3 3-D Body Scanner and software

As part of the "La Fabbrica si Misura" project, it was decided to use a 3-D body scanner to carry out 3-D scans of participants, and extract their anthropometric measurements, comparing them to the traditional method and integrating the results within the FsM project.

The 3-D body scanner "Vitus bodyscan" (Figure 27) is a product of "Avalution GmbH", a German company that is part of the "Human Solutions Group", specializing in 3-D Body scanning and related activities.

Figure 27. Photograph of the scanner. Left: closed, with calibration tube shown on the right. Right: open with seat up

Figure 28. Seat used for the sitting posture, platform with positioning arrows and feet positioning imprints

As per the ISO 20685-1:2018 [50]: "*The scanner hardware should be calibrated when first delivered and should be recalibrated periodically. The frequency of calibration should be related to the type of scanner and the frequency of use*". In the case of this scanner, the manufacturer recommends at least one calibration per week.

The calibration process relies on the use of a calibration tube that must be scanned on the platform on five different positions, which takes approximately 5-10 minutes. A registration "wizard" of the software guides the calibration procedure. The process is as follows:

1. The calibration tube is placed in the center of the platform; the arrow #4 on the calibration tube should face the direction of the entrance;
2. The first scan is then initiated (Figure 29);

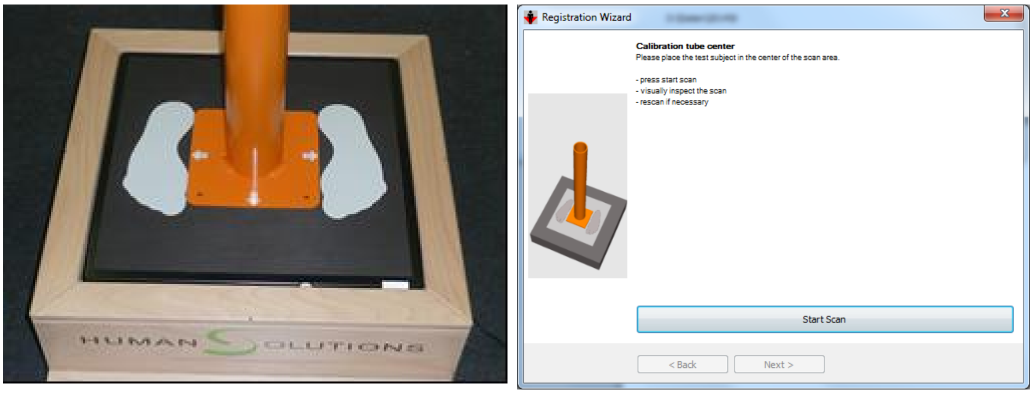


Figure 29. First position. Left: Calibration tube placed at the center of the platform, right: scanning wizard [54]

3. The tube is moved to the second position, to the front-end of the platform with the arrow #2 facing the arrow with the same number on the platform;
4. The second scan is taken (Figure 30);

Figure 30. Second position. Left: Calibration tube placed at the front-end of the platform, right: scanning wizard [54]

5. The tube is moved to the third position, on the left side of the platform with the arrow #3 facing the arrow with the same number on the platform;
6. The third scan is taken (Figure 31);

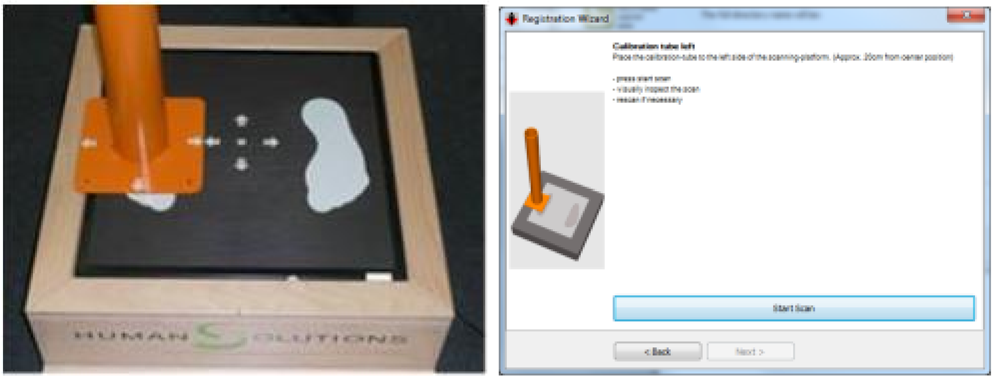


Figure 31. Third position. Left: Calibration tube placed at the left side of the platform, right: scanning wizard [54]

7. The tube is moved to the fourth position, to the back-end of the platform with the arrow #4 facing the arrow with the same number on the platform;
8. The fourth scan is taken (Figure 32);

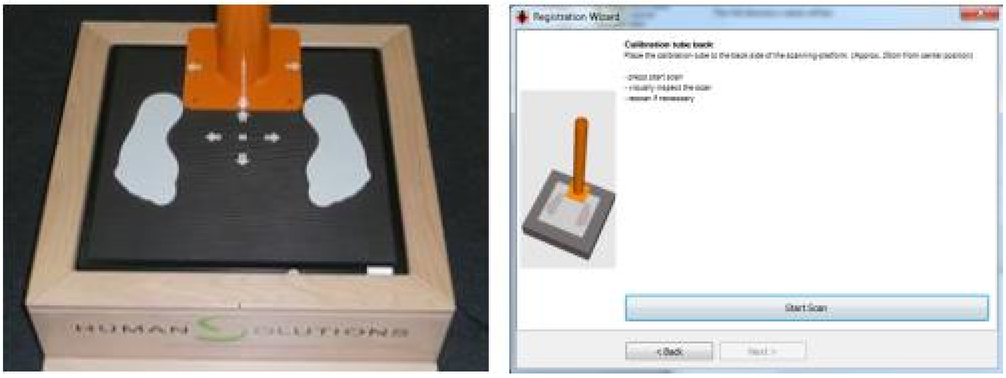


Figure 32. Fourth position. Left: Calibration tube placed at the back-end of the platform, right: scanning wizard [54]

9. The tube is moved to the fifth position, to the right side of the platform with the arrow #5 facing the arrow with the same number on the platform;
10. The fifth scan is taken (Figure 33);

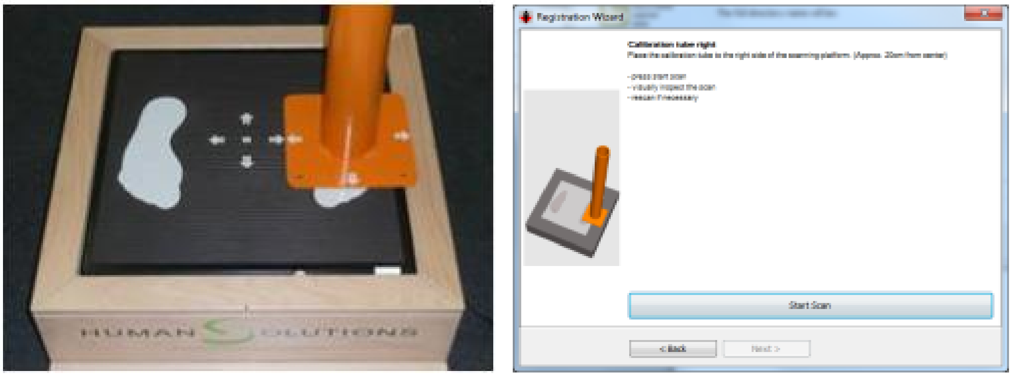


Figure 33. Fifth position. Left: Calibration tube placed at the right side of the platform, right: scanning wizard [54]

When the scanning process is complete, the software starts the automatic calculation of the calibration data, it displays the results of the five scans with a status message confirming the calibration, as shown in Figure 34.

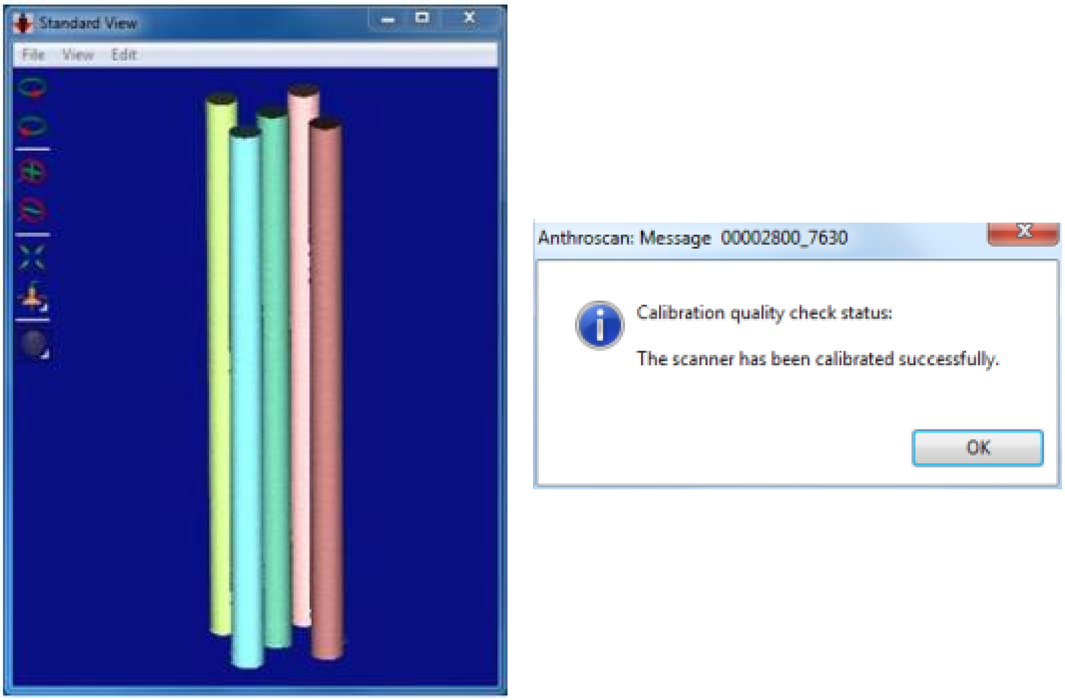


Figure 34. Calibration results [54]

3.4 3-D scanning and measurement procedure

The detection protocol was defined referring as much as possible to ISO 20685-1:2018 [50] both for the choice and definition of posture and the detection modalities.

It is important to define the posture to be assumed by the subject in the 3D scanner because it is precisely from the posture that derives the optimization of the detection itself and consequently the quality of the derived measures. Care must be taken that the areas of the body subject to anthropometric detection of interest are not "shadowed" thus preventing or altering the measurement. For this reason, the ISO 20685-1:2018 standard itself provides postures to be taken in the 3D scanner which may be different to those provided for the classic manual detection in the ISO 7250-1 standard. The optimal position to be taken in the scanner can therefore be different from the standard ones reported in the ISO standard and must therefore be described in detail.

According to these criteria, four postures have been chosen. They are to be assumed by the subjects during the 3D detection. These postures are explained in detail and illustrated in the following. Regarding the order of postures to be taken, it was decided to start from the sitting posture in order to perform the adjustment operations of the stool while the subject still dressed. The subject will be accompanied into the scanner and asked to sit on the stool in order to adjust its height; in this phase it will only be necessary that the subject removes their shoes. After the regulation of the height of the stool, the subject undresses, and once he/she has entered the scanner, the stool will already be adjusted and ready to be used.

The order of the postures was chosen based on their complexity, it was decided to start with the simplest and most intuitive posture for the subject and end with the reachability measures, which may be more complex, because of the different joint angles to consider and maintain.

The subject must maintain the posture chosen during the entire scan (maximum 12 seconds), breathing normally, keeping the trunk and shoulders erect, while keeping the muscles relaxed.

3.4.1 Initial phase

The subject is presented with the body scanner, the measurement procedure and the consent to the processing of personal data is collected. The data is collected anonymously through the assignment of a numeric code that has the sole purpose of helping in the management and analysis of data. The following data are collected:

- Sex (M/F);
- Date of birth;
- Region of birth (if the subject is Italian, if not then country of birth is listed);
- Region of birth of the father (if the subject's father is Italian, if not then country of birth is listed);
- Region of birth of the mother (if the subject's mother is Italian, if not then country of birth is listed);
- Workplace.

3.4.2 Preparation for scanning

The subject is accompanied in the dressing room adjacent to the body scanner entrance. In order to correctly evaluate body measurements, it is important to observe some basic rules:

- The subjects must only wear their underwear that have common and specific characteristics (Figure 35). The underwear must not be tight, dark, shiny nor padded. The labels must be hidden inside the underwear.

Figure 35. Examples of acceptable & unacceptable clothing inside the scanner

- Subjects must remove jewelry (necklaces, bracelets, earrings, watches, anklets) and glasses to avoid any possible reflection of light inside the scanner (Figure 36).

Figure 36. Examples of unacceptable accessories inside the scanner

- Wearing a swimming cap is recommended for detecting head measurements, which otherwise would be distorted by hair volume. In case of long hair, subjects need to tie it in a bun. The ears must remain outside the cap.

Figure 37. Example of acceptable and unacceptable hair setting

It is necessary to ensure that all of the above instructions have been adhered to before starting the scan.

3.4.3 Scanning

The four postures to be adopted to the subjects for the surveys are the following:

1. Sitting posture: subject is sitting on the provided stool, with a straight torso, the head is oriented according to the Frankfurt plane, legs are slightly apart. An angle of 90° is between the thigh and the torso, the knees are flexed at 90°, the tibias are parallel, the ankle is at an angle of 90° with the ground with the feet parallel. The arms are hanging laterally, slightly spaced from the hips, with elbows bent at 90° and hands with the palms facing each other, with the right hand in a closed fist with the thumb visible and the left hand open with fingers together.

This posture corresponds to the sitting posture D of the standard except for the posture of the right hand, which in the standard is open.

In fact, it was chosen not to keep both hands open but to ask the subject to keep the right hand closed in a fist and only the left open (fingers together) in order to maximize the number of measurements detectable considering also the reachability of the upper limb flexed at 90° to the fist.

Figure 38. Left: Sitting Posture, Right: Posture D of the ISO 20685-1:2018

2. **Relaxed posture:** subject is in an upright position with the head oriented along the plane of Frankfurt, feet are parallel and close, arms freely hanging along the side of the body, hands with the palms facing the body and fingers extended and joined. The abdomen is relaxed, and the subject breathes normally.

This posture corresponds to the upright posture B of the standard.

This position can be used particularly to obtain height measurements.

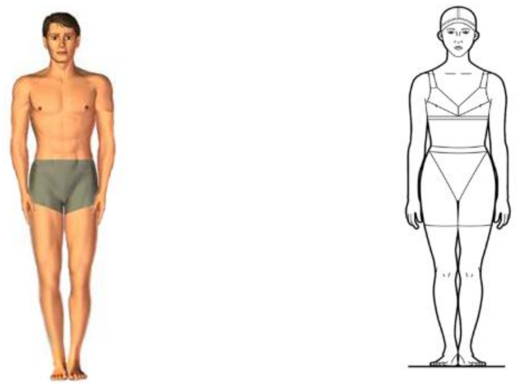


Figure 39. Left: Relaxed Posture, Right: Posture B of the ISO 20685-1:2018

3. Standard posture: subject is in a standing position with the head oriented according to the plane of Frankfurt, the feet are parallel at about 20 cm apart, the arms are along the sides with. The shoulder joints at about 20° with respect to the sides of the torso and the elbows are slightly flexed, the hands have the palms facing each other and both hands are clenched in fists with visible thumbs.

This posture corresponds to the erect posture A of the ISO standard except for the elbows that are here slightly bent, and of the hands that are oriented differently and closed here rather than open.

This is the posture foreseen for the automatic detection of anthropometric measurements through the 3-D scanner software used in the present project. It was therefore decided to insert it as a position to be taken during the project while highlighting the differences compared to the standard position of the ISO standard. This posture can be used to obtain circumferences of the whole body.

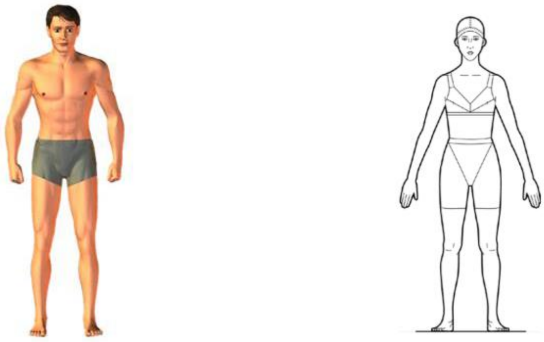


Figure 40. Left: Standard Posture, Right: Posture A of the ISO 20685-1:2018

4. Reaching posture: the subject is in a standing position with the head oriented according to the plane of Frankfurt, the feet are parallel and close, the left arm is stretched forward horizontally and the palm facing down with fingers extended and joined. While for the right arm, the elbow is bent at 90° with the palm facing the center and the fingers extended and joined. The shoulders are straight without twisting.

This posture corresponds to the upright posture C of the standard.

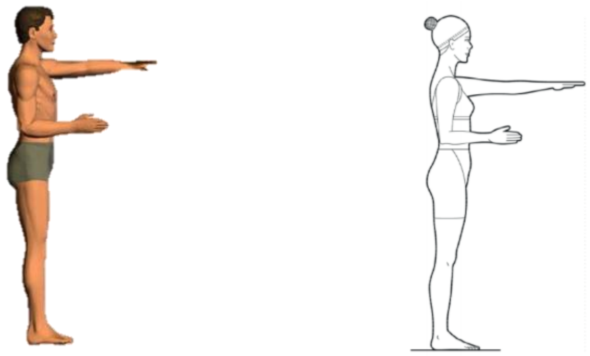


Figure 41. Left: Reaching Posture, Right: Posture C of the ISO 20685-1:2018

3.4.4 Measurement process

The measurement process is effectuated a posteriori to the scanning process; it consists of taking the anthropometric measurements of the subjects scanned. The measurement process begins with loading all the four scans of a subject into the Anthroscan software. A list of anatomical landmark points has to be chosen on the scan in which the measure is to be taken, they are specific points on the body that can be used for defining anthropometric measurements. For example, the cervicale height is taken in the relaxed posture, the software thus only shows the relaxed posture in the view (Figure 42 & Figure 43).

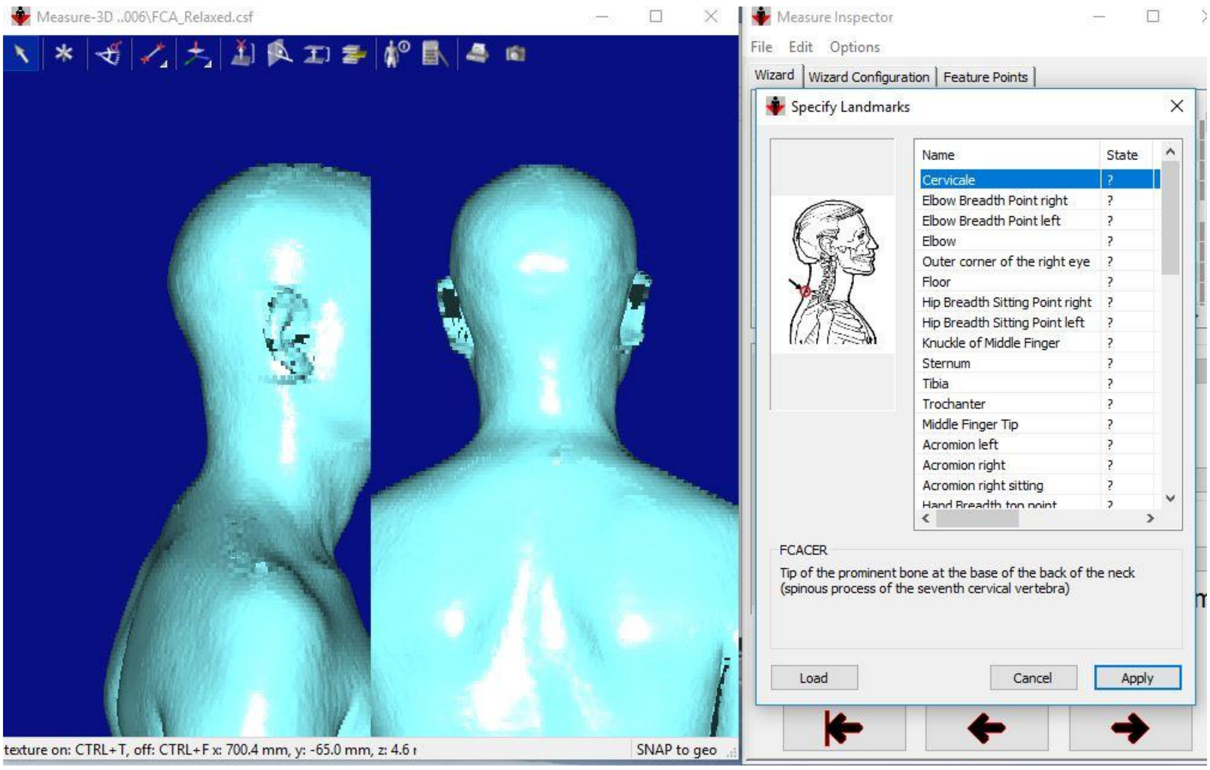


Figure 42. Example of choice of a landmark point (cervicale) in Anthroscan (1)

For each landmark point a picture and a small description of the point to be chosen are also present with the purpose of facilitating the choice and minimizing errors. For some subjects, some landmark points were also highlighted to render them clearly visible and distinguishable during the measurement process in accordance with the ISO 20685-1.

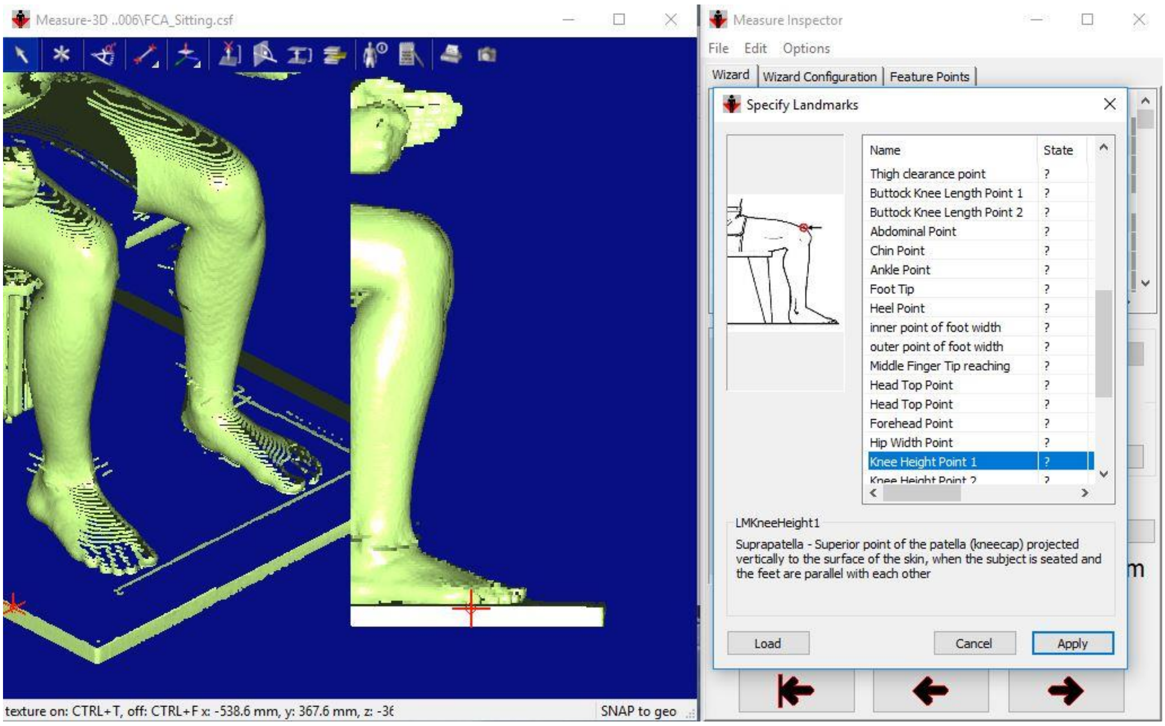


Figure 43. Example of choice of a landmark point in Anthroscan (2)

After the choice of the landmark points, the software calculates the distances between these points according to an algorithm already provided to it (Figure 44 & Figure 45).

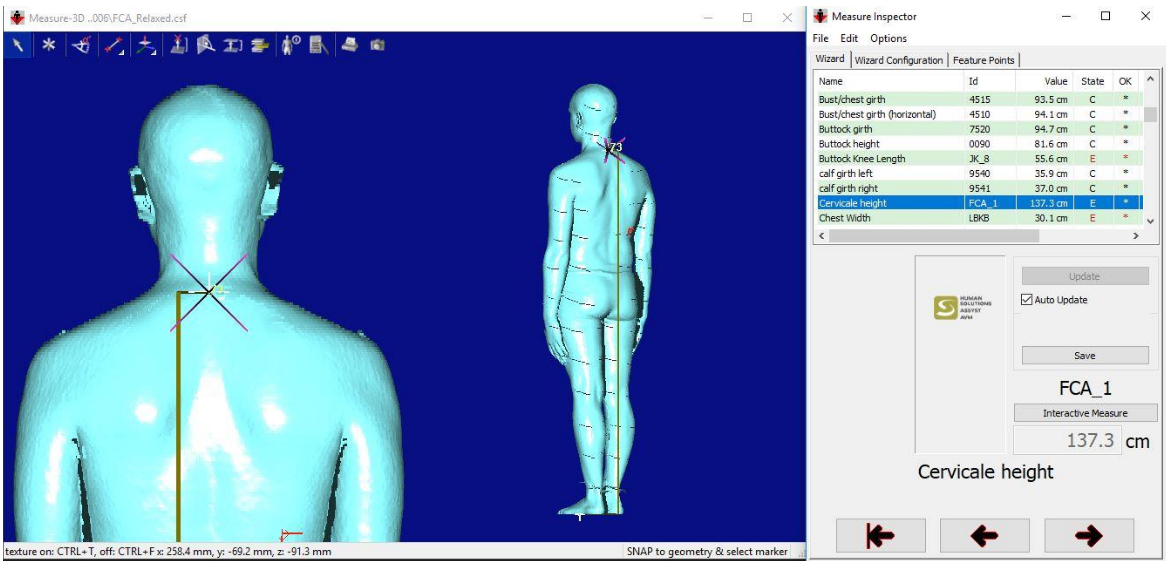


Figure 44. Example of a measurement calculated by choosing two landmark points (floor and cervicale)

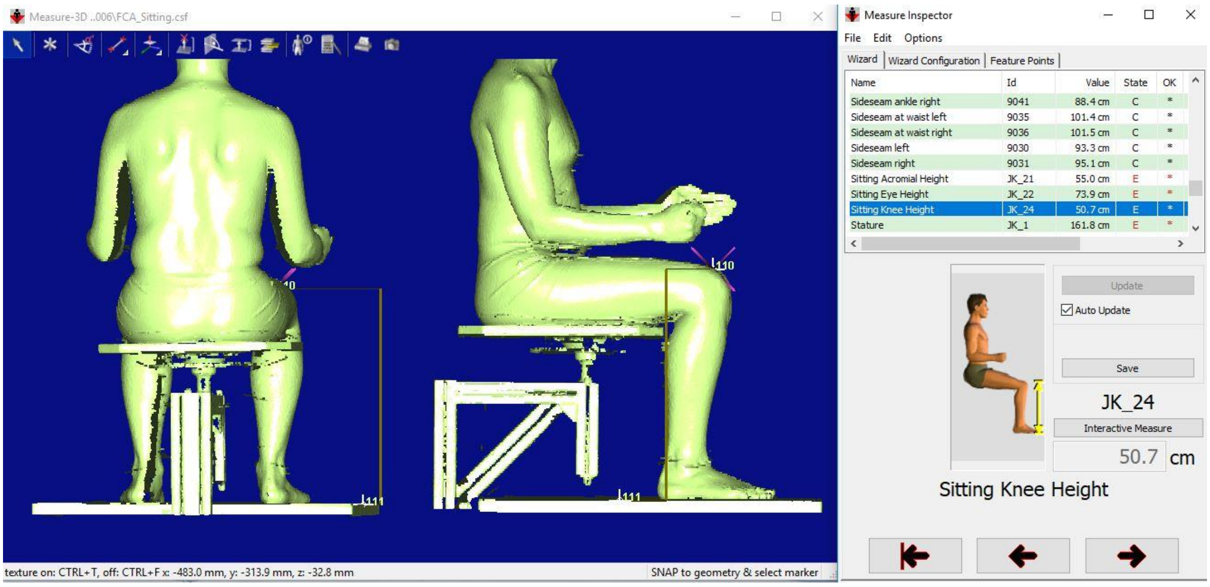


Figure 45. Example of a measurement calculated by choosing two landmark points (floor and knee height point)

For some measurements, such as breadths and widths, only one landmark is sufficient for the software to perform the calculation (Figure 46 & Figure 47).

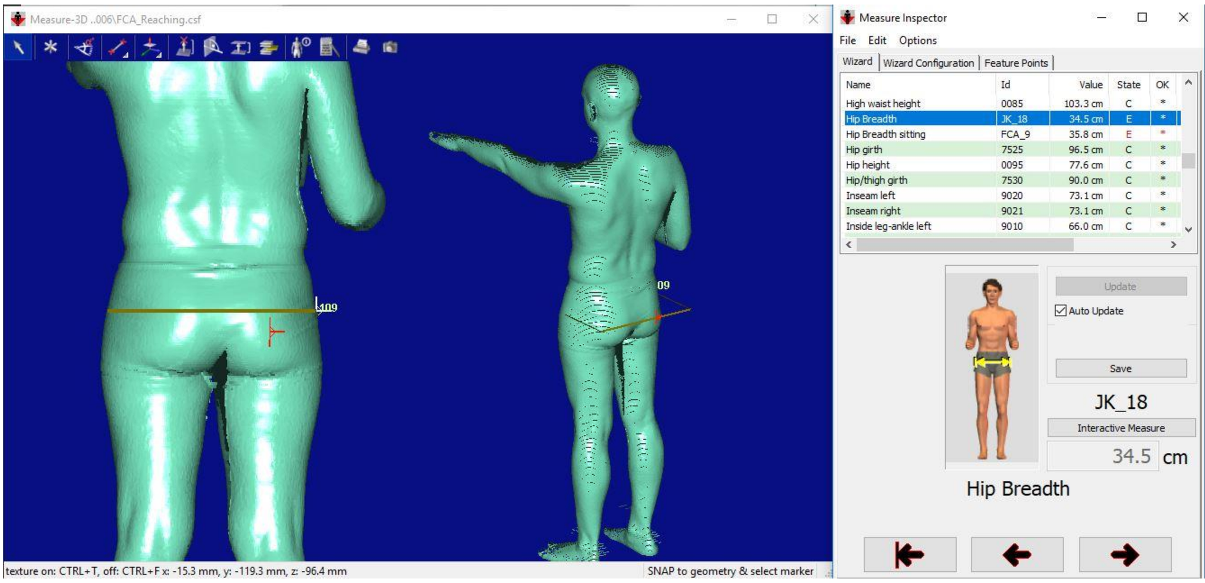


Figure 46. Example of a measurement calculated by choosing one landmark point (hip breadth)

The position of the anatomical landmark points can then be subsequently corrected while the software updates the value of the measurement accordingly.

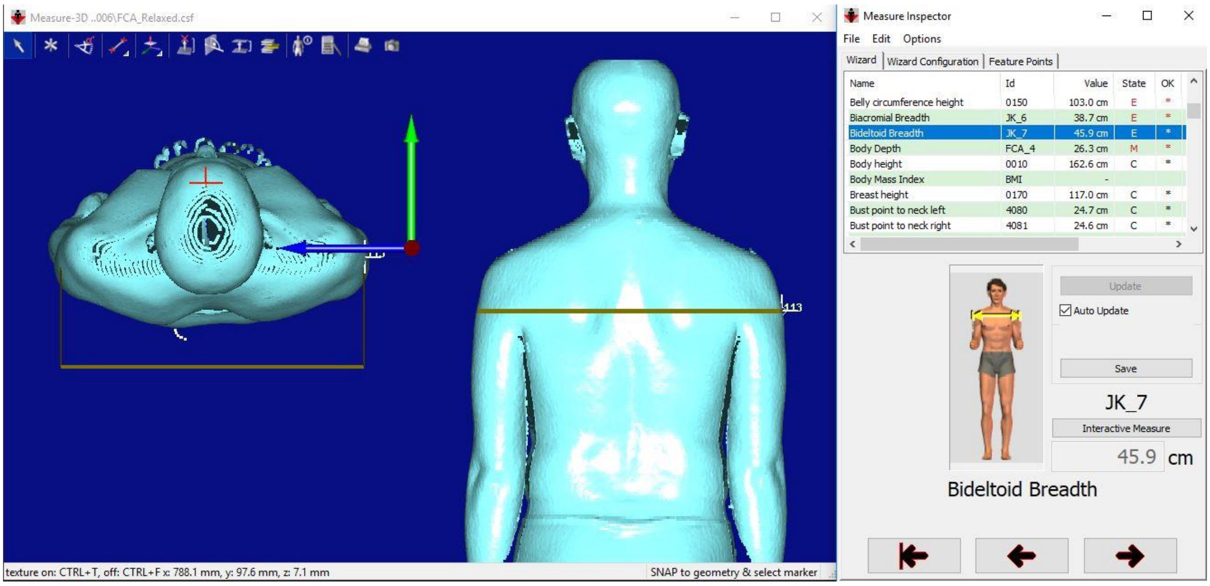


Figure 47. Example of a measurement calculated by choosing one landmark point (bideltoid breadth)

3.4.5 Chosen Measurements

As indicated above, every posture allows the detection of different variables. The variables were chosen to keep references and comparisons as much as possible with those previously measured during the "La Fabbrica Si Misura" project. Measurements that are necessary for the customization of virtual manikins (Jack) have also been added. The current international reference for anthropometric data is ISO 7250-Part 1 [51] and Part 2 [52] .

In addition to the automatic measurements detected through the scanner and those calculated through the identification of the points of reference directly on the avatar, it was required to enter ex novo some measurements useful for the different objectives of the project. In particular, the anthropometric measurements necessary for the modelling of the virtual manikins, using Jack Siemens, are those seen in Figure 48.

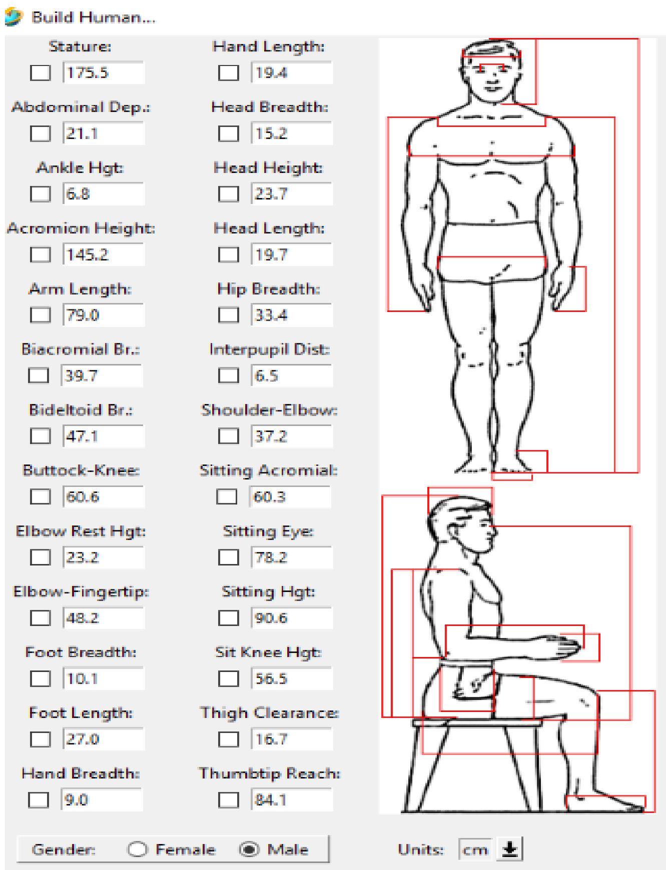


Figure 48. Measurements to build a Jack virtual manikin [Jack Siemens]

For comparison and correlation with the measurements of the FsM project, on the other hand, the measurements shown in Table 7 were also added.

Table 7. Measurements added for comparison with the FsM project

Anthropometric measurements	Reference code (ISO 7250)
Acromion (Shoulder) height	6.1.4
Body depth	6.1.10
Cervicale height	As per FsM
Chest breadth	6.1.11
Elbow height	6.1.5
Elbow-to-elbow breadth	6.2.9
Eye height	6.1.3
Hip breadth (sitting)	6.1.12
Knuckle height	As per FsM
Tibial height	6.1.8
Trochanter height	As per FsM

The full list of measurements taken by the Body Scanner is available in the Appendix.

3.5 Preliminary statistical analysis of the results

The sample was divided by sex and statistically analyzed, after controlling and eliminating potentially erroneous measurements. A summary of the data collected and the statistical analysis of the results, both for the female and the male samples, are presented in this section.

The target of the project was the scanning and measuring of 100 subjects, 50 males and 50 females. By the end of the project, 124 subjects were scanned, out of which 59 are females and 65 are males. Out of the 124 subjects, 38 subjects (30 males and 8 females) were also measured using the traditional instruments (anthropometer, sliding caliper). This allows the direct comparison between the two methods for the same subject.

3.5.1 Division by age

3.5.1.1 Male Sample

The average age and standard deviation are 41.5 ± 13.0 years. Table 8 shows the age distribution of the male Body Scanner sample subdivided in five age groups (18–25, 26–35, 36–45, 46–55, and 56–65 years). The chosen subdivision is the one adopted in FCA and consequently in the La Fabbrica si Misura (FsM) project [53].

It can be noted that, although the participation to the project was voluntary and the sample was not pre-determined, the distribution among age groups is not equal. The highest proportion of males in the Body Scanner sample have an age between 46 and 55 years (35.8%). This age group also has the highest proportion in the FsM sample (36.9%). The data for the FsM project was taken from [53].

For the FsM, the male age range 36-55 years represented 69% of the sample, while for the Body Scanner project it represents 50.8%. The second highest proportion in the BS project is that of males aged between 26 and 35 years (21.5%) while the second highest proportion in the FsM is that of males aged 36 to 45 years. This is due to the fact that the Body scanner sample is not only of FCA workers but also of external persons of which some are students and athletes and therefore are evidently younger.

Table 8. Male sample age distribution

Male sample age distribution		
Age groups (years)	Body Scanner	
	N	%
18–25	9	13.8%
26–35	14	21.5%
36–45	9	13.8%
46–55	24	36.9%
56–65	9	13.8%

3.5.1.2 Female Sample

While for the female sample, the average age is 34.3 years and the standard deviation is 12.1 years. Table 8 shows the distribution of the female sample with respect to the age groups previously mentioned.

By comparing the two samples, we can note that the female sample is on average younger than the male sample. In fact, the two highest proportions of the female sample are that of the age groups 18-25 and 26-35 years (both 26.2%) while the highest proportion for the male sample is that of the age group 46-55 years. This is perhaps due to the different workplace distribution of the female and male samples.

Table 9. Female sample age distribution (Body Scanner)

Female sample age distribution		
Age groups (years)	Body Scanner	
	N	%
18–25	17	26.2%
26–35	17	26.2%
36–45	10	15.4%
46–55	13	20.0%
56–65	2	3.1%

3.5.2 Division by workplace

Out of the 124 subjects scanned, 52% are workers in FCA, 77% of which are white-collar workers and 23% are blue-collar workers. On the other hand, 48% of the total sample are externals; out of which 33% are students, 28% are athletes and 39% are white-collar workers. The division of the subjects scanned by workplace is shown in Figure 49.

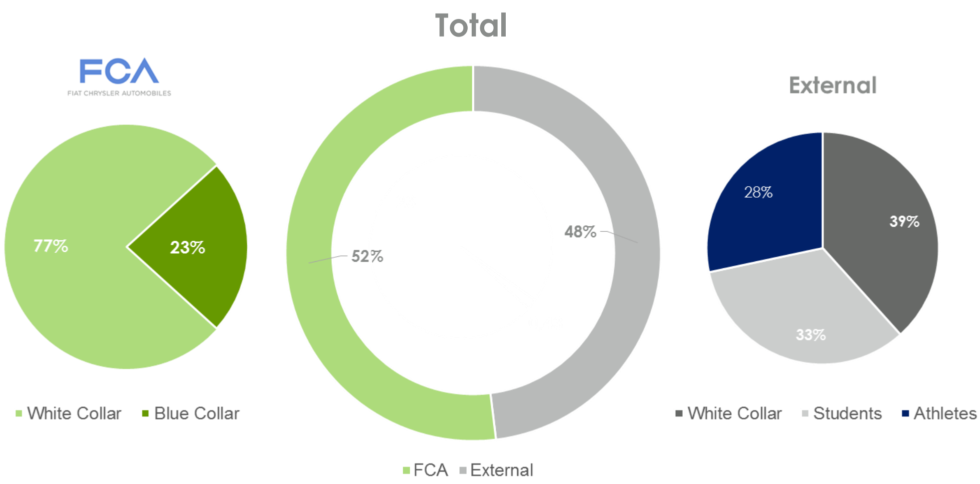


Figure 49. Distribution by workplace (Male & Female)

Alternatively, dividing the subjects by sex and by workplace, some differences emerge. The two samples have a relatively similar distribution between FCA workers and externals, but the proportions within each macro-division differs. The results are shown in Table 10 and Table 11.

For the male sample, for example, the white-collar workers constitute 65.7% of FCA employees while the blue-collar workers are 34.3%. This is in contrast with the female sample where only 10% of FCA employees scanned are blue-collar workers. This result is expected since the overall female proportion of blue-collar workers in FCA is only 13%.

It is worth noting that, as previously postulated, the two samples are diversely divided by workplace, the female sample has a higher proportion of students, athletes and white-collar workers, resulting in a lower average age overall with respect to the male sample.

Table 10. Female workplace distribution

Female workplace distribution - Body Scanner			
FCA	50.8%	White-collar	90.0%
		Blue-collar	10.0%
External	49.2%	White-collar	34.5%
		Student	48.3%
		Athlete	17.2%

Table 11. Male workplace distribution

Male workplace distribution - Body Scanner			
FCA	53.8%	White-collar	65.7%
		Blue-collar	34.3%
External	46.2%	White-collar	40.0%
		Student	20.0%
		Athlete	40.0%

3.5.3 Analysis of the anthropometric measurements

For what concerns the anthropometric measurements taken, a preliminary analysis was performed. Using the 3-D body scanner, 193 measurements were taken, out of which 156 were taken in automatic by the software itself and 37 were measured by the software using markers set by the operators.

Out of these 37 measurements, 13 were the same measurements taken in the FsM project so as to compare the results and integrate them within the database. Table 12 and Table 13 show the statistical values of mean and standard deviation of theses collected anthropometric measurements for the male and female sample respectively, along with the 5th and 95th percentiles which are used in workstation design.

Table 12. Statistical analysis of the male sample (all values are in mm, except body mass in kg)

Statistical analysis of the male sample of the Body Scanner				
Anthropometric measurements	Mean	SD	P5	P95
Body mass	77	12	62	97
Stature	1750	70	1627	1866
Eye height	1635	70	1537	1745
Cervicale height	1499	65	1388	1600
Shoulder height	1444	63	1351	1544
Elbow height	1062	49	983	1135
Trochanteric height	888	53	802	970
Knuckle height	748	39	681	812
Tibial height	457	27	416	500
Body depth	307	36	255	371
Shoulder biacromial breadth (sitting)	374	34	310	422
Elbow-to-elbow breadth (sitting)	547	47	461	617
Hip breadth (sitting)	379	22	353	426

Table 13. Statistical analysis of the female sample (all values are in mm, except body mass in kg)

Statistical analysis of the female sample of the Body Scanner				
Anthropometric measurements	Mean	SD	P5	P95
Body mass	61	11	43	76
Stature	1615	68	1476	1731
Eye height	1501	66	1361	1622
Cervicale height	1374	64	1235	1473
Shoulder height	1329	62	1197	1427
Elbow height	987	48	900	1065
Trochanteric height	808	49	714	882
Knuckle height	706	39	626	771
Tibial height	416	23	368	454
Body depth	291	34	250	332
Shoulder biacromial breadth (sitting)	306	27	252	355
Elbow-to-elbow breadth (sitting)	468	47	370	529
Hip breadth (sitting)	395	36	344	456

It can be noticed that, as expected, the mean of the male sample is greater than that of the female sample for all the measurements, except for the hip breadth. While for the standard deviation the samples have very similar values for most of the measurements.

Table 14. Comparison of mean and standard deviation SD of the male sample between Body Scanner and FsM

Male sample measurements	FsM		Body Scanner		Δ
Anthropometric measurements	Mean	SD	Mean	SD	Δ_{mean}
Body mass	81	13	77	12	-4
Stature	1726	71	1750	70	24
Eye height	1617	70	1635	70	18
Cervicale height	1496	68	1499	65	3
Shoulder height	1431	67	1444	63	13
Elbow height	1064	60	1062	49	-2
Trochanteric height	905	61	888	53	-17
Knuckle height	747	46	748	39	1
Tibial height	451	54	457	27	6
Body depth	259	45	307	36	48
Shoulder biacromial breadth (sitting)	392	44	374	34	-18
Elbow-to-elbow breadth (sitting)	474	51	547	47	73

Hip breadth (sitting)	350	42	379	22	29

Table 14 provides a comparison between the anthropometric measurements of the male samples of the Body Scanner project and the FsM project. For the FsM project, the data is taken from [53]. The difference Δ between the two mean values, Δ_{mean} is also reported. The difference is calculated as Δ = (Body Scanner – FsM), so that positive Δ values highlight greater measurements for the Body Scanner project and vice versa.

It can be noted that for some measurements, the Δ_{mean} is greater than that of other measurements. For example, the difference in means between the elbow-to-elbow breadth of the body scanner and of the FsM is 73 mm, while difference in means for the knuckle height is only 1 mm.

The difference in means is particularly high for breadths and for the body depth, which could be caused by two factors. The first could be that the two samples represent two different populations, as the sample of the Body Scanner is younger on average than that of the FsM and has a higher number of white-collar (office) workers. The second factor could be related to the reliability of the use of the 3-D Body Scanners when it comes to the measurement of breadths and widths.

For what concerns the standard deviation, it is lower for the body scanner measurements; this means a lower variability of the anthropometric measurements and a better estimation of the extreme percentiles.

In order to better understand the variability of the measurements and their distribution, both the male and female samples have been divided into 4 different classes depending on their measured stature. The division of classes and the number of subjects in each class are shown in Table 15.

Table 15. Male and female division by stature classes

Division by stature classes				
Class	Male		Female	
	Stature	N	Stature	N
1	1600-1699	17	1450-1549	10
2	1700-1749	18	1550-1599	14
3	1750-1849	22	1600-1699	28
4	>1850	8	>1700	7

The first class contains the shortest individuals, the second class contains the individuals with a stature below, but close to, the average, the third class contains the individuals with an average stature and slightly above and the fourth class contains the tallest individuals. After the division into classes, 19 measurements were chosen in order to define the proportions of the measured subjects (Table 16).

Table 16. Anthropometric measurements chosen to study the proportions of the subjects

Chosen measurements for the definition of proportions with respect to stature	
Anthropometric measurements	Reference code (ISO 7250)
Acromion (Shoulder) height	6.1.4
Ankle height	-
Arm length	-
Biacromial breadth	6.2.7
Cervicale height	-
Chest breadth	6.1.11
Elbow height	6.1.5
Eye height	6.1.3
Foot breadth	6.3.8
Foot length	6.3.7
Head height	-
Hip breadth	6.1.12
Knuckle height	-
Pelvis width	-
Seated height	6.2.1
Stature	6.1.2
Tibial height	6.1.8

Trochanter height	-
Weight (Body mass)	6.1.1

For these measurements, the mean, standard deviation (SD) and coefficient of variation (CV) were calculated. The following step is the calculation of the ratio (proportion) of the chosen measurements to the stature and then the calculation of the mean, standard deviation and coefficient of variation for these proportions. The coefficient of variation is the ratio of the standard deviation to the mean, the higher the coefficient of variation, the greater the level of dispersion around the mean. It is a dimensionless number and it is useful for understanding the standard deviation of the data within the context of the mean, specifically, the distribution of multiple sets of measurements with broadly diverse means.

The proportion of each measurement is calculated as: $Proportion = \frac{Measurement}{Stature}$ and therefore, it is a dimensionless unit that is less than 1 for all the proportions, except for the weight proportion which has a unit of kg/cm and can be greater than 1. For all classes, any proportion that has a CV higher than the threshold of 5 % is to be highlighted for further analysis.

3.5.3.1 Class 1

For the female and male samples, the first class represents the shortest subjects and contains the 5th percentile of stature.

Table 17. Class 1 proportions with respect to stature

Proportions of Class 1 with respect to stature						
Anthropometric measurements	Male			Female		
	Mean	SD	CV	Mean	SD	CV
Acromion (Shoulder) height	0.825	0.011	1.387	0.817	0.014	1.699
Ankle height	0.040	0.003	8.326	0.040	0.003	8.264
Arm length	0.453	0.010	2.153	0.435	0.011	2.522
Biacromial breadth	0.218	0.018	8.347	0.204	0.021	10.414
Cervicale height	0.856	0.009	1.032	0.844	0.008	0.963
Chest breadth	0.200	0.011	5.636	0.192	0.026	13.527
Elbow height	0.609	0.012	1.963	0.611	0.011	1.770
Eye height	0.934	0.008	0.812	0.929	0.007	0.760
Foot breadth	0.055	0.005	9.567	0.056	0.005	9.166
Foot length	0.153	0.005	3.239	0.150	0.006	3.877
Head height	0.136	0.009	6.735	0.141	0.009	6.676
Hip breadth	0.203	0.015	7.202	0.214	0.029	13.604
Knuckle height	0.426	0.014	3.235	0.436	0.012	2.758
Pelvis width	0.204	0.008	3.780	0.223	0.025	11.267
Seated height	0.522	0.012	2.349	0.540	0.010	1.909
Stature	-	-	-	-	-	-
Tibial height	0.260	0.010	3.706	0.256	0.010	3.848
Trochanter height	0.504	0.023	4.630	0.493	0.012	2.513
Weight (Body mass)	0.442	0.054	12.175	0.356	0.081	22.781

From Table 17 it is noticeable that for both samples of the first class, 7 measurement proportions have a CV higher than 5%. These are: ankle height, biacromial breadth, chest breadth, foot breadth, head height, hip breadth and weight. While for the female sample the pelvis width can also be added to those measurements.

For both samples, the weight proportion has the highest coefficient of variation, and it is especially high for the female sample (22.78%), which means that the variability between the measured subjects is high.

3.5.3.2 Class 2

The second class represents the subjects with a stature that is close but lower than the average.

Table 18. Class 2 proportions with respect to stature

Proportions of Class 2 with respect to stature						
Anthropometric measurements	Male			Female		
	Mean	SD	CV	Mean	SD	CV
Acromion (Shoulder) height	0.825	0.011	1.373	0.823	0.009	1.056
Ankle height	0.041	0.004	9.966	0.037	0.003	8.708
Arm length	0.453	0.010	2.267	0.442	0.013	2.915
Biacromial breadth	0.213	0.019	9.017	0.186	0.018	9.604
Cervicale height	0.859	0.010	1.216	0.850	0.008	0.917
Chest breadth	0.196	0.014	7.183	0.182	0.012	6.573
Elbow height	0.605	0.014	2.237	0.610	0.014	2.222
Eye height	0.933	0.008	0.838	0.930	0.004	0.467
Foot breadth	0.055	0.004	6.959	0.055	0.003	5.884
Foot length	0.152	0.005	3.409	0.150	0.004	2.749
Head height	0.136	0.012	8.873	0.141	0.005	3.659
Hip breadth	0.200	0.017	8.659	0.217	0.022	9.925
Knuckle height	0.426	0.010	2.427	0.435	0.015	3.412
Pelvis width	0.202	0.011	5.207	0.225	0.019	8.268
Seated height	0.515	0.016	3.068	0.527	0.010	1.818
Stature	-	-	-	-	-	-
Tibial height	0.260	0.008	3.127	0.258	0.008	3.233
Trochanter height	0.508	0.019	3.811	0.501	0.023	4.580
Weight (Body mass)	0.436	0.036	8.213	0.375	0.057	15.189

As seen in Table 18, for both samples, the measurements that have a CV higher than 5% are ankle height, biacromial breadth, chest breadth, foot breadth, hip breadth, pelvis width and weight. While for the male sample, head height can also be added to the previous measurements. For the second class, the weight proportion of the female sample has a higher CV (15.189%) than that of the male sample (8.213%) and is in fact the highest for all the measurements of the female sample. On the other hand, the highest CV for the male sample is that of the ankle height (9.966%).

3.5.3.3 Class 3

The third class represents the subjects hat have an average stature or slightly above. It contains the 50th percentile of stature.

Table 19. Class 3 proportions with respect to stature

Proportions of Class 3 with respect to stature						
Anthropometric measurements	Male			Female		
	Mean	SD	CV	Mean	SD	CV
Acromion (Shoulder) height	0.824	0.011	1.295	0.824	0.007	0.845
Ankle height	0.039	0.002	6.070	0.039	0.004	9.048
Arm length	0.448	0.014	3.104	0.438	0.008	1.756
Biacromial breadth	0.215	0.016	7.630	0.189	0.013	6.885
Cervicale height	0.856	0.012	1.407	0.852	0.007	0.786
Chest breadth	0.192	0.016	8.407	0.173	0.011	6.463
Elbow height	0.606	0.014	2.390	0.610	0.010	1.612
Eye height	0.935	0.010	1.039	0.929	0.006	0.678
Foot breadth	0.053	0.004	8.498	0.054	0.004	7.239
Foot length	0.150	0.007	4.434	0.150	0.005	3.366
Head height	0.132	0.010	7.388	0.137	0.009	6.794
Hip breadth	0.184	0.014	7.427	0.202	0.014	7.066
Knuckle height	0.428	0.011	2.577	0.437	0.009	2.119
Pelvis width	0.196	0.010	5.347	0.214	0.012	5.773
Seated height	0.517	0.009	1.759	0.527	0.010	1.916
Stature	-	-	-	-	-	-
Tibial height	0.260	0.008	3.083	0.257	0.007	2.604
Trochanter height	0.509	0.020	3.951	0.502	0.016	3.167
Weight (Body mass)	0.437	0.066	15.022	0.369	0.031	8.467

For the third class, Table 19 shows that the proportions having a CV greater than 5% for both samples are: ankle height, biacromial breadth, chest breadth, foot breadth, head height, hip breadth, pelvis width and weight.

The weight proportion of the male sample has a higher CV (15.022%) than that of the female sample (8.467%) and is in fact the highest for all the measurements of the male sample. Contrarily, the highest CV for the female sample is that of the ankle height (9.048%).

3.5.3.4 Class 4

The fourth class represents the tallest subjects and contains the 95th percentile of stature.

Table 20. Class 4 proportions with respect to stature

Proportions of Class 4 with respect to stature						
Anthropometric measurements	Male			Female		
	Mean	SD	CV	Mean	SD	CV
Acromion (Shoulder) height	0.827	0.014	1.719	0.828	0.006	0.773
Ankle height	0.041	0.003	7.271	0.040	0.003	7.642
Arm length	0.448	0.011	2.532	0.437	0.014	3.252
Biacromial breadth	0.203	0.025	12.081	0.179	0.019	10.622
Cervicale height	0.858	0.013	1.459	0.853	0.006	0.646
Chest breadth	0.181	0.018	9.817	0.168	0.012	7.110
Elbow height	0.610	0.015	2.478	0.617	0.010	1.659
Eye height	0.939	0.009	0.963	0.934	0.004	0.455
Foot breadth	0.054	0.004	6.992	0.055	0.003	4.817
Foot length	0.153	0.003	2.006	0.147	0.007	4.917
Head height	0.132	0.009	7.022	0.131	0.006	4.491
Hip breadth	0.179	0.024	13.163	0.205	0.025	12.153
Knuckle height	0.433	0.008	1.878	0.442	0.014	3.159
Pelvis width	0.190	0.018	9.415	0.217	0.023	10.540
Seated height	0.518	0.016	3.087	0.525	0.011	2.155
Stature	-	-	-	-	-	-
Tibial height	0.269	0.009	3.372	0.262	0.007	2.712
Trochanter height	0.507	0.015	3.002	0.500	0.018	3.662
Weight (Body mass)	0.449	0.103	23.006	0.432	0.100	23.118

Table 20 shows that for the fourth class, the proportions that have a CV higher than the threshold, for both samples, are: ankle height, biacromial breadth, chest breadth, hip breadth, pelvis width and weight. Additionally, for the male sample, the CV for the head height and foot breadth proportions is higher than the threshold.

Comparably to the first class, the CV of the weight proportion is the highest between the other proportions for both samples, indicating that its variability is high for both extremes of stature (short and tall).

3.5.3.5 Summary

Analyzing the measurement proportions, it can be noticed that some of them are similar for all 4 classes of stature. For example, the proportion of the acromion height for all 4 classes of the male sample is approximately equal to 0.825 of the stature, while the eye height is approximately equal to 0.934 of the stature.

Nevertheless, it can also be noticed that, for the 4 classes of stature, the same 8 measurement proportions usually have a coefficient of variation higher than 5%. These measurements are: ankle height, biacromial breadth, chest breadth, foot breadth, head height, hip breadth, pelvis width and weight. It is thus interesting to try and find an explanation for this apparent variability.

For what regards ankle height and head height, this variability could be related to the fact that for the extraction of measurements of smaller body parts, the resolution from full-body scanners might not be sufficient to ensure accuracy. In fact, the ISO 20685-1 [50] recommends using head and foot scanners for such measurements.

Furthermore, weight in an intrinsically variable measurement and can often rapidly vary even for the same person in a short period of time. Similarly, a tall person does not necessarily weigh more than a short person, thus the proportion of weight to stature must be taken as a general trend rather than a fixed value. On the other hand, breadths and widths can also depend on weight and body types, i.e. somatotypes and therefore their correlation to stature alone must be further analyzed.

Therefore, it is interesting to look at the proportion of these measurements when all the classes are combined. Table 21 shows the values of the selected measurement and their proportion with respect to stature for all the male sample. Measurement values are in mm, except for weight which is in kg.

Table 21. Male selected measurements and proportions with respect to stature

Measurements and proportions of the whole male sample						
Anthropometric measurements	Measurement Value			Proportion		
	Mean	SD	CV	Mean	SD	CV
Acromion (Shoulder) height	1444	63	4.334	0.825	0.012	1.404
Ankle height	70	6	8.809	0.040	0.003	8.283
Arm length	788	35	4.441	0.451	0.012	2.645
Biacromial breadth	374	34	8.965	0.214	0.019	9.043
Cervicale height	1499	65	4.330	0.857	0.011	1.281
Chest breadth	338	26	7.755	0.194	0.016	8.125
Elbow height	1062	49	4.614	0.607	0.014	2.276
Eye height	1635	70	4.284	0.934	0.009	0.941
Foot breadth	95	8	8.889	0.054	0.005	8.390
Foot length	265	14	5.223	0.152	0.006	3.706
Head height	234	19	8.113	0.134	0.010	7.777
Hip breadth	337	30	8.823	0.193	0.019	9.841
Knuckle height	748	39	5.253	0.428	0.012	2.704
Pelvis width	348	20	5.807	0.199	0.012	6.067
Seated height	906	41	4.470	0.518	0.013	2.564
Stature	1750	70	4.016	-	-	-
Tibial height	457	27	5.896	0.261	0.009	3.478
Trochanter height	888	53	5.916	0.507	0.020	4.024
Weight (Body mass)	77	12	15.331	0.440	0.063	14.218

It is immediately noticeable that the same 8 measurement proportions that have a CV higher than the 5% in most of the classes also have a CV higher than 5% when the statistical analysis is done on the complete male sample.

For the female sample, Table 22 shows the values of the selected measurement and their proportion with respect to stature for all the sample. Measurement values are in mm, except for weight which is in kg.

Table 22. Female selected measurements and proportions with respect to stature

Measurements and proportions of the whole female sample						
Anthropometric measurements	Measurement Value			Proportion		
	Mean	SD	CV	Mean	SD	CV
Acromion (Shoulder) height	1329	62	4.681	0.823	0.009	1.135
Ankle height	63	6	10.366	0.039	0.003	9.037
Arm length	708	34	4.828	0.439	0.011	2.464
Biacromial breadth	306	27	8.758	0.189	0.018	9.702
Cervicale height	1374	64	4.654	0.851	0.008	0.916
Chest breadth	286	22	7.835	0.178	0.017	9.647
Elbow height	987	48	4.866	0.611	0.011	1.834
Eye height	1501	66	4.368	0.930	0.006	0.660
Foot breadth	88	7	7.406	0.055	0.004	7.231
Foot length	241	12	5.156	0.150	0.005	3.597
Head height	223	13	5.913	0.138	0.009	6.323
Hip breadth	335	34	10.071	0.208	0.022	10.599
Knuckle height	706	39	5.463	0.437	0.012	2.740
Pelvis width	352	30	8.501	0.218	0.019	8.676
Seated height	854	33	3.863	0.529	0.011	2.149
Stature	1615	68	4.212	-	-	-
Tibial height	416	23	5.621	0.257	0.008	3.088
Trochanter height	808	49	6.022	0.500	0.018	3.648
Weight (Body mass)	61	11	18.389	0.375	0.064	16.978

Comparably to the male sample, the 8 measurements previously mentioned also have a CV higher than 5%, for the same reasons previously discussed.

The proportions of the male and female samples present in Table 21 and Table 22 were illustrated in Figure 50 and Figure 51 respectively.

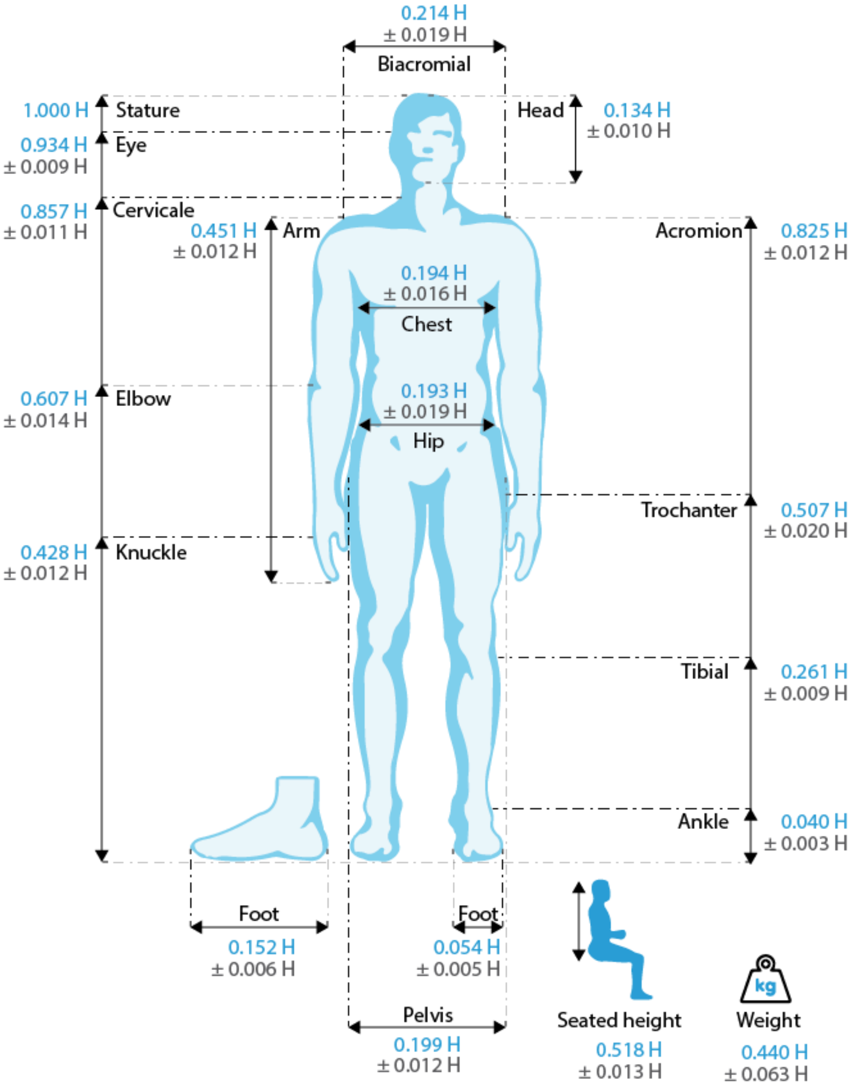


Figure 50. Proportions of the male sample with respect to stature

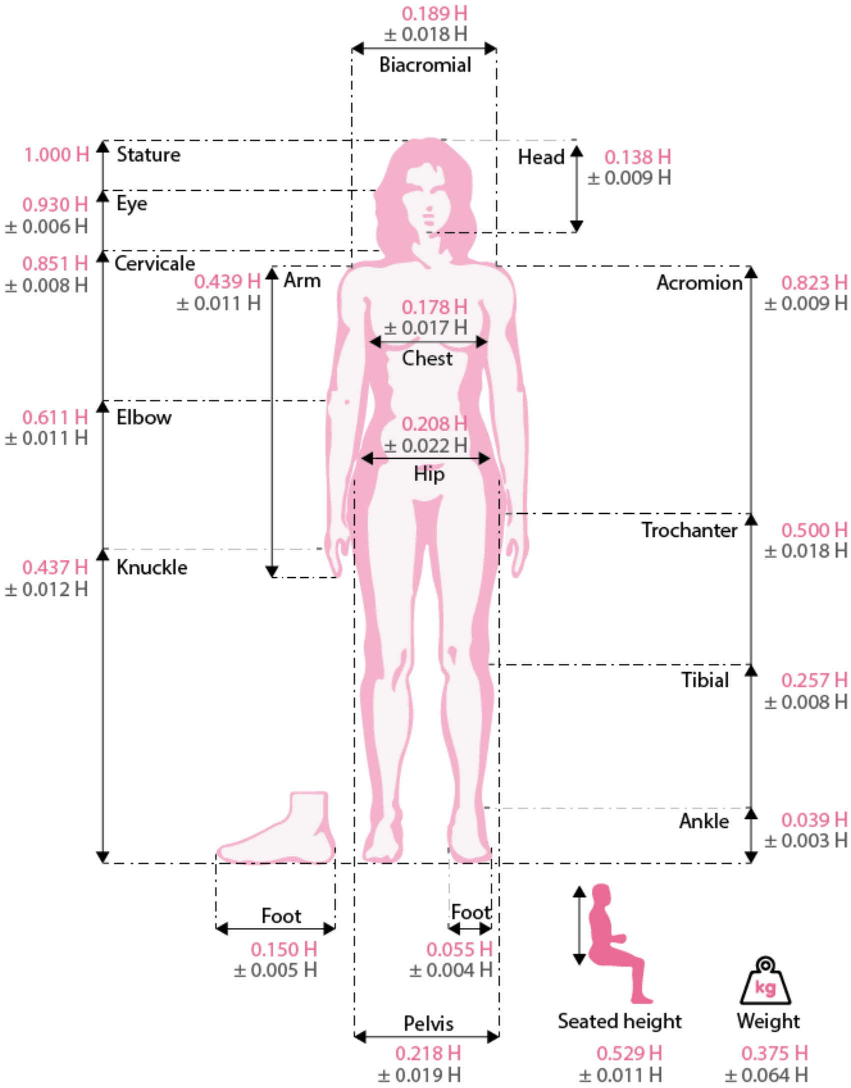


Figure 51. Proportions of the female sample with respect to stature

4 Approach to the virtual validation of the design and application of an exoskeleton

As seen before, there are many challenges that are faced by exoskeletons, especially in the automotive industry. These challenges can relate to the product or to the application itself. For what concerns the product, comfort, weight, adaptability and safety are some of the key characteristics to be taken into account when designing an exoskeleton. As for the application, standards and legislations are currently lagging and need to be updated and reviewed.

As any product, the design of an exoskeleton has to follow a certain process in order to achieve the required results. New Product Development (NPD) is the state-of-the-art method to the development of a new product; it covers the complete process of bringing a product to market. The eight components of NPD process as commonly found in literature are as the following:

1. **Idea Generation**: Brainstorming of possible new products, through internal and external stimuli;
2. **Idea screening**: Eliminate unwanted/unfeasible ideas and focus on a few key product ideas;
3. **Concept development and Testing**: The product concept is developed and is then tested on a group of target customers. Results are used in later phases;
4. **Market strategy/business analysis**: It is comprised of “the four Ps”, product, price, promotion and placement;
5. **Business analysis**: The analysis of the potential sales, costs and profits that the product will have and their comparison to company objectives;
6. **Product development**: Turning the prototype or concept into an actual product by integrating all the previous phases;
7. **Test marketing**: Testing of the product and its proposed marketing programme in realistic market settings before launch;
8. **Commercialisation**: Introducing the product to the market.

Exoskeletons differ from other products in many ways, especially by the need to have an extensive phase of prototyping and testing, which might entail a closed loop of continuous testing and modifications, thus risking the exhaustion the available resources without having the desired final product or having an inadequate final product.

Virtual design allows the company to escape this closed loop and to move on to the next phases of the exoskeleton development, as it allows the continuous virtual validation of the prototype as it evolves into the final product. Research into the virtual design and application of exoskeletons can be found in literature. In the following, some studies about these subjects are presented and briefly discussed.

Researchers [55] have developed a methodology to simulate the deployment of a passive and an active exoskeleton prototypes (Robo-Mate) in an industrial setting. The study focuses on the Jack Siemens humanoid coupled with the exoskeleton in Classic Jack software and then used in the Process Simulate software to simulate different industrial operations and perform basic ergonomics analyses. The simulations showed that the exoskeleton is not compatible in some areas because of high investments for layout changing or because of working environment restrictions but the study concluded that exoskeletons will be a necessity in the factories of the future. One advantage of this methodology is the possibility to perform ergonomic analysis of the Jack humanoid coupled with the exoskeleton using the widely common Siemens Task Analysis Toolkit. The analysis can include Fatigue Analysis, Rapid upper limb assessment (RULA), static strength prediction (SSP) and NIOSH risk evaluation. Such an ergonomic analysis should be done with and without the exoskeleton to determine if the application of the exoskeleton would have a positive impact and to potentially quantify this impact in ergonomic terms. Another advantage is the possibility of identifying appropriate workstations for the application of the exoskeleton.
For what concerns the design of the exoskeleton, such a methodology offers the possibility to test exoskeleton prototypes in a virtual environment equal to the real environment, thus allowing the redesign and testing of the exoskeleton in multiple iterations until reaching the

desired final product. However, the limitations of such a methodology originate in the limitations of the Jack humanoid that is a simplified representation of the human body. Even though the exoskeleton can be regulated to fit the different percentiles of manikins, the methodology lacks the ability to examine the fitting and wearability of the exoskeleton correctly and accurately as opposed to using 3-D scans, for example, that are more representative of the actual human body.

A paper on the computer-aided design of an exoskeleton for gait assistance was written by [56] .The authors designed an active lower-body exoskeleton with the aim to assist the gait and daily activity of elderly people. The design process started from the generation of anatomically correct 3-D human models in an open source software called MakeHuman. The models were then imported into the CAD modelling software SolidWorks where the components were designed and then assembled around the human model. Subsequently, a finite element analysis to test fatigue and failure was performed. A redesign loop of the components was initiated when the assembly of the exoskeleton was not ergonomic or when the stress on the components exceeded yield strength limits of the chosen material. According to the study, future developments include the use of OpenSim software to perform biomechanical kinematic simulations of the exoskeleton with musculoskeletal models in order to define the forces applied by the actuators.
The advantage of such a method of design is the possibility of verifying the wearability of the exoskeleton and its adaptability to different human bodies while at the same time, performing failure and fatigue analysis on the components of the exoskeleton. However, the disadvantages of this method are that of the open source software MakeHuman. The software allows the scaling and creation of the human models, but it has a limited capability with regards to the few anthropometric measurements that can be exactly set. Thus, it is not possible to create 3-D models that have the exact measurements of percentiles.

A Human-centred approach may decrease the health and safety risks related with the operation of a system. Human-centred approaches require greater resources in the beginning periods of the lifecycle; however, they have been found to decrease in-service costs and also to diminish development costs. Specifically, human-centred approaches decrease the probability of unplanned changes in prerequisites and also diminish re-work and installation costs [20].

In the following a human-centred approach to the design and application of an exoskeleton is proposed and explained. The MATE exoskeleton, by Comau, was chosen as a case study for this approach. The approach is also suitable to be applied on exoskeletons in development and on prototypes. The MATE was specifically chosen because FCA participated in its development process and is one of the main beneficiaries of the use of such a device.

4.1 Case Study: MATE - a passive exoskeleton for the upper limbs

4.1.1 Overview

The **MATE** (Muscular Aiding Tech Exoskeleton) by Comau S.p.a, is a passive upper-body exoskeleton designed to help the user upper limbs in flexion-extension movements. It is integrated to the body in three distinct locales: back, waist and arms through a wearable garment.

The exoskeleton provides an auxiliary variable torque on the shoulder joint to compensate fractionally for the gravitational torque created by the weight of the upper limbs. Its purpose is to reduce fatigue and enhance the quality of work in operations that require repetitive movements with raised arms. The reactions are discharged on the human-robot interface (a system of padding and strings) and transferred to the lower back of the wearer.

The company lists some typical applications of the MATE, such as:

- screwing with raised arms;
- sealing with raised arms;
- assembly operations performed with raised arms;
- underbody operations in the automotive sector.

The MATE is a device designed for use by a single worker. Although, it can be shared among multiple workers subsequent to having cleaned and washed the fabric parts.

It is suggested that the use of MATE be gradual; starting from one hour on the first day, two hours on the second day, and 4 hours on the third. From the fourth day on, it would be feasible to use the exoskeleton for the full work shift of 8 hours. It is recommended that MATE is undressed during work breaks, and its use limited to a maximum of 8 hours per day.

The MATE (Figure 52) consists of:

1. **Physical Human-Robot Interface (pHRI)**: all parts that are in direct contact with the body of the wearer;

2. **Passive degrees of freedom (pDOFs)**: parts that facilitate the free movement of the user, such as sliding and rotation joints;

3. **Torque Generator Box**: a mechanism capable of storing and transforming the potential energy of a series of pretensioned springs in order to create a variable assistive torque for the arm. The assistive torques are maximum for arm angles of approximately 90°.

Figure 52. MATE exoskeleton - front view [57]

The physical Human-Robot Interface (pHRi) composes of non-allergenic and non-toxic materials. It is available in two sizes: S/M and L/XL; the choice of size depends on the body of the user. The pHRI is made up of (Figure 53):

1. Removable rear padding
2. Removable padded shoulder straps
3. Removable nylon arm supports with padding
4. Velcro belt
5. Removable panel
6. Adjusting straps
7. Adjustable front buckle
8. Belt extenders - to be installed if necessary, only for size L

Figure 53. Physical Human Robot Interface (pHRi) - front view [57]

The passive degrees of freedom (pDOFs) allow the correct wearing of MATE and its adaptation to different body sizes. They also allow the user to move freely once the device is worn. The pDOFs are (Figure 54):

1. Horizontal axis hinge
2. Back elastics
3. Vertical axis hinge
4. Horizontal axis rear sliding elements
5. Arm supports sliding cuffs

Figure 54. Passive degrees of freedom (pDOFs) [57]

The Torque Generator Box provides seven levels of assistance to the wearer. The user indicatively based on a table selects the value of the assistance level. This table was created taking into account ergonomic assessments and calculations based on the height and body mass of the potential group of users. The use of an incorrect assistance level can generate discomfort but no harm to the user. The Torque Generator Box consists of (Figure 55):

1. Structure of the mechanism housing

2. Hexagonal seat for adjusting the assistance level
3. External cover
4. Locking mechanism

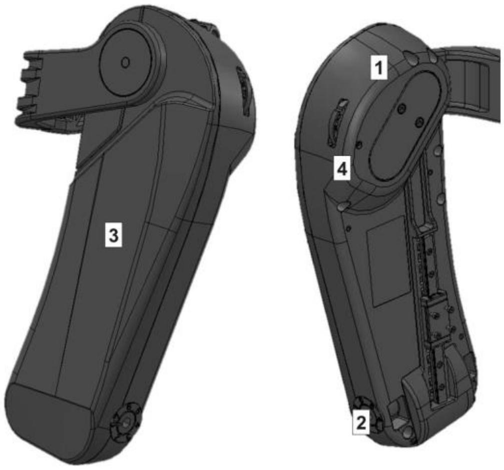


Figure 55. Torque Generator Box [57]

The locking mechanism (Figure 56) positioned on the Torque Generator Box is a safety mechanism that prevents the Torque Generator Box from activating when the exoskeleton is not worn. The LOCK position is to be set every time the device is removed, while the UNLOCK position is to be selected only during the wearing procedure. The locking mechanism can be activated (switching from LOCK position to UNLOCK position and vice versa) only when the Torque Generator Box is in the rear rest position.

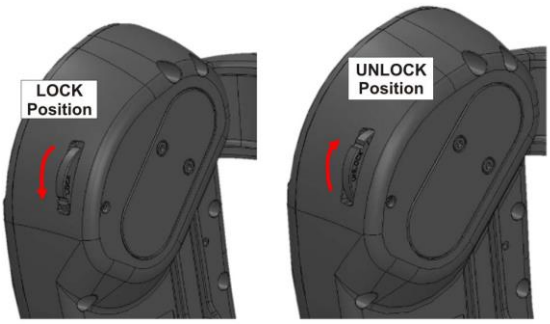


Figure 56. Torque Generator Box (TGB): locking mechanism [57]

4.1.2 Development process

The MATE was born from a collaboration between Comau, Össur and IUVO, a spin-off of the Scuola Superiore Sant'Anna. The three companies combined their experiences and developed the MATE exoskeleton. The development process of the MATE exoskeleton also involved ergonomists and specialists from FCA. It started from the benchmarking and lab tests in FCA of some actual available upper-limb exoskeletons in which their points of strengths and weaknesses were identified. The next phase was an idea generation workshop, following the approach of design thinking. The workshop directly involved workers from FCA, who are the end users of the device, in a day that had the objective of understanding their expectations and needs, and the generation of multiple ideas and concepts for a new upper-body exoskeleton. The workshop was managed by ergonomists from FCA, occupational psychologists and specialists from Comau, and was divided in the following key phases:

1. Understanding the needs and wants of the end users;
2. Creating a point of view that is based on those needs and wants;
3. Brainstorming and creation of the maximum possible number of ideas;
4. Physical construction and representation of the ideas (Figure 57).

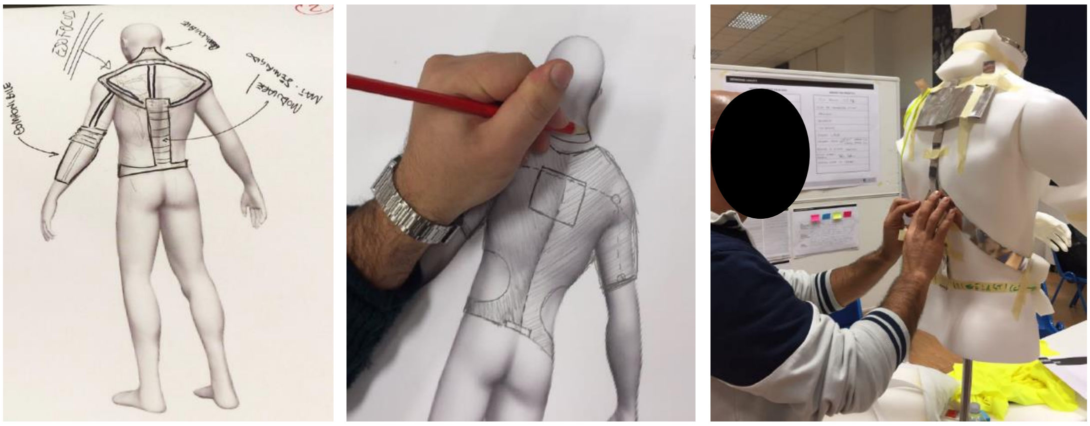


Figure 57. Idea representation and creation in the MATE workshop [FCA]

Subsequently, the design of the exoskeleton was launched, and the first prototype was realized. Thus began the loop of lab testing and redesign/improvement of the prototype. The lab tests were carried out in the "Ergolab" of FCA, where workers participated in tests similar to those described in [23]. The results of these tests were positive, as they showed an improvement in the performance of the required tasks and a reduction in muscle fatigue. All these steps lead to the final product which obtained the ISO 13482 certification and CE marking and then was extensively tested in FCA plants. Figure 58 summarizes the development process of the MATE exoskeleton.

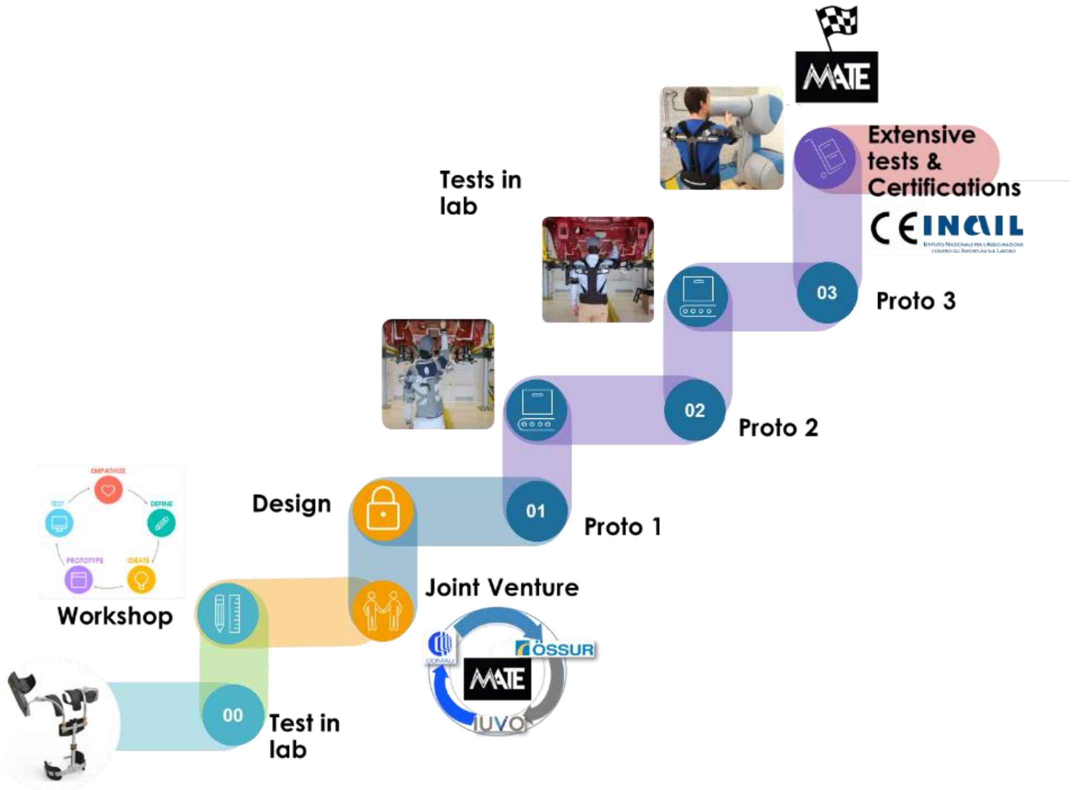


Figure 58. MATE development process [FCA]

4.1.3 Extensive testing phase

As of September 2018, FCA began an extensive testing phase of the MATE exoskeleton in 6 plants in Italy. In total, 25 units were given to the plants, they were divided based on the number of workstations in which the tests will be effectuated: 3 units were placed in Mirafiori plant, 3 in AGAP, 9 in Sevel, 3 in Pomigliano, 3 in Cassino and 4 in Melfi.

The testing phase was divided into 4 parts: On-boarding, Training, Pilot and Follow-up. The on-boarding is a week-long introduction of the exoskeleton to the workers of the plant. In this week, ergonomists from the plant and from the headquarters of FCA, Comau specialists and doctors are involved. In this week, all the involved parties worked to build an understanding of the device by the workers of the plant and to answer all their questions. A booth is set up inside the plant (Figure 59), where all the workers of the plant, even the ones that have workstations where it won't be used, can try on the exoskeleton for the first time and perform some simple tasks (mounting a light-bulb for example) while using it. This allows the workers begin understanding the functionalities of the device and its use.

Figure 59. A trial booth for the MATE in the on-boarding week [FCA]

Subsequently, for every first day at the beginning of every week the plant ergonomists meticulously explain the functionality of the exoskeleton to each voluntary worker that is going to test it and train them on how to use it. During the week, and for the 5 working days, each volunteer can wear the exoskeleton during their work and perform the tasks they normally do. It is recommended that the use of the exoskeleton is incremental, 2 hours for the first day, 4 hours for the second and 8 hours for the rest of the week. This procedure is always followed unless the worker asks to stop the test and remove the exoskeleton.

The extensive testing phase was performed on 84 workstations divided between the 6 plants. In total, approximately 140 volunteer workers participated in the tests, using the device for a total amount of more than 800 hours.

At the end of the testing period, whether it was fully completed by the worker or not, the plant ergonomists administered a follow-up session with questions concerning the usability and acceptability of the exoskeleton. Some recurrent comments about the exoskeleton were received from the workers. These comments are aggregated in the following:

1. **Wearability and fitting**: It’s crucial to fit the exoskeleton through all the recommended regulations in order to optimize the perceived comfort. For this reason, it’s important to increase the number of checks and parameters used to fit the device and to choose the right size. Eventually manufacturer should improve the adjustments available in order to match the main anthropometric requirements. Concurrent the training on the correct use and fitting of the device must be enhanced;
2. **Safety system**: Safety is a key point: it’s not only important to include safety- related elements, but also to reach them autonomously;
3. **Weight, sweating and interference**: Weight remains a core subject, since it is the main annoying issue for all the workers, especially after some hours of use of the exoskeleton. Weight also affects other points: increasing sweating and the possibility of interfering with the workstation.

It can be noticed that the main comments by the workers that participated in the extensive trial phase can be related to the issue of wearability and the correct fitting of the exoskeleton on all people that will use it. As a reason of the incorrect fitting and excessive weight, most of the workers complained of discomfort caused by the exoskeleton.

The same comments were also relevant during benchmark trials of other commercial exoskeletons. Therefore, highlighting the need for a human-centred approach to the design of an exoskeleton, as the human body, in all its variability should be the focal point of the whole design process from its beginning to its end.

4.2 The approach

After the scanning, measurement and analysis of the data, the next step is the surface reconstruction of the scans, so as to obtain a unique fully closed surface. This process permits the generation of a closed triangle mesh with no overlaps of the patches, i.e. it combines separate surfaces to create one surface and closes all wholes/gaps the 3-D scan may feature (Figure 60).

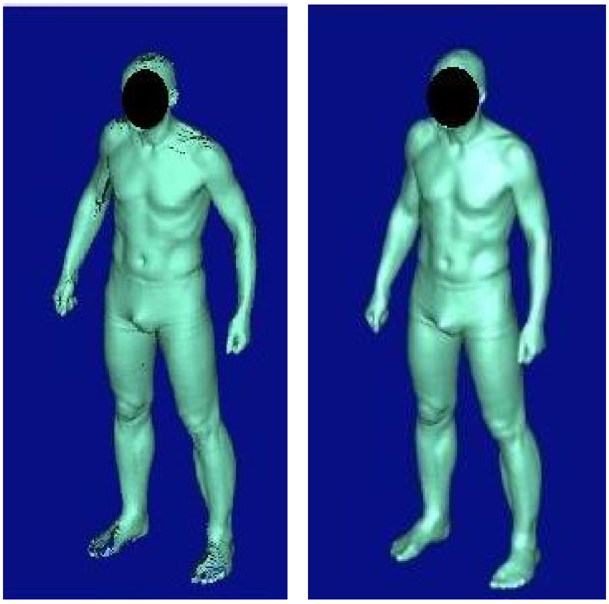


Figure 60. Left: Scan as is, right: scan with reconstructed surface [Anthroscan]

In order to ensure the privacy of the subjects scanned, after the reconstruction of the surface of the scans, a process of anonymization is executed. This process consists in transforming the scans into what the Anthroscan software calls a “homodel”, which is a humanoid that has the same envelope and definition of the real scan, but with a manikin-like face and less pronounced features, so as to render the scan unrecognizable and untraceable to the original subject (Figure 61).

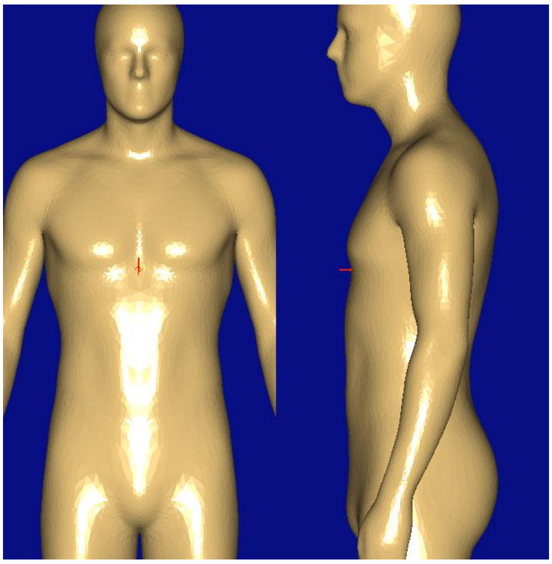
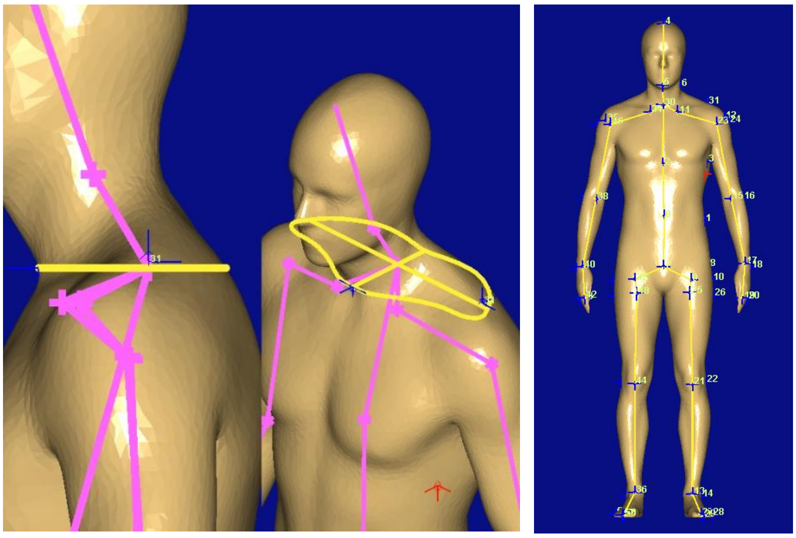


Figure 61. "Homodel" of a scan [Anthroscan]

The subsequent step is to export the reconstructed anonymized "homodel" scans into common file formats that can also be used in other softwares. The chosen file formats were ".obj", a geometry definition file format and ".stl" (stereolithography) a file format that consists of triangulated surface meshes. Both files are widely used to represent 3-dimensional objects, with the ".stl" format being particularly used in 3-D printing and computer-aided manufacturing.

Subsequently, starting from the "homodel" scans of the subjects, in "standard posture", it is possible to create a virtual model of the skeleton for each subject using the Anthroscan software. This skeleton consists of segments and joints and is a simplified virtual model of the real human skeleton.

The Anthroscan software allows the choice of multiple joints and landmark points, starting from the head and proceeding down to the toes (Figure 62). The placement of the joints is, of course, not random as the location of the joints affects the potential movement of the skeleton and it should be as similar as possible to the real human skeleton. While "creating" the skeleton, the software shows the joints and points to be chosen and suggests their location, by comparing the scan of the subject to a reference scan present in the system. The user can then modify the location of the joints in 3-D space, so as to have the correct placement.



Joints and Landmark Points
Forehead Point
Head, Neck Joint
Neck Base Joint Left and Right
Shoulder Joint Left and Right
Chest Joint
Elbow Joint Left and Right
Belly Joint
Wrist Joint Left and Right
Hand Point Left and Right
Hip Joint
Joint In-Buttock Height Left and Right
Femoral Joint Left and Right
Knee Joint Left and Right
Foot Joint Left and Right
Toe Joint and Tip Point Left and Right

Figure 62.Left: neck joint, right: full "Homodel" scan with joints and landmark points of the skeleton created in Anthroscan

The created skeleton is then saved in ".bvh" format; this format is a character animation file format usually used as an output of motion capture data, this is also the format used to export the skeleton file in the Anthroscan software.

The "homodel" scans and the skeleton can only be exported separately and therefore need to be combined in order to form a virtual manikin that has the outer skin of the scan and the movement of the skeleton.

This combination process is executed with Blender, an open-source 3-D computer graphics software, usually used for 3-D animation and modelling. The choice of using Blender was influenced by the fact that it is available to use freely, flexible and has the capabilities to perform the needed requirements of this approach. Although, it is not intuitive to use, Blender is quite commonly adopted by 3-D animators and modelers, and therefore, instructions/videos on how to use it are easily available online. This was also one of the motivation factors for its choice.

After importing both the scan (in ".stl" format) and the skeleton in Blender, the combination of the two can be performed. This is done using the function "Parent with Automatic Weights" that allows the coupling of the scan to the skeleton, as if the skeleton was the "Parent" that guides the movement of the couple "scan-skeleton", this function also permits the deformation of the scan with to the movement of the skeleton which renders the coupling more realistic. Figure 63 shows the coupling of a scan to its corresponding skeleton.

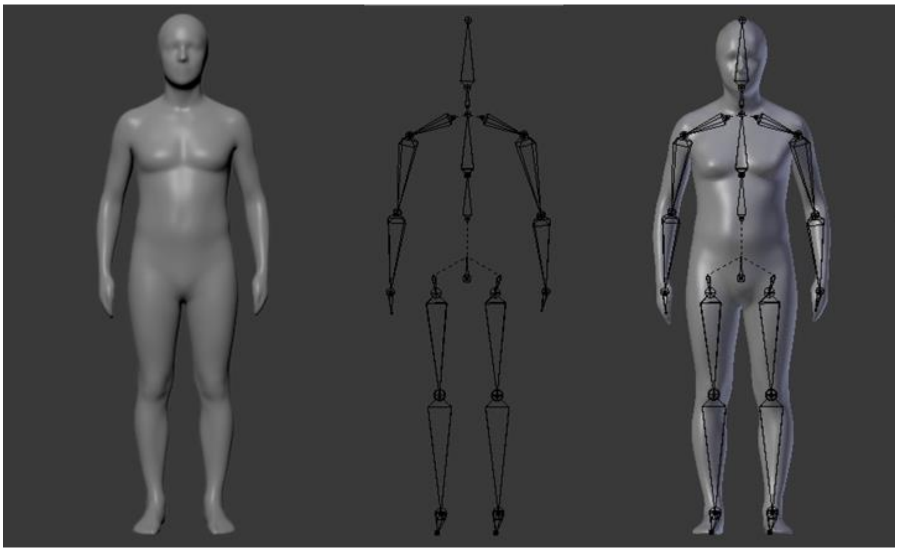


Figure 63. Coupling of the scan to the skeleton in Blender

In order to have a realistic movement of the humanoid and to avoid having to move each bone of the skeleton individually, the inverse kinematics function is used. By creating two new bones, that serve as end effectors, for the left and the right arm, it is thus possible to move the arms by controlling just the two end effector bones that are connected to the hand bones (Figure 64).

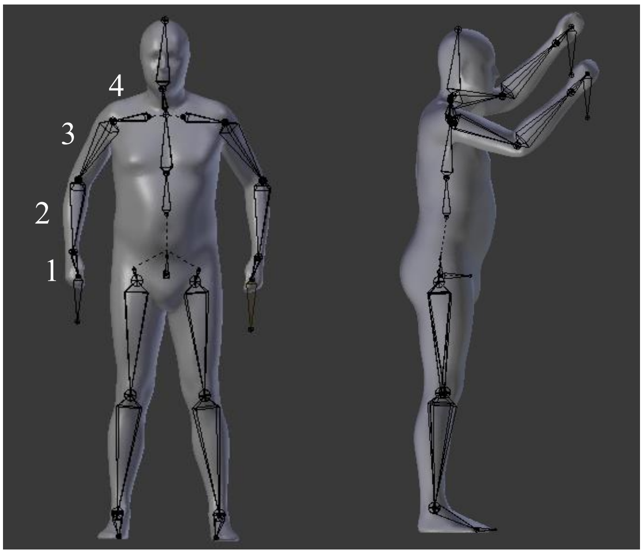


Figure 64. Example of movement of the humanoid with the end effector bones

The joints of the human body have natural ranges of movement, the average joint motion ranges chosen were adapted from [58]. For each bone of the upper limbs, the rotation limit around the local axes X, Y and Z are summarized Table 23.

Table 23. Bone rotation limits around the local axes of the upper limb-bones

Bone Name	Rotation around X	Rotation around Y	Rotation around Z
Hand (1)	From -23° to 24°	Unconstrained	From -90° to 99°
Forearm (2)	From -180° to 0°	Unconstrained	From -45° to 45°
Shoulder (3)	From -134° to 48°	Unconstrained	From -180° to 61°
Collar (4)	From -20° to 20°	From 0° to 20°	From -90° to 0°

Subsequently, after the process of animating the human models, the animation of the exoskeleton can be done. This is done by exporting the exoskeleton from the CAD software where it was designed into ".stl" format and then importing it into Blender. Successively, the superposition of the exoskeleton onto the human model is performed.

As previously mentioned, the wearability and fit of the exoskeleton is verified first and then the movement can be simulated. This is done in 2 steps:

4.2.1 Step 1: Static verification

The exoskeleton is adjusted to have the correct fit on the model. The parts of the exoskeleton that are designed to be physically adjustable to adapt to different persons (such as straps, belts, length of the back structure, etc.) are the ones adjusted in this step.

The exoskeleton is fitted on the virtual manikin visually ensuring that the wearability is verified. In this case study, since the approach is applied to an existing exoskeleton, the recommendations of the fitting of the exoskeleton specified by the manufacturer are followed.

In Figure 65 an example of the incorrect fitting of the MATE exoskeleton is shown, as the Torque Generator Box is in direct contact with the shoulder of the wearer, in this case the rear elastic straps are too tight and the rear sliding element is working at its limit.
However, Figure 66 shows the correct positioning of the Torque Generator Box, as it is 1 cm away from the shoulder and the sliding element is working in the correct central position.

Another incorrect example of the fitting of the MATE could be the misalignment of the center of rotation of the Torque Generator Box with the center of rotation of the shoulder. All These verifications are done in Blender when the exoskeleton is fitted on the virtual manikins.

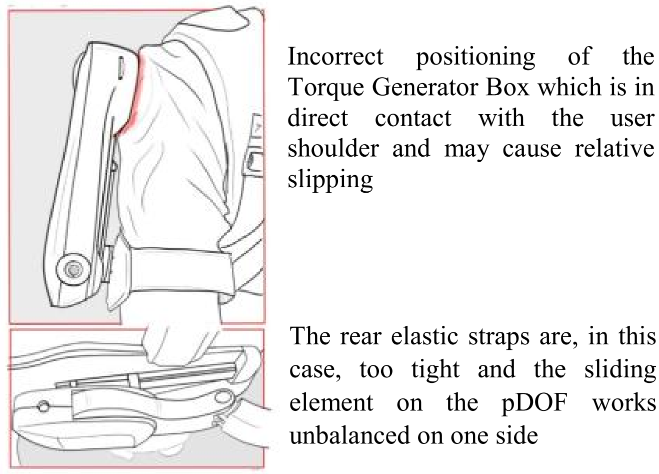


Figure 65. Incorrect positioning of the Torque Generator of the MATE exoskeleton [57]

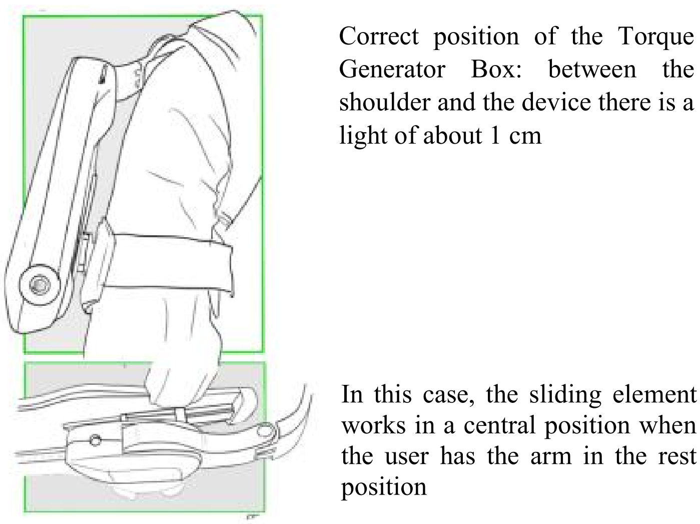


Figure 66. Correct positioning of the Torque Generator of the MATE exoskeleton [57]

An example of the incorrect positioning of the torque generator is shown in Figure 67. Here the Torque Generator Box is in contact with the manikin and thus the fitting is no optimal. On the other hand, Figure 68 shows the correct positioning of the Torque Generator Box, as required by the manufacturing company.

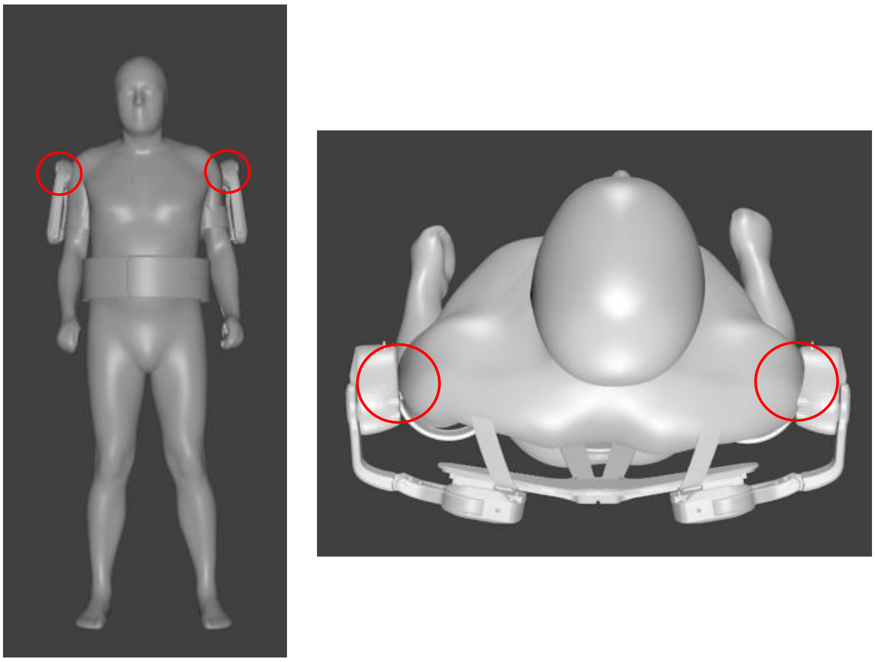


Figure 67. Incorrect fitting torque generator box of the MATE as seen in Blender

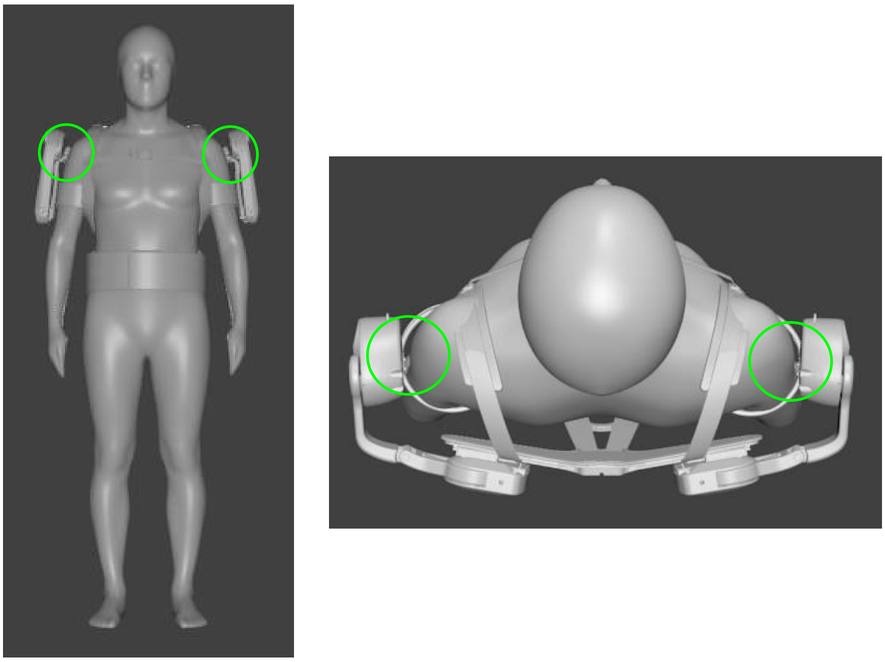


Figure 68. Correct fitting torque generator box of the MATE as seen in Blender

4.2.2 Step 2: Dynamic Simulation

After the verification of wearability of the exoskeleton, the second step is the dynamic simulation of the movement of the exoskeleton while it is coupled to the virtual manikin. This is the coupling of the exoskeleton to the human model. Thus, the movement of the exoskeleton will be controlled by that of the human, similarly to when it is worn in real contexts.

Comparably to the human model, the exoskeleton must have its own "bones" in Blender in order to consent its movement. Thus, the third step in the animation of the exoskeleton is the creation of two armatures (left and right). The armatures are made of a set of connected bones of which the limits of rotation and translation are then set.

The bones are created for the following parts of the MATE: the horizontal axis hinge, the vertical axis hinge, the horizontal axis rear sliding elements and the torque generator box. As before, in order to have a realistic movement, another bone is needed to act as the End Effector.

The bones created for each armature, are the following (Figure 69):

1. Horizontal sliding bone
2. Horizontal axis hinge bone
3. Vertical axis hinge bone
4. Torque generator bone
5. End effector bone

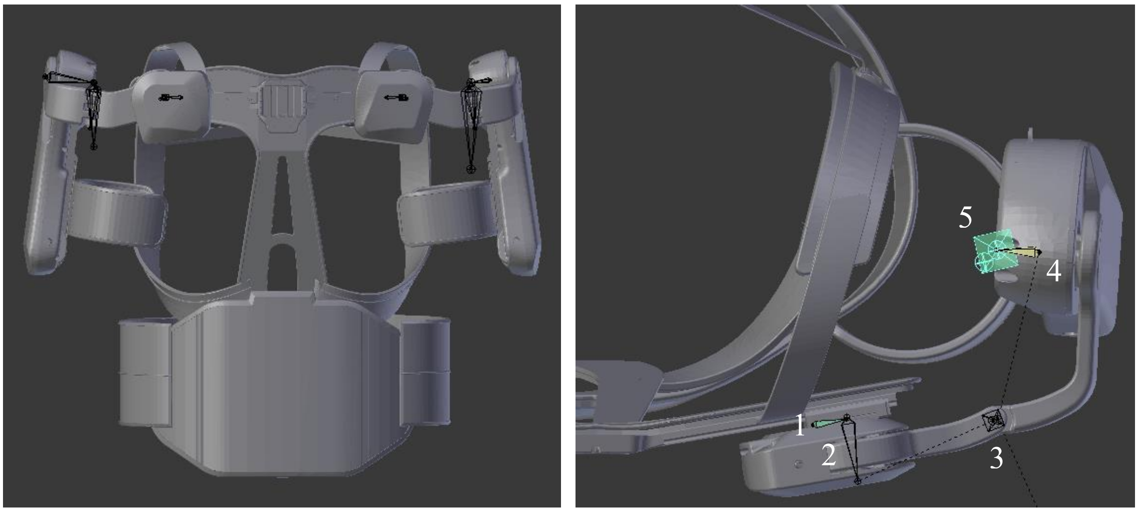


Figure 69. Left: MATE with the 2 sets of armatures, right: detailed view of the bones

In reality, the moving parts of the exoskeleton have rotation and translation limits, therefore these limits have to also be imposed on the corresponding bones. The sliding bone can only translate along its local Y-axis while the other bones are rotating bones. The limits of rotation for these bones around their local X, Y and Z-axes are shown in Table 24.

Table 24. Rotation limits around the local axes of the exoskeleton bones

Exoskeleton Bone	Rotation around X	Rotation around Y	Rotation around Z
Horizontal axis hinge	Blocked	From 0° to 70°	Blocked
Vertical axis hinge	Blocked	From -60° to 90°	Blocked
Torque Generator	Blocked	From 0° to 120°	Blocked

The coupling is performed by making the end effector bone of the exoskeleton follow the shoulder bone of the virtual manikin, using the function “copy location”. This gives the virtual model of the exoskeleton a realistic movement.

The dynamic simulation is performed by operating on the end effector bone of the skeleton of the human model, in a way to have the upper limbs perform all the movements that are realistically possible while wearing the exoskeleton, such as abduction, adduction, extension and flexion.

The main movement that is replicated in this simulation is that of raising the arms above shoulder level to where the shoulder is at a 120° from the starting rest position (arms along the body), as shown in Figure 70.

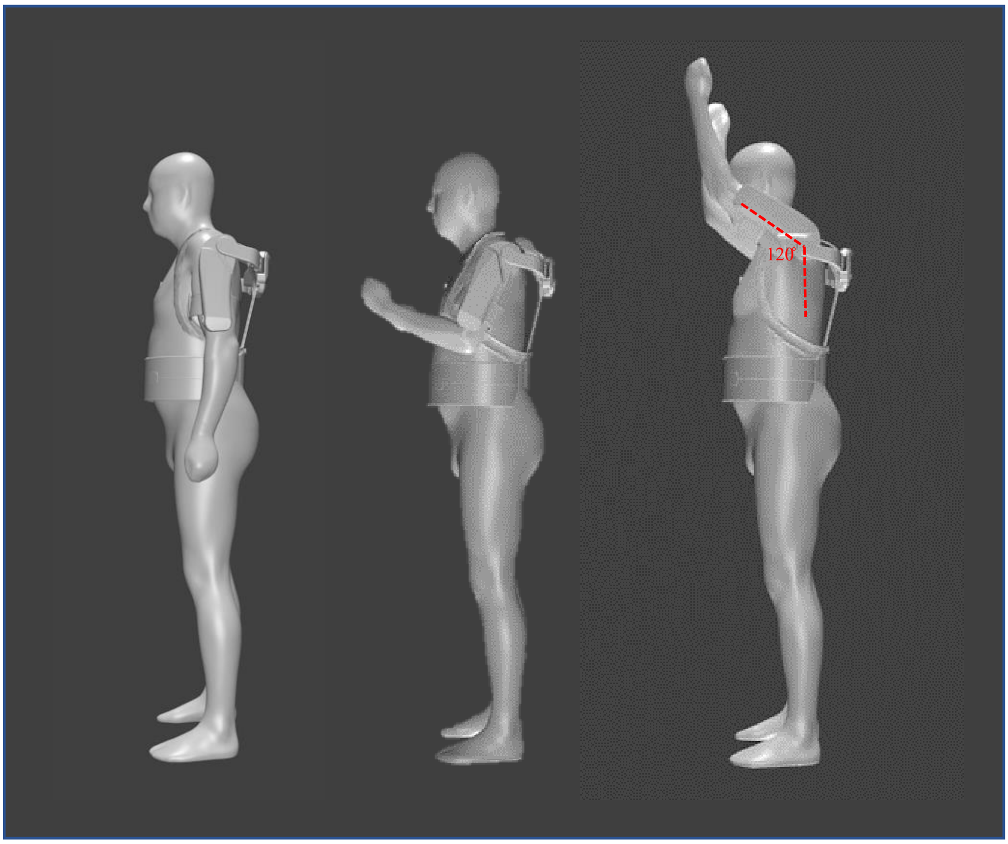


Figure 70. Dynamic simulation of the movement of the exoskeleton

As previously mentioned, the MATE comes in 2 sizes: S/M, and L/XL that can be further regulated to allow the correct fitting of the exoskeleton. The choice of the size depends on the anthropometric measurements of the user, to facilitate the choice, Comau provides indications (Table 25) according to the height and size of clothes of the user.

Table 25. Indications for the choice of the MATE exoskeleton

	Suggested MATE exoskeleton size		
	Clothes size (Italian)	Stature (cm)	Exoskeleton size
Male	44-48	164-176	S-M
	50-60	175-196	L-XL
Female	36-48	154-176	S-M
	50-52	175-182	L-XL

For the fitting of the exoskeleton on the human model, the appropriate sizes must be chosen. Due to time restrictions, the approach was applied only to the human model that represents the 50th male percentile of the FsM project. The 50th male percentile has a stature of 175 cm therefore the L/XL size was chosen for the simulation. In the future, after having identified the subjects that represent the 5th, 50th and 95th percentile of both the female and male samples, the approach can also be applied to them, so as to ensure the exoskeleton fits the extremes of the human anthropometric dimensions.

The dynamic simulation consists of the verification of the expected movement of the exoskeleton. Criticalities, such as unsafe or unwanted movements, can be easily observed. This simulation allows the designer to foresee the real movement of the exoskeleton while still in the design phase. Thus, the designer can avoid the long iteration cycle of physical prototyping, testing and redesign.

4.2.3 Summary

As a summary, the approach proposed in this thesis is illustrated in Figure 71. The approach starts from the 3-D body scanning of male and female sample populations. The scans are transformed into 3-D manikins and their corresponding skeletons are created. Subsequently, by coupling the skeleton and the manikin, the human model is created. The design of an exoskeleton can be executed, based on this 3-D model, as shown in [56]. The design takes into

account many requirements, such as the final application of the exoskeleton, the type of the exoskeleton, and the business and market strategies of the manufacturing company.
After the exoskeleton is designed, the pairing of the exoskeleton and the human model, i.e., the virtual prototype, is then tested. First statically and then dynamically. An FEM analysis for the exoskeleton can also be performed.

If the testing phases give acceptable results, the physical prototypes can then be realized, otherwise the redesign of the exoskeleton components is necessary, and the iteration is performed again until reaching the required output. The physical prototypes that are realized can then be further tested in real conditions, either in labs or in plants, similarly to the traditional method.

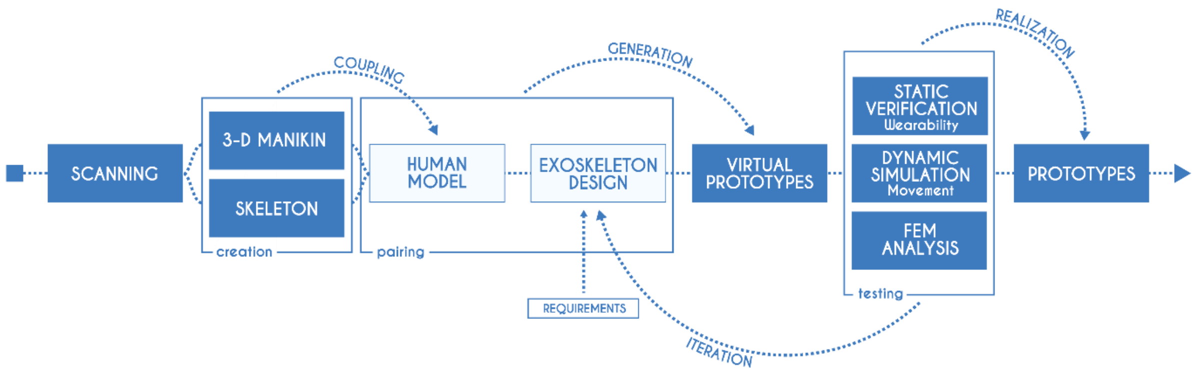


Figure 71. The proposed approach

Future developments of the approach can include the use of thermography scans of healthy workers before, during and after the work shifts. This could help the designers understand the critical hottest spots of the human body and ensure that the exoskeleton provides the correct breathability in such spots at all instances of use.

Another future development could be the addition of a fourth testing phase, that includes the use of software such as OpenSim, to perform biomechanical kinematic simulations of the exoskeleton with musculoskeletal models. This phase would be of specific interest to the design of active exoskeletons, such as in [56][59].

Conclusions

The presented thesis proposes a human-centred approach, based on the principles of Industry 4.0, to design and apply effective wearable devices such as exoskeletons. Extrapolating from scientific literature and comments of final users that participated in trials of exoskeletons, it is important to underline that the use of anthropometric data in human-centred design, is a key feature to ensure the success of a wearable device in the current market.

The proposed approach starts from the 3-D scans of male and female samples and details the steps required to achieve the required results of the design process. The approach is firstly applied to an existing commercial passive upper-limb exoskeleton: The MATE exoskeleton, but it can also be applied to a new exoskeleton.

The advantages of the proposed approach lie in the time and resources that can be saved by applying it. An extensive cycle of prototyping – testing – redesign, can be fully done in virtual settings, thus gaining valuable time, human and capital resources that would have otherwise been used if the cycle was done in physical settings. The approach allows designers to anticipate the outcome of their design, and to act accordingly, early in the design phase.

The proposed approach highlights the need of a new classification of wearable devices, based not only on the main features such as type and power but also on the final goal of the application of such devices and the benefit that it would incur. For what concerns the application of exoskeletons to the industrial sector in general and to the automotive sector in particular, there is no consensus on the legislative definition of exoskeletons when it comes to the health and safety of workers. At the present time, two main definitions could be applied to exoskeletons: work equipment or personal protective equipment.

Article 2 of Directive 89/391/EEC defines 'work equipment' as: any machine, apparatus, tool or installation used at work. This is a wide definition that can also be applied to exoskeletons. While the Italian legislation, in article 69 of the Legislative Decree 81/08 defines "work equipment" as: any machine, appliance, tool or system, intended as the complex of machines, equipment and components necessary for the implementation of a production process, intended for use during work. The key difference here between the two legislations is the necessity of the work equipment for the implementation of a production process, and whether exoskeletons fall within the Italian definition of a work equipment.

On the other hand, a personal protective equipment (PPE) is defined as any device or appliance designed to be worn or held by an individual for protection against one or more health and safety hazards, in both the Italian and European legislations previously mentioned. Similarly, it is necessary to understand whether exoskeletons should be considered as personal protective equipment as some companies have already done, such as Toyota that has made the AIRFRAME exoskeleton mandatory personal protective equipment in two of its plants in the US [41].

Discussing this issue, the authors of [60] propose the division of exoskeleton into 3 different categories depending on the intended application:

1. Assistive exoskeletons: that have the exclusive purpose of assisting the worker in performing the required tasks while improving the production output (qualitatively and quantitively) and thus can be defined as work equipment;
2. Protective exoskeletons: that have the exclusive purpose of reducing the risk of work-related injuries or musculoskeletal disorders for the worker that use them. These can be defined as PPE if they abide by the respective standards and obtain the necessary certifications;
3. Mitigative exoskeletons: that are hybrids of the previous two categories as they augment the capacity of the workers while also inducing a positive effect on their

health. For this category the authors acknowledge the need to update the legislations concerning workers safety and health.

In conclusion, it is thus clear that current legislations and standards are lagging when it comes to wearable devices. It can be said that exoskeleton technology is still in its infancy when it comes to both the design and application areas. Many developments are yet to come, but one thing is clear, exoskeletons must always be thought of as devices that compliment humans and thus their designs must be centred around the human body with all its needs, limits and capabilities.

Appendix

This appendix contains the full list of the 193 measurements taken by the 3-D body scanner.

3D waist band	Crotch length, front	High waist girth	Sideseam at waist right
3D waistband back height	Crotch length, rear	High waist height	Sideseam left
3D waistband back to vertical	Dev. waist band from waist (back)	Hip Breadth	Sideseam right
3D waistband front height	Dev. waist band from waist (front)	Hip Breadth sitting	Sitting Acromial Height
3D waistband front to vertical	Dev. waist band from waist (side)	Hip girth	Sitting Eye Height
3D waistband left to crotch	Distance 7CV - vertical	Hip height	Sitting Knee Height
3D waistband right to crotch	Distance abdomen to vertical	Hip/thigh girth	Stature
Abdominal Depth	Distance across back width (armpit level) - waist	Inseam left	Thigh Clearance
Acromion Height	Distance back in belly height to vertical	Inseam right	Thigh girth left (horizontal)
Across back width	Distance back in breast height to vertical	Inside leg-ankle left	Thigh girth right (horizontal)
Across back width (armpit level)	Distance back in hip height to vertical	Inside leg-ankle right	Thumbtip Reach
Across front width	Distance back in maximum belly height to vertical	Interpupil Distance	Tibial height
Ankle girth left	Distance belly to vertical	Knee girth left	Torso width at waist
Ankle girth right	Distance breast to vertical	Knee girth right	Total torso girth
Ankle height	Distance buttock to vertical	Knee height	Trochanter Height
Ankle Height	Distance crotch to waistband	Knuckle height	Underbust circumference (horizontal)
Arm Length	Distance front in hip height to vertical	Maximum belly circumference	Upper arm diameter left

Arm length left	Distance maximum belly to vertical	Maximum belly circumference height	Upper arm diameter right
Arm length right	Distance neck front to vertical	Mid neck girth	Upper arm girth left
Arm length to neck back left	Distance neck to buttock	Middle Hip	Upper arm girth right
Arm length to neck back right	Distance neck-knee	min. leg girth left	Upper arm length left
Arm length to neck left	Distance scapula to vertical	min. leg girth right	Upper arm length right
Arm length to neck right	Distance waist back to vertical	Neck at base girth	Upper torso torsion
Belly circumference	Distance waist-knee	Neck diameter	Waist band
Belly circumference height	Distance waistband - buttock	Neck front to waist	Waist girth
Biacromial Breadth	Distance waistband-high hip back	Neck front to waist over bust line	Waist height
Bideltoid Breadth	Distance waistband-knee	Neck height	Waist to buttock
Body Depth	Elbow Fingertip	Neck height front	Waist to buttock height left
Body height	Elbow girth left	Neck left to waist back	Waist to buttock height right
Breast height	Elbow girth right	Neck right to waist back	Waist to high hip back
Bust point to neck left	Elbow Height	Neck right to waist over bust	Waist to hip/thigh left
Bust point to neck right	Elbow Rest Height	Neck to across back width (armpit level)	Waist to hip/thigh right
Bust points around neck	Elbow to Elbow Breadth	Neck to waist center back	waistband back height
Bust points width	Eye height	Pelvis Width	waistband back to vertical
Bust/chest girth	Foot Breadth	R1.07	waistband front height
Bust/chest girth (horizontal)	Foot Length	scapula height 2	waistband front to vertical
Buttock girth	Forearm girth left	Seated Height	Waistband height
Buttock height	Forearm girth right	Shoulder angle left	Waistband to buttock height left

Buttock Knee Length	Forearm length left	Shoulder angle right	Waistband to buttock height right
calf girth left	Forearm length right	Shoulder Elbow Length	Weight
calf girth right	Hand Breadth	Shoulder width left	Width armpits
Cervicale height	Hand Length	Shoulder width right	Wrist girth
Chest Width	Head Breadth	Side upper torso length left	Wrist girth left
Cross shoulder	Head circumference	Side upper torso length right	Wrist girth right
Cross shoulder over neck	Head Height	sideseam 3D waistband left	
Crotch height	Head height	sideseam 3D waistband right	
Crotch length	Head Length	Sideseam ankle left	
Crotch length at waistband	Height of shoulder blades	Sideseam ankle right	
Crotch length at waistband A	High hip girth	Sideseam at waist left	

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