Robo.Mate

Intelligent exoskeleton based on human-robot interaction for manipulation of heavy goods in Europe's factories of the future

Project Final Report

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1. Executive summary

Even though trends in industry seem to be directed towards higher levels of automation, significant amounts of manual handling tasks exist and will remain in most industries. Manual handling tasks are always associated with risks for the health of the human worker. Direct and indirect costs related to health issues of the workers are substantial and the main source are musculoskeletal issues and injuries, which are often related to lifting and carrying of goods and tools.

The Robo-Mate exoskeleton is based on a modular design. By selecting the modules which fit a specific task best, the human is less impeded by the exoskeleton and the weight can be significantly reduced. We designed a trunk module, which is actuated at the hip of the worker and reduces the compression forces in the lower back. Two different arm modules were developed. The passive arm uses springs only to support the worker with a constant force counteracting gravity in the lower arm. The active arm is motor driven and the force can be dynamically adjusted depending on the load carried in the hand. In addition, the human machine interface module interacts with the exoskeleton but also can be used as a production advisory system. With the trunk and arm modules, by reducing the forces and moments acting on specific parts of the body, the worker can be protected from injuries to the musculoskeletal system.

To develop and validate the system, many more important activities were carried out. As no industrial standard for exoskeleton systems exists, the experience gathered during all the phases was used to liaise with the standardisation bodies to drive the development of existing and potentially new standards. To analyse the benefit, the Robo-Mate modules were integrated into a digital factory environment allowing to directly assess the physical loading of the human worker. To validate the functionality and the usefulness of the modules, tests in a laboratory setting where the physical effect on the user's body was investigated. As hoped, the test proved that the stress in the lower back is reduced. However, the benefit is less pronounced than expected. All modules were thoroughly tested in an industrial setting by workers usually performing the same tasks. A promising result is that cycle time was not significantly changed, giving hope that an exoskeleton may well be an option for the future. Feedback from the workers was received and evaluated, giving valuable suggestions to improve the technology in the development of a product.

Robo-Mate attracted the attention from industry and the media from the beginning, even at a time when we had only plans and nothing concrete to show. We thus decided to concentrate our resources on attracting not just *more* attention but on attracting the attention specifically of organisations with a high potential for a collaboration after the end of the project. With these organisations we were then in close contact, showed them our prototypes, discussed potential application areas and possibilities for future collaboration. These measures were successful in that follow-up R&D projects are planned/have started, start-up preparations have been made and pilot tests/partnerships with companies are negotiated after the official project end.

2. SUMMARY DESCRIPTION OF PROJECT CONTEXT AND OBJECTIVES

2.1. Introduction and project objectives

2.1.1. Industry challenges and demands

Production efficiency relates the rate of production to the use of resources and the quality of the goods being produced. Increasing production efficiency is often the main driver for automating production steps. However, by automating production the flexibility to vary products decreases [1]. Therefore, for small lot sizes automation does not increase production efficiency, as the related costs cannot be distributed on large product volumes. In addition, the human worker has sensory and manual skills, which are unchallenged in respect of flexibility. It is therefore often more attractive and therefore cost effective to keep a worker in the production steps. To optimise production efficiency many facets are considered. These include *i)* lot sizes *ii)* quality *iii)* production complexity *iv)* seasonal aspects or limitations *v)* health aspects and many more.

The Robo-Mate project focuses on the needs identified by extensive evaluations of our end-users production processes. These production processes vary significantly from each other. For *CRF* the production process is a classic automotive production line with a very high automation level with very similar products, for *Indra* it is a dismantling line for cars, where every car is different (small lot size, no automation) and for *Compa* these processes produce mainly isolated components for the automotive industry with a medium level of automation. Robo-Mate has therefore a potential to be used in many industries in Europe.

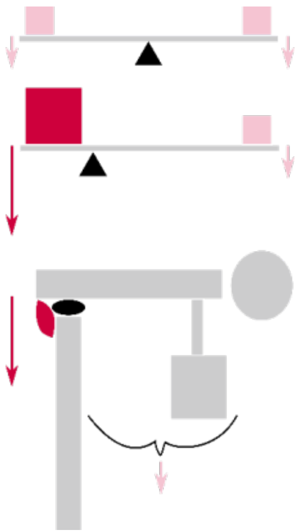
Based on the extensive discussions with our end-users in the consortium, we defined the following two use-cases:

1. Two handed manipulation of goods between 5 and 15 kg targeting frequent lifting, carrying and lowering of goods.
2. One handed positioning of an object up to 7.5 kg targeting postural support (e.g. for handling tools).

2.1.2. Health issues and worker's needs

We limited our use-case to loads below 15kg. For frequent manipulations, ergonomic indicators like [2] assess high risks for lifting and carrying objects. According to the European Council directive [3] the employer needs to take appropriate measures to avoid the need for manual handling. Especially for loads above 20kg, solutions (manipulators) to support the manual handling task exist and are available on the shop floor. It is known that companies have difficulties in enforcing the usage of these manipulators for light loads and for frequent manipulations. This relates to the fact that the actual load is still manageable for the worker and using the manipulator slows down the task considerably. Therefore, finding new solutions, which do not slow down the worker in their tasks and support the worker are necessary.

According to [4] about 44 million EU workers are affected of musculoskeletal conditions resulting in annual costs of more than 240 billion Euro to the European economy. Similar numbers are found in Switzerland [5] and in the United States [6]. Typically, the companies visited reported a fraction between 30% and 50% of their staff having musculoskeletal issues, confirming indirectly therefore these studies. The majority of musculoskeletal issues relate to lower back pain. In particular, back pain can be caused by a specific pathology or be unspecific (more than 90% of the cases) caused by muscle tension or stiffness [7]. To balance the body, muscles contract and this results in significant compression forces acting on the skeletal structure but also on other muscles and ligaments. This is visualised on the figure to the left. The body can be viewed as a scale. Scales with a symmetric pivot will need the same weight on both sides to balance. Scales with an unsymmetrical pivot however will have a much heavier weight on the short arm. In the latter case, the pivot as such needs to sustain a much higher force than in the former. The human body is especially for lifting tasks an unsymmetrical scale. The force to balance the upper body is generated by the muscles of the lower back. The resulting compression forces act therefore on the musculoskeletal structure and spinal discs. Even without carrying heavy loads, frequent lifting and maintaining postures over longer periods increase the risk of injury significantly. Companies in Europe are seeking new solutions to protect their workers as health care providers and insurances are unwilling to carry costs generated by high risk activities.



All these considerations were confirmed in the many visits to our partner's production sites and to potential end-users outside the consortium.

2.1.3. Project objectives

The project addresses not only the identification of the industrial need and the corresponding electro-mechanical design of the exoskeleton. It also focuses on objectives, which are important for the introduction and the use of an exoskeleton in an industrial setting.

Today many production processes, especially in the automotive industries, are optimised in respect of cycle efficiency and ergonomic indicators by simulating the production line in a digital environment [8]. It is therefore necessary to integrate the exoskeleton into this digital simulation environment. For the future evaluation of an exoskeleton for a specific task, the simulation will be able to show the requirements to successfully use an exoskeleton and the potential benefits reached for specific tasks.

The use of an exoskeleton suggests that there is an ergonomic benefit for the user or a benefit in respect of production efficiency. To proof the benefit in respect of production efficiency a series of end-user site tests were performed and evaluated against the a worker without an exoskeleton. These tests were performed on the shop floor at our partner's sites. The suggested ergonomic benefit needs to be addressed as well by investigating the muscle activities of the worker. When using an exoskeleton the distribution of the forces acting on body are differently distributed. This may have a negative impact on other body parts of the user [9]. For this purpose laboratory testing, where muscle activity and qualitative measures can be recorded for well defined tasks need to be performed and evaluated.

A very different aspect are regulatory and safety related issues when using exoskeletons in an industrial setting [10]. In general, the industry follows corresponding standards to ensure a safe operation of a device like a robot. For exoskeletons, these standards need yet to evolve and therefore it is still very difficult to introduce an exoskeleton to the shop floor for regular use. Within the Robo-Mate projects a set of activities was carried out to drive and develop standards relating to the development of such devices and the use of them in an industrial setting.

2.2. Concept of the Robo-Mate exoskeleton

2.2.1. Considerations

The Robo-Mate exoskeleton concept is best understood by two main considerations represented in Figure 1, where the supporting force is shown against a qualitative complexity measure. The complexity measure includes many system characteristics like the number of used sensors and actuators, mass and volume of the exoskeleton, but also power requirement and safety measures.

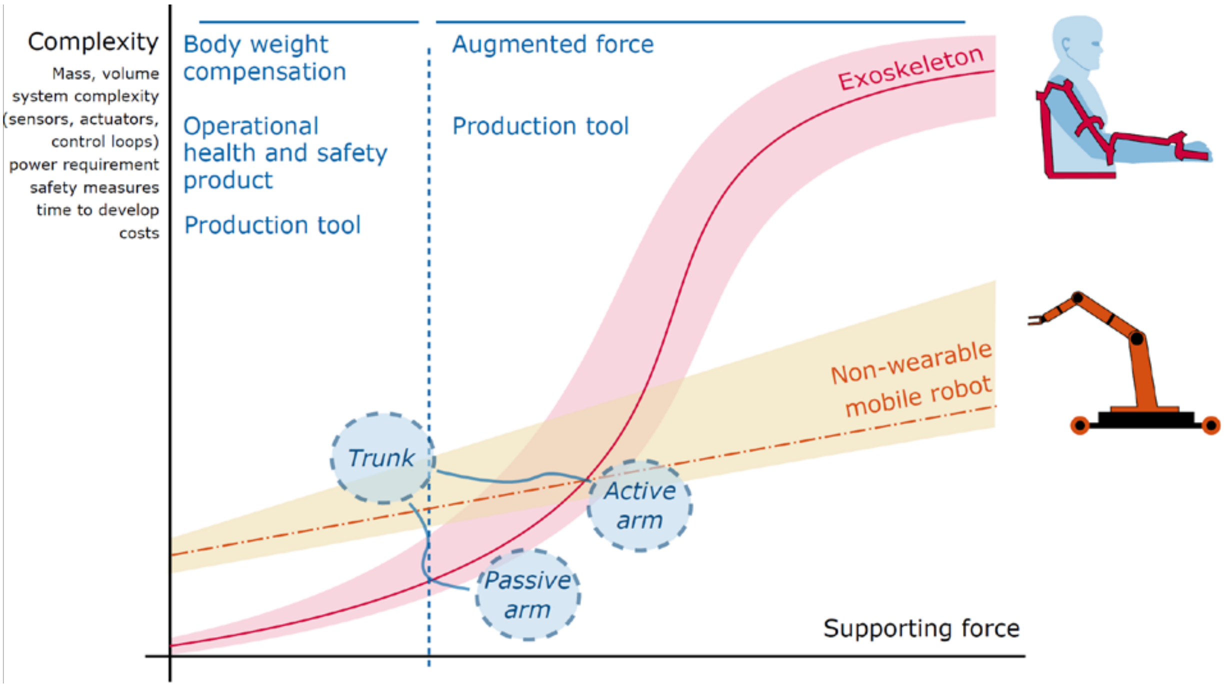


Figure 1: System complexity versus supporting force for an exoskeleton and a non-wearable mobile robot

The complexity scales as a function of the supporting force. To compare the scaling of an exoskeleton the scaling of a non-wearable mobile robot is used as a benchmark. We are convinced that the non-wearable mobile robot satisfies the main industrial needs for carrying, lifting and positioning of objects. Starting at the lowest possible supporting force throughout to the largest, the same functionality is available in the robot. Resulting in approximately a constant scaling rate. For an exoskeleton and low supporting forces, i.e. in the range of the users own bodyweight, the goal is to compensate partially gravity, which can be solved by using springs only or by using only additional actuators but without an additional skeleton. Increasing the supporting force will however require at some stage motors and sensors to be added. Hence, this will start driving the complexity and as the exoskeleton is worn by a human, costly light-weight materials, safety measures and ergonomic and hygienic aspects will boost the complexity beyond the complexity of the non-wearable robot. From this it is clear that moving up the supporting force axis too far, means that the non-wearable robot is probably the better solution to the problem. For exoskeletons it important to focus on the lower end of loads.

A second aspect considered is that not all tasks should be handled by the same exoskeleton. Any functionality beyond the needed functionality will increase the exoskeleton weight. The weight is crucial, as most of the user's movements will not be supported. Excess weight will lead to impeded movements and quicker tiring and therefore to low acceptance by the workers. Moreover, some simple tasks may only need the user's body weight to be compensated. Others may need a sophisticated intention detection scheme and actuation principle to support the worker appropriately.

Hence, the variability of the tasks considered ask therefore for an exoskeleton, which can be adapted to a specific task.

An interesting concept is to compensate body weight only even though the worker may be holding an object of significant weight. Simulations show that approximately 60% of the compression force in the lower back when stoop lifting result from the workers own body and 40% of a 25 kg load held in the hands. It should be noted that holding a weight in upright posture even of 25 kg does in general not produce a critical compression force. The compression forces for stoop lifting are on the other hand in this case beyond the mark where it is considered safe. Considering these facts, postural support during lifting and positioning results in an operational health and safety product, rather than in a tool to enhance production efficiency and flexibility (see Figure 1). Obviously, the benefit in respect of production efficiency and flexibility results indirectly by keeping the worker in the production process. Nevertheless, the range where an anthropomorphic exoskeleton is beneficial as a production tool is narrow (low to mid supporting force range). Moreover, uncertainty related aspects lead to the conclusion that the success of such a design may be questionable. Considering our limited development time and the beneficial position of a non-wearable mobile robot for high supporting forces it seems a good idea to modularise the anthropomorphic exoskeleton and to start from the lower end of the supporting force range where the anthropomorphic exoskeleton has a lower complexity index than the non-wearable mobile robot.

2.2.2. Modular exoskeleton concept

Based on these considerations we decided on the following design concept:

- The exoskeleton should be modular to be adaptable to different tasks and to remove functionality (i.e. weight) where it is not needed.
- A core trunk module (anthropomorphic) with the main goal to reduce the compression forces in the lower back and providing a base for arm extensions.
- A selection of different arm modules, which can be connected to the core trunk module. The arm modules can be passive, partially or fully activated and can be anthropomorphic or not. The arm modules are designed to support the use case defined.
- A minimal number of actuated joints should be targeted to minimise weight.
- Objects are held in the workers hand, no grippers will be used.

In Figure 1, these main modules developed are placed to indicate their complexity. In particular, the trunk module seems to reach beyond the reasonable range. Here the intention is to add the arm modules to the trunk module. Therefore, the trunk module is powered to carry the weight of the arm modules as well as supporting the load carried in the hands.

3. A DESCRIPTION OF THE MAIN S&T RESULTS/FOREGROUNDS

3.1. Requirements and regulatory aspects

3.1.1. Needs

In the initial phase of the project, we focused on identifying the needs from several perspectives. These are the business and social needs, the industrial company needs and the individual workers needs.

Business and social needs

We identified the business and social needs by literature review and stakeholder analysis addressing the major trends in manufacturing and the human role, value and cost of manual work in manufacturing. According to our analysis, the Robo-Mate concept shows the highest potential for manual work tasks, which are necessary in manufacturing but difficult to automate. The main business needs are

- Need to increase the flexibility of production
- Need to increase the flexibility of workers
- Need to increase the productivity of manual work
- Need to increase the quality of manual work

and the main social need is

- to reduce the physical load and the risks of injury.

Therefore, Robo-Mate's exoskeleton could be most useful where i) flexible production cannot be achieved through automation because of frequent changes of activities, product types and order sizes, ii) knowledge and experience is critical for the production process, iii) weights of parts are just too high to be lifted by a person but task execution is not on a specific location (thus, local cranes are not an option),

Industrial company needs

We identified the industrial company needs by defining a catalogue of manual handling scenarios (based on inputs from our three end-users), formulating the needs from industry perspective, and finally defining the use cases. The following table shows an overview of manual tasks that an exoskeleton could support.

Manual tasks that Robo-Mate could support	Application areas / manual handling scenarios	
1. Lifting, low/medium level weight (3-15 kg), high frequency (5-15x/min)	Compa Logistics	paintshop palletizing
2. Lifting, high level weight (15-25+ kg), low frequency	Indra Compa Logistics	wheel removal handling of metal components palletizing

3. Pushing / pulling, high level horizontal force	Indra	dashboard removal
	Compa	pushing heavy carts
4. Postural support – static loads, awkward postures	Fiat	dashboard assembly
		seat assembly
	Indra	windscreen cutting
5. Precision support – postural support and movement guidance at low speeds	Compa	welding

The variety in the end-user's tasks also originate from the very different level of automation in their production lines and product characteristics and how they are produced. In CRF/FIAT the production line is highly automised, for INDRA the disassembly line has hardly any automation integrated and for COMPA the production focuses on single.

The manual handling tasks encountered at our end-users show that a human worker is required to ensure the flexibility and sensory versatility in the process. For example, for INDRA the product (i.e. the car which needs to be disassembled) is never the same. A human worker can identify efficiently the required steps in the disassembly process. For example, he uses multiple senses to assess jammed screws and selects appropriate tools and measures to loosen them. By implementing Robo-Mate into the production process, both the advantages of a human operator and the advantages of a machine would be combined.

Individual workers needs

We identified the individual worker needs by visiting our three end-users COMPA, INDRA and CRF/FIAT and using our human factors specialists knowledge to interview workers, analyse the manual handling scenarios and associated health risks and define the potential support from the exoskeleton. Based on this procedure we defined a list of main worker needs in relation to the Robo-Mate exoskeleton, and grouped these, as follows:

Help me do the work	**Be comfortable**

• Lifting, preferably all kinds
• Pushing, pulling
• Force application
• Support working postures
• Not restrictive (speed, posture, space, tool usage, …)
• Provide information:
    • Work information at hand (less walking / looking up info)
    • Give instructions (prevent me from making mistakes)
	• No pressure points
	• Thermally neutral
	• Silent
	• Not heavy / light weight: eventual added weight is in balance with gained performance
	• Easy to use, no manuals
	• Easy to put on / take offAesthetical: appealing for workers

Keep me healthy • Reduce internal forces and torques	**Optional / desirable** • Correct my posture / provide feedback

• No additional - counter natural – forces, such as shear forces, joint forces outside ROM • Provide feedback on posture	

3.1.2. Human aspects, ergonomics and health risks

A questionnaire was designed and carried out to gather information from managers and primary decision-makers about manual handling activities in their companies. The survey included questions about the frequency of manual handling activities to indicate the proportion of time workers participate in manual handling activities. The survey showed that almost 53% of respondents indicate that their employees carry out manual handling activities for more than 4 hours per day and almost 71% of respondents indicated that they participated in the decision making process to purchase a manual handling assistive device. The primary factor in the decision making process was to reduce the likelihood of workers developing injuries.

There exist many ergonomic indicators to assess manual handling tasks. One commonly used indicator is the NIOSH Lifting Index [2]. To assess the health risk based on the task performed it is important not only to look at the weight of the object handled, but also at the duration performing that same task, the frequency at which the objects are manipulated and finally at the posture of the worker performing the task. In Figure 2 the relation between the time factors (duration and frequency) and the force delivery by the worker is shown simplified. The maximum human output follows the diagonal between the maximal duration and frequency combined with low force levels to low durations and frequencies combined with maximal force levels as indicated by the blue line. The closer the human output is to that maximum, the higher the health risk is.

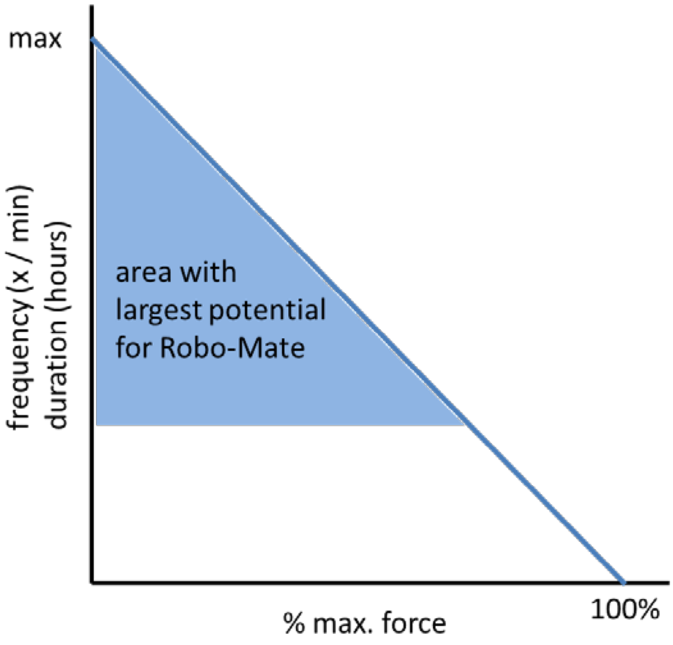


Figure 2: Relationship between time factors and force delivery by the worker. The blue area has the largest potential for Robo-Mate.

According to the evaluation of the most critical tasks at our end-users sites the health risks associated were evenly distributed between medium, high and very high risk tasks. Industrial reality is that typically, the tasks were the objects carried are above 15kg, manual handling assistive devices are common. Within our end-users group the workers from INDRA are regularly handling heavier objects because their disassembly line is hardly automated, the space to manoeuvre within a car highly restricted and the variability caused by the different cars being dismantled is huge. Severely increased risk levels were found also for tasks with high frequencies but low to medium weights. Hence, the area with the largest potential for Robo-Mate is for high time factors (frequency and duration) and low to medium force delivery as indicated by the blue area in Figure 2.

3.1.3. Use-cases and Design Requirements

Based on the manual handling scenario's, the industry needs and the above considerations on applicability, the following two use cases were defined for further elaboration into design needs and specifications:

Use-case 1	**Use-case 2**
Frequent two handed lifing of loads of medium weight	One handed manual operations (assembly or disassembly) in stressful body posture

Specifications:
• Load weight: up to 15 kg
• Load coupling: with hand
• Load size: undetermined, provided handleable by worker
• Time factors: frequency: 5-15 lifts/min; duration: 8 hours
• Lifting position: frontal, hand position within 45° left and right from saggital plane
• Vertical lifting trajectory from near-ground level to maximal reach height
• Horizontal distance to lifting object (hands to ankles) up to 63 cm (NIOSH limit)
• Lifting task space within 5 meter radius, no restrictions in head room
• Environmental conditions: standard, not excessive
	Specifications:
	• Load weight: up to 7.5 kg per hand
	• Load coupling: can be gripped with one hand
	• Load size: undetermined, provided handleable by workerwithin envelope specified below
	• Time factors:
	  ◦ Holding time arms up to 1 minute
	  ◦ Holding time trunk flexion up to 2 minutes
	• Working area:
	  ◦ Frontal, hand position within 45° left and right from saggital plane
	  ◦ Reach: not yet specified, combination of trunk flexion and arm reach
	  ◦ Similar to use case 1
	• Trunk postures:
	  ◦ Holding time arms up to 1 minute
	  ◦ Holding time trunk flexion up to 2 minutes
	• Environmental conditions: standard, not excessive

As mentioned in Section 2.1, by analysing the catalogue of manual handling scenarios the use cases were derived (two handed manipulations up to 15kg and one handed manipulations up to 7.5kg). These form the basis for requirements targeting the operational range of the exoskeleton. By analysing company and individual worker needs, specific design requirements were identified. The main requirements identified are:

i. Safety and usability should be matched to the task carried out
ii. It should be comfortably worn
iii. The exoskeleton should have an anthropomorphic fit
iv. It should stabilise movements within the users range of movement
v. It should have wide adaptability
vi. Easily allow workers to rotate between task
vii. It should be risk assessed and trial tested throughout the design process
viii. It should meet all applicable standards and codes of practice

3.1.4. Safety and Standards

The close proximity between users and exoskeletons exposes the users to multiples of hazards that require extreme consideration [10]. In Figure 3 the relevant safety and standardisation aspects are shown graphically. It illustrates that standards exist to guide the inherently safe design of service

[11], industrial [12], collaborative [13] and personal care robots [14], there are no standards that manage industrial worker exoskeletons and moreover, the harmonised standards published under the Machinery Directive [15] do not relate to a machine and wearable tool combined device [10]. Hence, there is a strong need to develop new and update existing standards to suit the emerging exoskeleton technology.

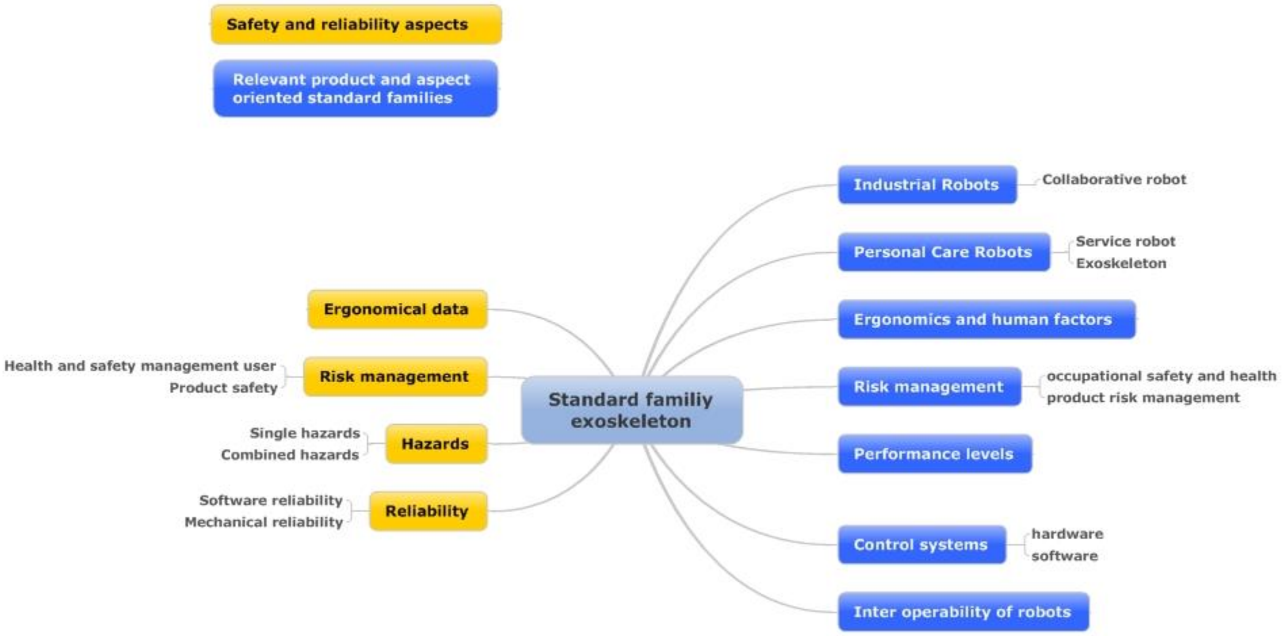


Figure 3: Overview of relevant exoskeleton safety and standardisation aspects

Safety

The Robo-Mate project focuses on the development, testing and using of an exoskeleton in an industrial environment and safety aspects need to be considered throughout these phases (Figure 4). As discussed earlier, no standard that specifically addresses industrially used exoskeletons exists and it is therefore important to ensure that risk scenario and safety standards are taken into account. Moreover, it is important to ensure safe manufacturing and assembly technologies and functionalities and finally, safe handling and cooperation between the Robo-Mate technology and the operator.

To address these issues a safety expert group met periodically and exchanged safety information and findings. The goal of the group was to manage individual work package related safety issues and to anticipate safety issues early in the development and design phase. A list of potential hazards was set up as part of a hazard log. The risks of these potential hazards were assessed and where found necessary measures to mitigate were initiated and resulted in a white paper for public use [16]. A catalogue on relevant standards was set up. In particular, ISO 10218 [12] and ISO 13482 [14] being crucial for our work, were studied in detail to make inventory of potential hazards.

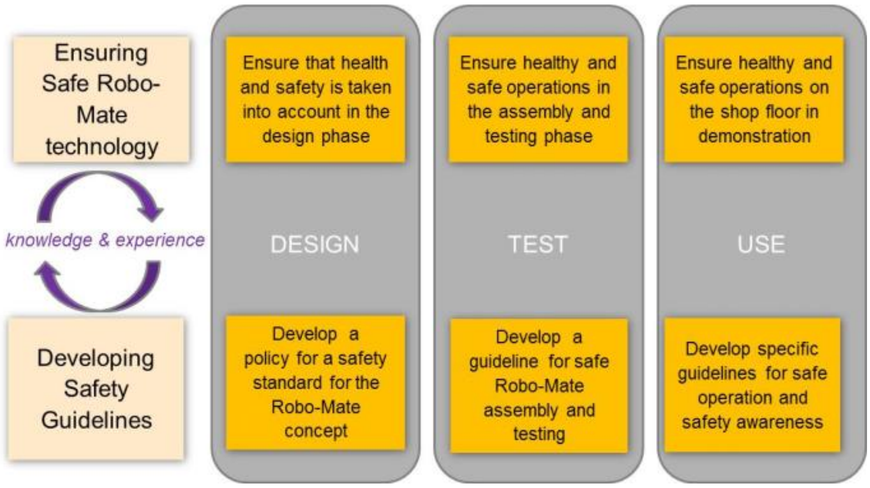


Figure 4: Interrelationship between project phases within the safety and standards work package.

Standards

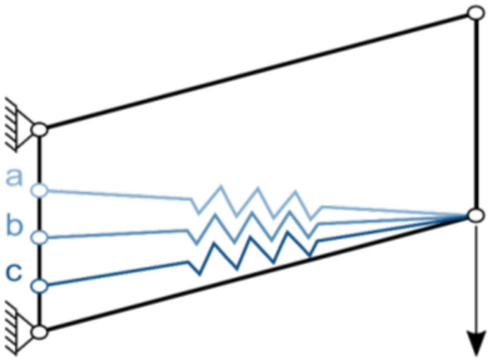
The purpose of recording and analysing meticulously the safety procedures used within Robo-Mate and the comparisons with existing standards for these project phases was to prepare a basis for discussion around standardisation processes for industrial exoskeletons.

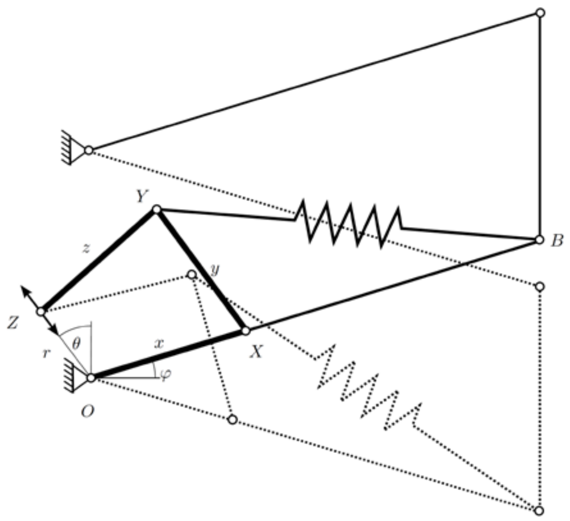
The international standardization arena was explored to create foresight on which standardization work would potentially benefit from Robo-Mate knowledge. Potential stakeholders were identified in order to build liaisons from Robo-Mate project to international standardization organizations. This ultimately resulted in the participation of Robo-Mate team members in the ISO technical committee on robots and robotic devices (TC 184/SC2) where the detailed activities within Robo-Mate [17] and the corresponding white paper [10] was presented and discussed thoroughly. ISO standard 13482 at the time was still being developed and the input from Robo-Mate was recognised as knowledge source and benchmark in ISO TC 184/SC2.

3.2. Robo-Mate modules

3.2.1. Passive parallelogram arm module

The passive parallelogram arm module is designed as an energy efficient and robust tool to support a non-varying load. Handling continuously a tool (for example an angle grinder) over a longer period or to compensate the users own arm weight in awkward and strenuous postural positions are typical applications. Spanning a spring within a parallelogram structure as shown in the adjacent figure will produce an equilibrium position as a function of the load acting at the end-effector (indicated by the error). Moving the end-effector up and down means that for the former the spring is released and therefore the user will carry the additional load, for the latter the spring is stretched and therefore the user will experience additional resistance. Depending on the location of fixture (a,b,c) of the spring, the supported load will change. Ideally, for such a system to make sense as part of an exoskeleton arm, the reaction force of the spring is independent angular arrangement of the parallelogram. This can be seen in Figure 5 on the left. The shaded area between the ideal curve (horizontal line) and the characteristic curves of the above parallelogram system indicate the energy needed to move the load out of the equilibrium. To achieve close to horizontal characteristic curves, the spring is connected to a four-bar linkage instead of spanning the entire diagonal of the parallelogram as shown in the adjacent figure. The four-bar linkage is denoted x, y, z and r in the diagram. When moving the end effector up and down, the point of attachment (Y) of the spring moves as well and therefore the spring is kept approximately at the same tension. The resulting spring force in the parallelogram structure provides a gravity counteracting, lifting force. Choosing appropriate lengths x, y and z and the angle θ the lifting force Fz is nearly constant independent of the angle φ. By changing length r the lifting force is changed and can be therefore used to adjust it according to the user's needs. Two parallelograms are connected in series to provide an unrestricted arm movement. Lateral movements are unsupported and unhindered in the required reach space. The final prototype was designed by taking into account the maximum required movements ranges and the maximum load (Actual load carried in hand 7.5kg plus weight of the user's arm 4.5kg totals in 12kg). The dimensions of the parallelogram were derived by optimization [18].





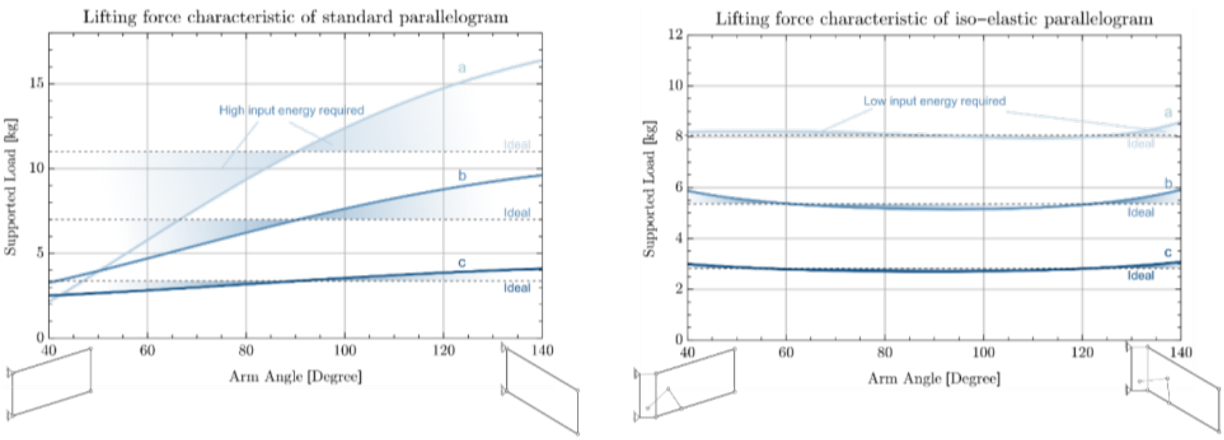


Figure 5: Characteristic curves for standard spring parallelogram system (left) and a spring parallelogram system extended with a four bar linkage (right).

In Figure 5 on the right, the angle φ – which defines the arm location and the shape of the parallelogram – versus the lifting force is shown. Each line represents a different value of length r. For small values of r a horizontal line is achieved and for larger values of r the difference is about ±2% of the total lifting force. This indicates that only little energy (corresponding the shaded areas) is required to move the arm to any location the whole movement range. The prototype was manufactured from aluminium and weighs approximately 3.7kg. It is shown in Figure 6. The advantages are i) very simple to use ii) no electronic components and therefore very robust and durable in polluted environments and iii) low weight. The downside is that only a fixed supporting force can be set depending on the length r. To change length r a screw and nut system was integrated and therefore this prototype can accommodate loads between 4kg and 12kg per arm.

Figure 6: Passive parallelogram arm module (final prototype)

Best task match and suggested improvements

The passive parallelogram arm is a very robust and simple to use exoskeleton, which makes it ideal for rough environments. The tasks matching best the functionality of the passive arm are listed below.

Posture compensation, i.e. tasks where hands and arms are held in an uncomfortable position for a long time carrying no or just small loads up to 3kg. Using an exoskeleton for this task will relax the shoulder of the worker significantly. An example would be for example overhead work below the car body or the test case carried out by CRF/Fiat where a rubber sealing was mounted on the frame of the boot of a car at approximately shoulder height. An arm of a human is approximately 5% of his or hers total weight, i.e. approximately 4kg. Reducing the design to carry only 4kg would reduce the footprint (volume, mass) significantly. We expect that such device could weigh less than 1kg per arm. Attaching such a lightweight device to the body of the worker is much easier and much less intrusive. Acceptance would be much better.

Tool balancing, i.e. the idea is not to support the arms of the user but only the tool the worker is carrying. In this case even only one arm is necessary and the design can match perfectly the tool weight. This would also simplify the construction as the adjustment mechanism can be removed. This application raised interest especially by tool makers as the current power levels in their grinders and drills are mainly restricted by the weight a worker can handle. Increasing the power level would mean that tasks can be finished quicker and hence more efficiently. A model application would be the removal of the casting flash with an angle grinder.

An important feedback for improvement is related to the attachment of the exoskeleton to the lower arm. At the moment rotating the lower arm and hand is restricted. This part needs a significant redesign.

3.2.2. Active parallelogram arm module

Original the arm module was based on an anthropomorphic design, where two motors powered the shoulder and the elbow joint. The experience showed that the weight of the exoskeleton was far beyond any acceptable level. The main reason being the motor and gear units, which can be hardly removed. With the anthropomorphic design, there is always a need of minimally two motors to provide one force compensating gravity (shoulder and elbow joint). Hence, the idea was to use again the parallelogram structure and replace the spring (which provides always a constant support) with a motor and wire systems (Figure 7), which can be controlled to provide the required support dynamically. Again, the active parallelogram module is set-up of two segments. However, only one motor unit fixed closed to the body of the user is used and a single wire passes through both segments Figure 8. In the front parallelogram, two sides (upper and front) were removed to reduce weight (reducing essentially the front parallelogram segment to a triangle). A single motor (brushless motor EC-i40 from maxon motors in connection with a worm gear and spindle) at the trunk end of the module provides the load supporting force. For pick and place activities the lifting force is dynamically adapted based on pressure sensor inputs. These are sewn into a glove and are placed in the palm of the worker. The rear parallelogram and the front triangle are connected in series to provide an unrestricted arm movement corresponding to the passive version. The final prototype was manufactured from aluminum and weighs approximately 2.3kg, which includes the motor, but no battery pack or other electrical components. To control the supporting force accurately and highly dynamically a force sensor is connected in the front segment between the end effector and the wire.

The main advantage is that it is lightweight. Compared to the original design only one motor and gear is used, which halves the weight of the heaviest components. Placing the motor close to the users body is advantages as the motor is close to the user’s centre of gravity. The pick and place support is essential for many applications. The downside is that the electronics (sensors, batteries, motor and control system) increases the maintenance and reduces the robustness of the system significantly. Again the design can accommodate 7.5kg payload plus 4.5kg of the users arm.

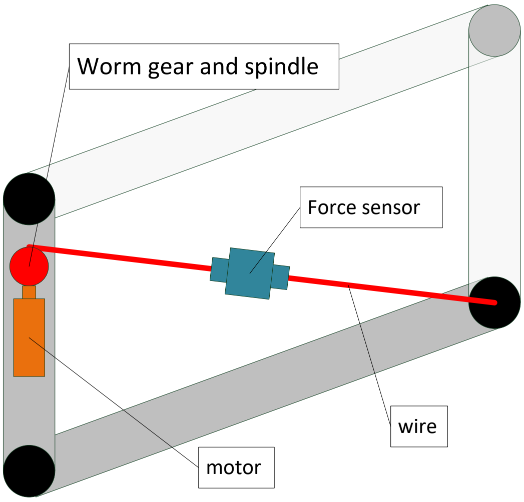


Figure 7: Main components of the active parallelogram arm section.

Figure 8: Active parallelogram arm module (final prototype)

Best task match and suggested improvements

The active parallelogram arm has a lightweight design for an active arm. The design is impressively robust even though the wire running along the length of the arm is exposed. Batteries and electronic components however make the arms sensitive to rough environements.The design is not anthropomorphic as required. However, we still see possibilities in this direction too. The task matching best the functionality of the active arm are:

Pick and place tasks, i.e. tasks where load in the hand change frequently. Examples are manifold and range from wheel removal at INDRA to the breaking disk assembly at CRF/Fiat or any packing and carrying task. As with the passive parallelogram arm, rotating the lower arm and hand is restricted with the current design. When assembling this additional degree of freedom is essential and hence the design of the arm cuff needs to be improved.

3.2.3. Trunk module

The trunk module Figure 9 underwent several design iterations. An initial design is described in [19]. It is designed to reduce the compression forces in the lower back of the user (see Section 3.1.2).

Figure 9: Trunk module (final prototype)

The actuator unit, composed by a brushless motor EC90[1] and a Harmonic Driver[2] with a gear ratio of 160:1, connects the two segments of the system: thigh segment and torso segment. The system provides the required assistive torque, transmitting it to the body by applying a pressure on the upper leg (thigh segment) and to the user's upper back (torso segment). The system rests on the hip of the user, which is the main connection point between the system and the body. In [20]it is shown how such a system would have a positive net effect on the user, since the assistive torque has a significantly larger effect on the compression forces compared to the gravity forces (weight). To increase the wearability of the system, the trunk module has also a number of passive joints, which allows the user to move freely. For the upper body, this is mainly a spherical joint attached between the backpack structure on which the straps are mounted and a beam, which connects to the stiff exoskeleton structure on which the motors are mounted. Movements in the sagittal plane are stiffly coupled to the exoskeleton and therefore the moment provided by the exoskeleton can be transferred efficiently to the body of the user. Movements in the frontal and transverse plane can rotate by a few degrees and therefore the movements of the upper body are smoother and more comfortable for the user. The exoskeleton is attached on the thighs of the user by Velcro straps. Here, several joints ensure that legs can move freely sideways and rotate.

The total weight of the initial trunk module design as described in [19] is significantly higher than 15kg, including actuators but excluding batteries for power supply. In addition, due to the selection of motor and gear the maximum speed was limited and restricted the natural walking movement of the user considerably. Within the last iteration, the motor and gear concept was redesigned to remove these limitations. The goal of the new actuator principle was to increase the speed without reducing the supporting torque. Typically reducing the motor power will lead to higher rotation speeds but reduce the available torque. Reducing the gear ratio, will have a similar effect. To overcome this dilemma, the motor was designed with a mixed actuation principle. A motor with less power was chosen to increase the speed. This will have the beneficial effect that less battery power will be required as well. To compensate the reduction in available torque, a spring system, which acts in parallel to the motor was added. The design can be seen in Figure 10 (left), where label (e) corresponds to the spring. The other main components are the brushless motor (a), the harmonic drive (b), the torque sensor (h), the stiff exoskeleton structure (g) and the leg attachments connectors (c). The advantage of this motor system with a parallel passive actuator (spring) is that while bending down the motor will compensate the spring force acting against the direction of movement and therefore an unrestricted movement is possible. While bending down, some energy

[1] Maxon motor AG, www.maxonmotors.com
[2] www.harmonicdrive.de

is loaded in the spring. Moving upwards, the spring and the motor act in the same direction and therefore less torque is needed by the motor to provide the same support as before. The stored energy in the spring will further reduce the power need (Figure 10, right).

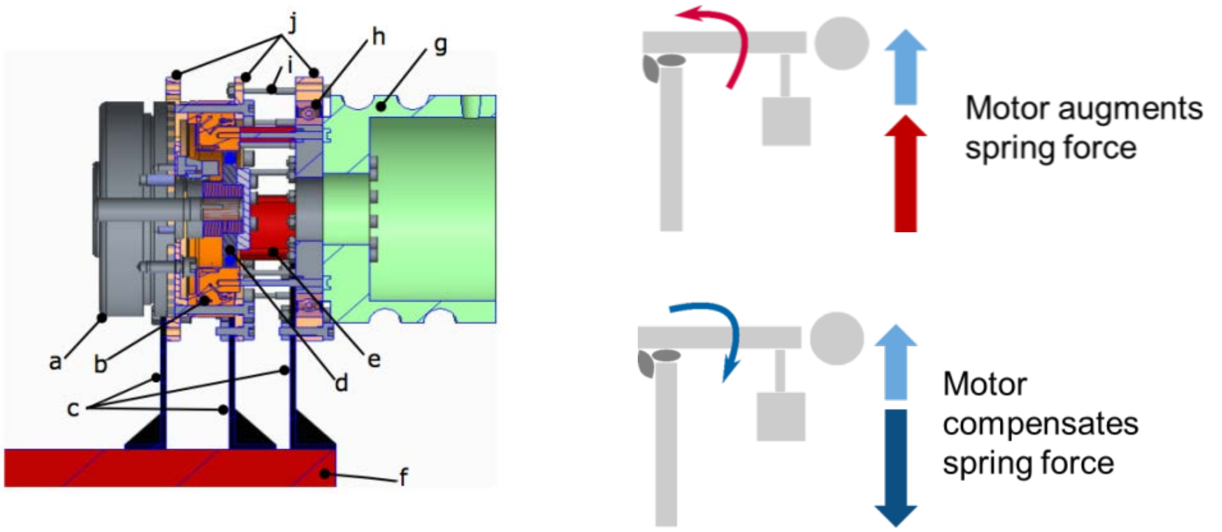


Figure 10: Actuator with mixed actuation (left) and principle of action of the new motor unit for up- and downward movements (right).

This newest design is manufactured from aluminum tubes, which house most of the wiring. It weighs below 10kg. Walking at a fast pace is easily possible.

Best task match and suggested improvements

The trunk module changed most over the development phases. Currently the design provides an good functionality, allows close to transparent walking (i.e. the exoskeleton does not impede walking and nearly all movements are possible up to fast pace walking). Batteries and electronic components however make the trunk module sensitive to rough environments. The design is anthropomorphic as required. The task matching best the functionality of the active trunk module are:

Any bending tasks, i.e. tasks where the worker needs to bend forward with or without any load. Examples are manifold and again the wheel removal at INDRA is a model application. This is the module, which raised most interest by end-users. We estimate that approximately 70% of all tasks where the human worker needs support the trunk module will suffice.

3.2.4. Sensorised glove

Figure 11: Sensorised glove

For both the active parallelogram arm module and the trunk module, a sensorised glove Figure 11 can be used to control the action of the exoskeleton. Pressure sensors in the palm of the user detect when objects are handled and various operating modes can be configured. The most common mode was to use a sensor on the mid finger to control the supporting force proportionally to the pressure applied. This allows an easy and reliable interface to control the exoskeletons behaviour.

3.2.5. Human Machine Interface Module

The human machine interface (HMI) has two main purposes. Firstly, it provides a high-level interface with the exoskeleton allowing for example to monitor the exoskeleton system conditions like battery state or applied torques Figure 12. Secondly, it connects to a cloud based application, where configurations of different users can be stored and retrieved. The HMI was implemented on two different devices a hand held mobile phone device (Android device) and to smart glasses (Moverio BT-200) [3].

The following features are implemented:

CONNECT	Secure connection to the exoskeleton and to the server	HMI app is connecting the exoskeleton and the cloud API after secure log in.
CONFIGURE	System configuration around the user preferences	Before using the exoskeleton, the user identifies himself and personalised settings are loaded. This can include for example size and other physical properties if the user but also personal operation mode preferences.
MONITOR	Real time monitoring	Continuous monitoring of the parameters of the exoskeleton (i.e. temperature, angular speed and applied torque) and safety features.
APPLICATIONS	Training Apps	Specific training and safety and security usage applications are accessible to the user. This feature can also be extended to include task related information or integration to work planning tools.

[3] https://epson.com/For-Work/Wearables/Smart-Glasses

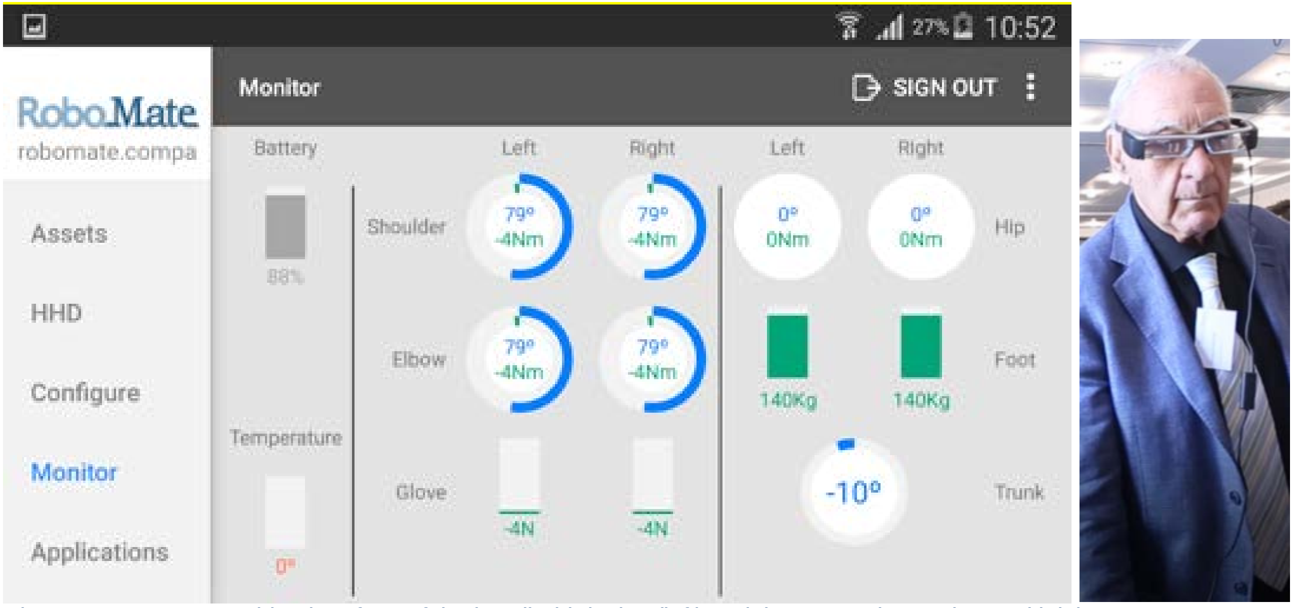


Figure 12: Human machine interface of the handheld device (left) and the smart glasses in use (right).

3.3. Validation and test results

3.3.1. Lab tests

The Robo-Mate modules were tested and validated at the physiotherapy lab at ZHAW in two phases: the pilot-testing phase and the data acquisition phase. It is critical to assess proper functioning of the system in a controlled environment, since a number of measurements can be made which are not possible in industrial environments.

The evaluation test plan was developed using [21] as a foundation guide, with additional guidance documents referenced to aid the development of the test protocol and plan [22] [23]. The ethical committee of the canton of Zurich approved the test protocol.

Eight subjects were assessed carrying out four task activities both with and without the Robo-Mate exoskeleton. The subjects were evaluated under the following metrics:

Effectiveness: demographic data, effectiveness checklist, and efficiency checklist.

Efficiency EMG sensors, Vicon 3D motion capture system, and ground reaction forces to determine kinematic data. A test subject with markers attached is shown in Figure 13.

User satisfaction Visual Analogue Discomfort scale (VADS) as shown in Figure 14.

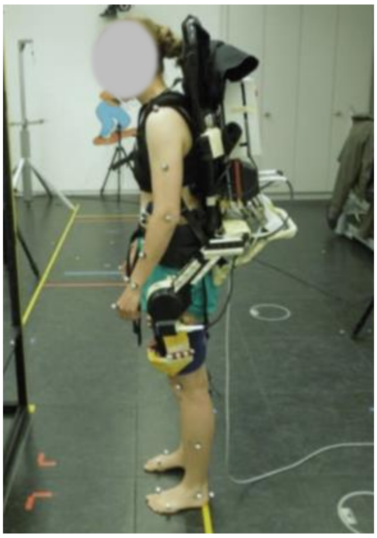


Figure 13 Test subject with trunk module and markers

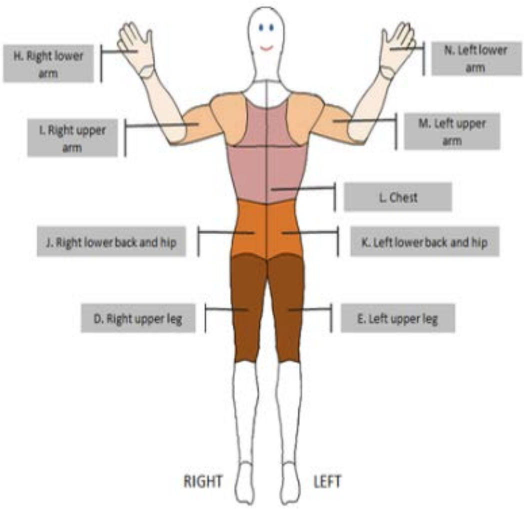


Figure 14 VADS pressure perception diagram

Pilot testing phase

Pilot testing was carried out with two different subjects wearing the trunk module only and together with the arm module as shown in Figure 15.

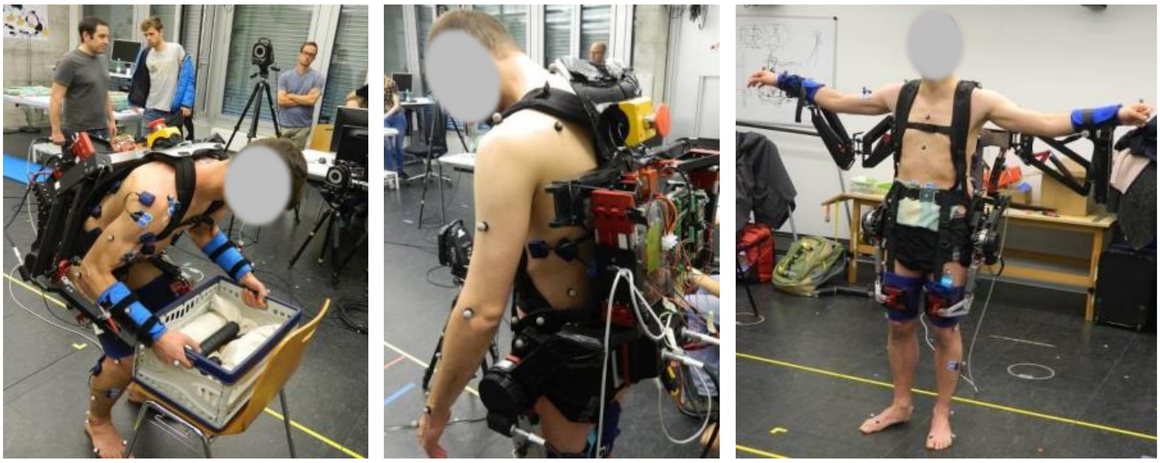


Figure 15 Prototypes used for pilot testing

The users could perform all tasks with some minor limitations. The main issues detected during pilot testing were:

- All modules were too heavy (total system weight approx. 17 kg)
- Unbalanced weight distribution between shoulders and hips
- Motors at the hips too slow for natural movement
- Limited and unnatural range of motion of arm modules

Data acquisition phase

For the data acquisition phase, many improvements were made to the modules to improve comfort and usability, and reduce weight. The active arm modules could not be tested for technical reasons.

Each test subject performed the tasks shown in Table 1 while 3D motion, EMG and ground reaction force data were recorded. After each test and at the end of all testing, each subject was asked a series of questions to evaluate effectiveness and satisfaction.

Task	Load	Modules
Lifting from knee to waist height	1. 15kg	1. No system 2. Trunk module
Static overhead work	1. 0kg 2. 2kg	1. No system 2. Passive arm
Isometric forward trunk bending	Body angle from 0 to 50 degrees	1. No system 2. Trunk module

Table 1 Tests for data acquisition phase

Results

The passive arm module significantly reduced muscle activity and perceived exertion in the arms whilst performing a static overhead task, particularly in case of holding a load of 2 kg (e.g. a hand tool). Pressure on the body was perceived as 'Strong'. Subjects expressed mixed feelings about the usability: half of the subjects would use the equipment at work, the other half would not.

The trunk module showed significantly reduced muscle activity of the lower back and hamstrings for both lifting and lowering, whereas muscle activity of the Rectus Abdominis was significantly increased by the module. perceived pressure was highest on the back.

Isometric bending task

During the bending tasks, EMG measurements showed reduced muscle activity of the back and hamstrings when using the trunk module as shown in Figure 16. The largest reductions were shown for the greater bending angles. Perceived exertion of the trunk by the participants corresponded to the measurements, as shown in Figure 17. Perceived exertion of the legs, however, increased with the use of the exoskeleton. Usability is still rated low due to factors such as pressure and weight.

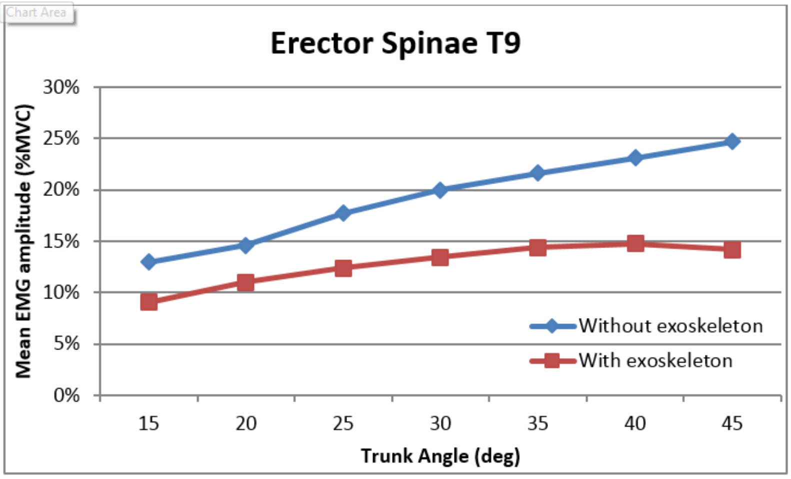


Figure 16 Mean EMG amplitude for static bending tasks

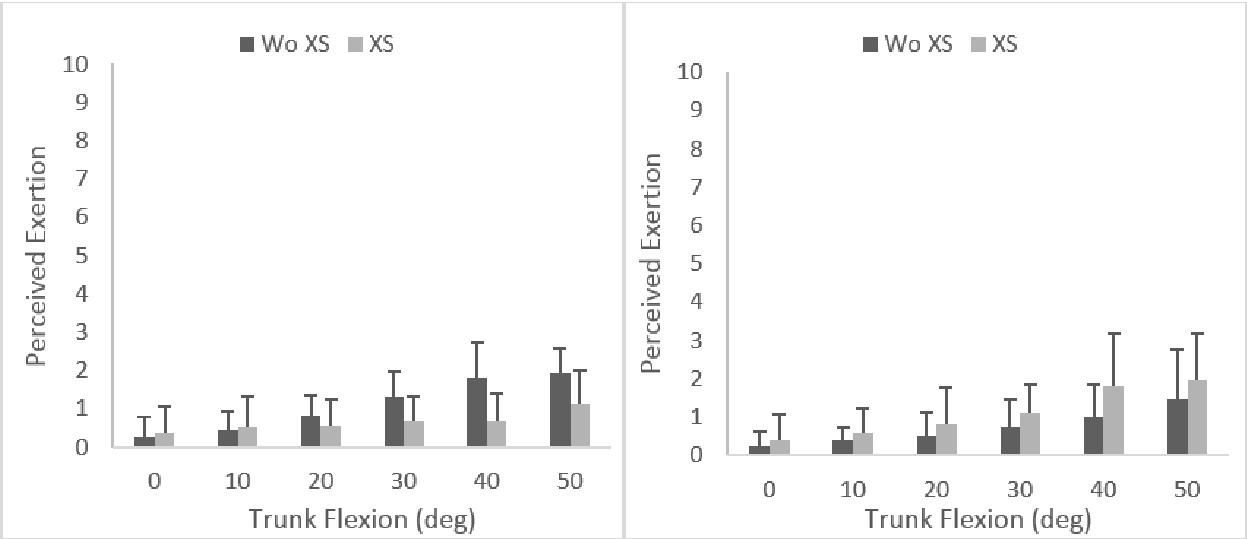


Figure 17 Perceived exertion during static bending tasks. (left) exertion of trunk (right) exertion of legs.

3.3.2. Industry implementation

CRF/Fiat

The test selection for Robo-Mate was performed based on assembly tasks in which the operator has to maintain an awkward posture for long periods of time or in which the use of the manipulator could be replaced. In CRF/Fiat the tasks selected are listed below and shown in Figure 18.

- Cap mounting (operation under car body)
- Car headlights mounting
- Disk brake lifting
- Anterior cable positioning and fixing

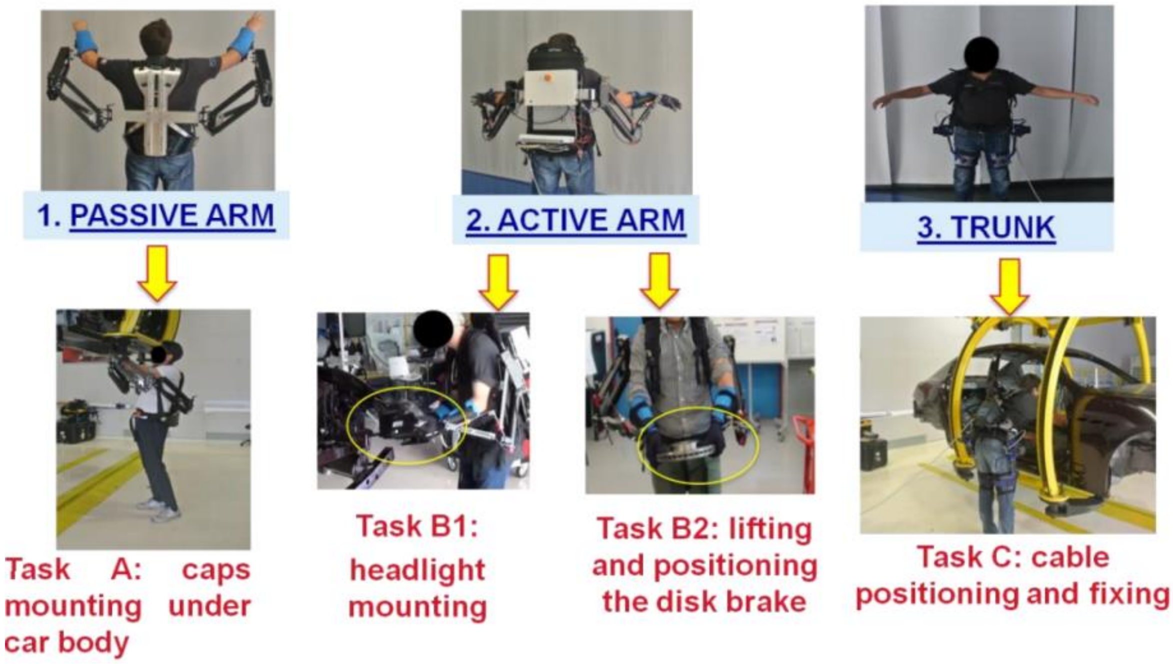


Figure 18 Tasks selected for the exoskeleton modules

Test criteria were metabolic energy expenditure, task duration and subjective perception of the operator. The results from testing are summarised in Table 2.

	Passive arm	Active arm	Trunk
Metabolic expenditure	Task A: slightly increased for most test subjects	Task B1 & B2: Mostly unchanged	Task C: Reduced for most users
Task duration	Task A: Increased	Task B1 & B2: Mostly unchanged	Task C: Slightly reduced for most users
Subjective evaluation	• Movement and range is generally restricted • Weight needs to be reduced • Materials should be more breathable		
	• Good range of movement • Arm attachment heavily restricts wrist movement • Not suitable for pick and place operations • Least preferred module	• Reduces physical effort • Finger sensor could be located better	• No mental effort required • Most preferred module • Movement could be more fluent • Leg attachment constrictive

Table 2 Test result summary

For an effective implementation of exoskeletons in an automotive assembly line, two different analyses were performed. The first involves workplace selection to ensure overall benefit; the second focuses on the cost of implementation and use.

The workplace analysis was carried out on the whole assembly line of the FCA production plant in Poland. In each of the workplaces, three existing tools were evaluated for possible substitution as shown in Figure 19.

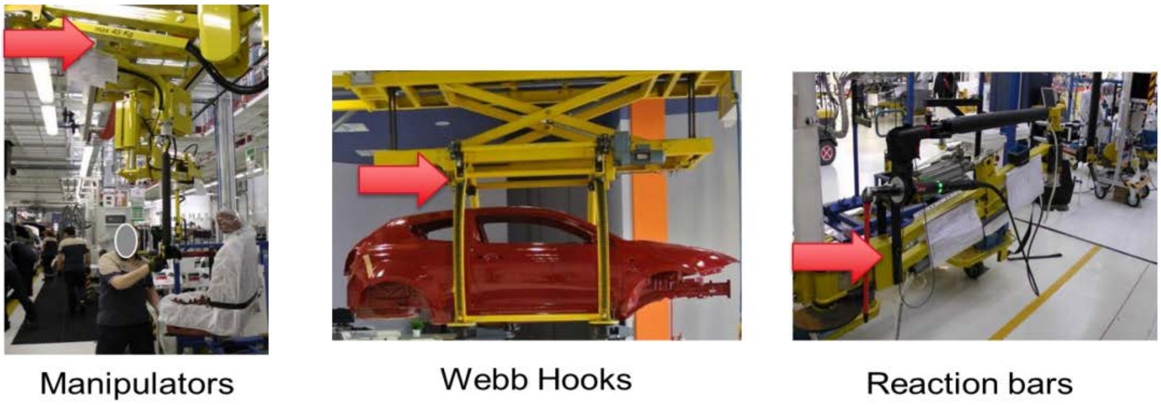


Figure 19 Common tools used in the workplace which could be substituted

According to the first analysis, 22 workplaces out of 250 in a designated CRF factory would benefit from the use of an exoskeleton.

Based on a cost-benefit analysis carried out for 20 Fiat and 27 Chrysler plants, there are 2068 workplaces eligible for exoskeleton implementation. Taking into account 10% spare exoskeletons, the total number of required exoskeletons would be 2303.

The following figure shows the result of the cost benefit analysis showing the net value per year. After five years from the first implementation the investment, the gain equivalent is that of salary of about 3 people. This highlights the positive effect of the ergonomic improvement and the benefit of a new technology such as passive exoskeletons on the workplace.

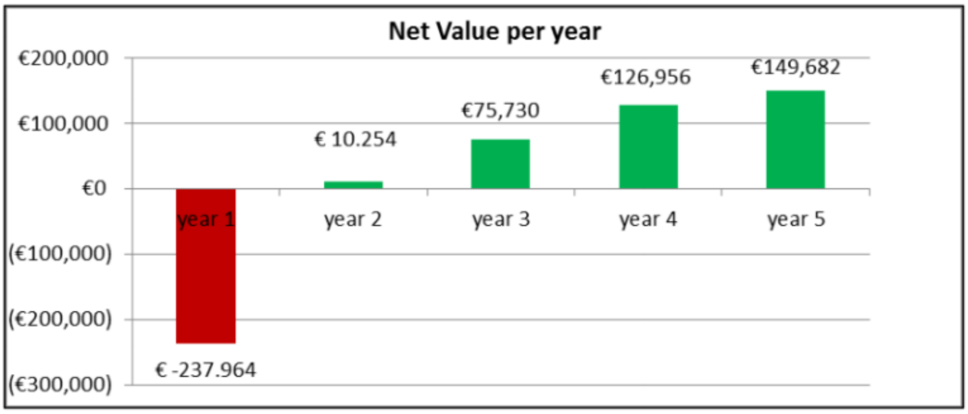


Figure 20 Cost-benefit analysis

The main conclusion from testing is that the Robo-Mate exoskeletons would be interesting for implementation in industry if some refinement is carried out on the prototypes.

The results of the analysis carried out clearly show that the investment and costs related to the exoskeleton implementation (the passive one for safety and regulation matters) are recovered in less than one year. This is a sustainable objective for a company that wants to implement a new technology for ergonomic improvement.

INDRA

Five tasks were selected for testing the RoboMate modules as shown in the images below. These tasks represent common activities requiring a range of motions in different positions and postures. Three metrics were evaluated; local perceived pressure (LPP), system usability score (SUS) and subjective evaluation.

Hood removal

Wheel removal

Door storage

Wheel assembly

Battery removal

Subjective evaluations

A summary of the subjective evaluations received from the test subjects over all tasks is shown in Table 3. In general, the modules are too heavy and bulky so they restrict the operator movement and attachment to the body needs improvement. The passive arm module was not suitable for the given tasks, whereas the trunk module showed promise for bending and lifting tasks.

Module	Remarks
Trunk Module	• Good support for bending and lifting • Good freedom of movement • Power cable restricts movement • Too big and heavy  *Figure 21: Not ideal for standing tasks*  *Figure 22 Good for bending tasks*
Active arm module	• Good support when carrying and lifting objects when standing and walking • Arm attachment needs improvement • Finger sensor not always easy to activate • Too big and heavy, module interferes with the work environment • Operator movement is slowed

	 *Figure 23 Good for carrying objects*  *Figure 24 Arms interfere with the work environment*
Passive arm module	• Good support when carrying objects and holding tools • Arm attachment needs improvement, wrist movement is impeded • Not useful when bending over • Too big, module can interfere with the work environment  *Figure 25 Good for carrying objects*  *Figure 26 Provides no assistance when bending over*

Table 3 Subjective responses from Indra test subjects

COMPA

To properly test the performance of the Robo-Mate exoskeleton, the following two processes were carried out:

1. Arm modules: Preparation and dyeing of windscreen wiper arms and blades. A curtain of wiper blades was taken from the trolley and placed on the conveyor while in the upright position, as shown in Figure 27 and Figure 28.
2. Trunk module: Preparation and handling of metal parts after laser cutting and bending operation in the welded assemblies workshop. This task requires the operator to lift, bend and reach for the objects as shown in Figure 29.

Figure 27 Lifting wiper curtains with the passive arm module

Figure 28 Lifting wiper curtains with the active arm module

Figure 29 Handling of metal parts with the trunk module

Local Perceived Pressure

The perceived pressures in various body parts were obtained from eight subjects. Both arm modules apply pressures exceeding 'moderate pressure' in the neck-shoulder region, the back region and to a lesser extent in the hip and arms.

The trunk module resulted in 'more than moderate' pressure in the chest, stomach, hip and upper leg regions.

System Usability

The System Usability Score of 57,5 was obtained using statements from the test subjects. None of the subjects rated scores above the criterion level of 70. Based on a study by [24], a score of 70 is necessary for acceptance and scores in the high 70s to upper 80s represent better products. A SUS score of less than 70 indicates significant improvement is required and that the equipment is not ready yet to be applied in real industrial settings.

Subjective evaluation

Table 4 lists the primary responses received from the test subjects. The responses are in general similar to those received from the other test locations.

Positive	Negative
• Operators were enthusiastic about the technology • Generally easy to don, adjust and doff. • Learning to operate the exoskeleton was generally considered easy • Functioning of modules was quiet, smooth and responsive • No health and safety incidents with the exoskeleton during the tests	• Too heavy, prolonged use causes fatigue • Risk of tripping or snagging the power cord of the trunk module • Using the equipment at maximum reach/movements is limited, thereby hindering certain movements of the hands and legs • Operator cannot self-operate the emergency button • Due to the arms module sizes and large necessary space, operators had difficulties handling the pieces. The workspace had to be adjusted for the tasks. • Use of the modules reduced the pace of work

Table 4 Subjective responses from COMPA test subjects

As a result of tests at the COMPA facility, the following recommendations have been proposed to improve and further develop the Robo-Mate exoskeleton modules:

- Reduce the weight and size of the modules
- Ensure ease of access to the emergency button for all tasks/movements
- Redesign the power supply for the trunk module to eliminate the tripping hazard
- Increase the range of movement for the modules/joints to meet the needs of the industrial tasks.
- Improve the exoskeleton ergonomics

3.3.3. Digital factory integration

Simulating production tasks, sections of production lines or even whole lines in a digital framework is a standard method to optimise the production in respect of efficiency. In case human workers are involved the optimisation criteria also includes a quantitative value for the negative impact on the workers' health. Hence, by including this in the optimisation, injury risks for the workers can be reduced and the production line can be ergonomically optimised before it is actually realised. This is an important cost saving instrument the industry relies on, when designing and changing their production procedures and facilities.

The Robo-Mate exoskeleton modules are in the view of production planners a tool to protect the worker and to enhance the production efficiency. It is therefore important that within this digital simulation and optimisation environment, the exoskeleton modules are fully integrated. This means that the "human worker" in the digital factory can wear them and that the software tool provides feedback for example

- on collisions due to restricted working space
- on ergonomic indicators
- on predicted cycle times with and without exoskeleton use
- on suggested changes to the layout to improve efficiency when using the exoskeleton.
- etc.

For this purpose, several activities were carried out to support the integration in a digital factory environment. We used the Tecnomatix® Softwate portfolio, which is designed for developing and verifying process plans and can be extended with Process Simulate Human, an add-on application enabling realistic simulations of human tasks, allows to assess human performance (e.g, to avoid injury) and create effective ergonomic studies [25]. Within the software tool, humans are referred to as 'Jack'.

The main workplaces and processes if interest of our end-user's were mapped into the digital factory. An example task at COMPA, where two workers handle heavy metal sheets on a bending machine in reality an in the digital factory are shown in Figure 30 and Figure 31, respectively.

Figure 30: Workers at COMPA handling heavy metal sheets on a bending machine.

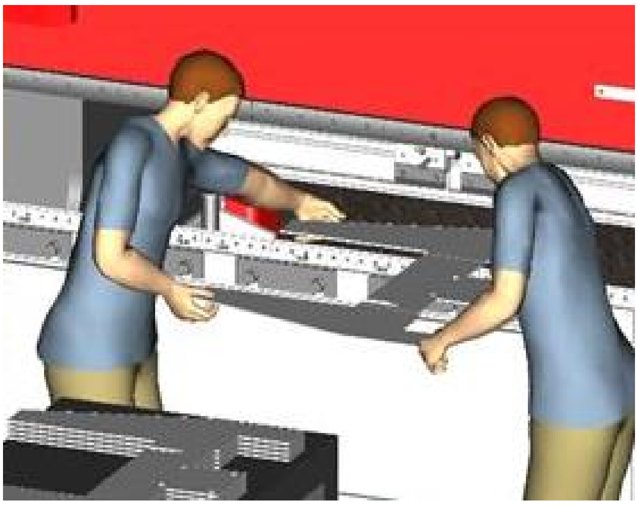


Figure 31: Digital factory implementation of bending machine operated by two 'Jack' workers models.

With the implementation of our end-users tasks, the workers activities can be ergonomically assessed. Tasks with increased risk for the workers can be identified and are used for further evaluation of relevance for the application of Robo-Mate. An example evaluation for a test case at INDRA, where the worker removes the driver's seat from an end-of-life vehicle is shown in Figure 32. The yellow dotted line, shows where the burden on the L4/L5 spinal segment reaches critical levels. The red line shows the forces exerted by the *erector spinae* muscle on this segment. The highest peaks are reached when the worker bends over the seat. This is expected because of the unhealthy posture combined with load handling during this phase.

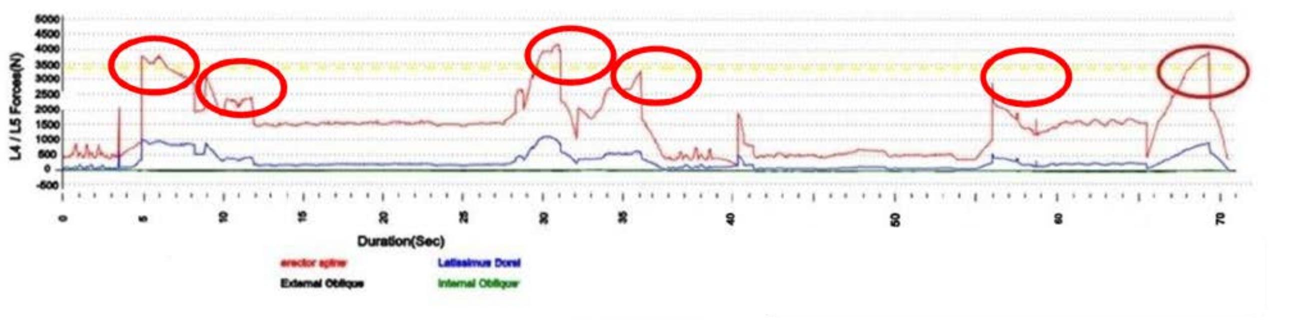


Figure 32: Evaluation of the of the L4/L5 compression forces for the INDRA test case, where the driver's seat is removed from the end-of-life vehicle.

To provide in an early stage of the project valuable input for simulating the exoskeleton behaviour in a virtual environment, an innovative methodology to analyse human exoskeleton interaction was developed based on the Jack and extended by the AnyBody Software packages[4]. The results were validated by setting up four test cases in the laboratory and by capturing human motion data, the relevant kinetic and kinematic data was extracted by inverse dynamics. The evaluation tools in the simulation software enable ergonomic and functional evaluation of the use and test cases.

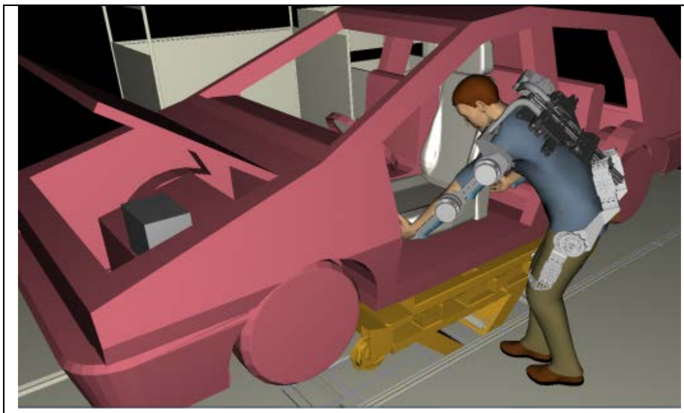


Figure 33: Feasibility test case from INDRA, where 'JackEx' removes a driver's seat.

The integration of the exoskeleton within the digital factory is based on prototype designs from an early stage. In Figure 33 an exoskeleton consisting of the initial anthropomorphic arms and a early trunk design is shown. The extension of 'Jack' with an exoskeleton is called 'JackEx'. With this step, the movements of the human using an exoskeleton on a particular production step can be analysed. This is a major result, as for example restrictions within the movement range can be detected early. In Figure 34 this is called the standard approach. To compare the risk levels for the worker performing a task with and without an exoskeleton not only the geometrical properties need to be considered. The interaction between the worker and the exoskeleton needs to be modelled. For this new modelling approach (Figure 34) the key is on how the exoskeleton is connected to the human in the simulation environment, this will influence the ergonomic and functional analysis. For this the assumption is made, that the interaction can be simulated by the exchanged forces between specific contact points on the human body.

[4] http://www.anybodytech.com/

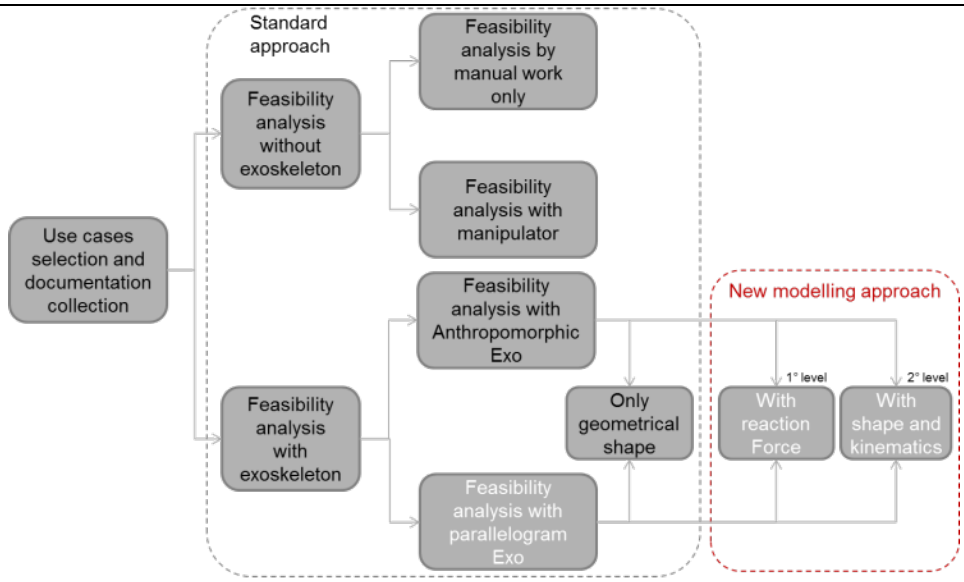


Figure 34: Task evaluation and modelling approach

Using the simulations from Jack and JackEx, we are now able to assess and compare the ergonomic indicators. In Figure 35 the same task as in Figure 32 is performed and the compression forces recorded. Here the red line, which shows the forces exerted by the *erector spinae* muscle on the L4/L5 spinal segment, never exceeds 2500N and is therefore below the critical level (approximately 3400N).

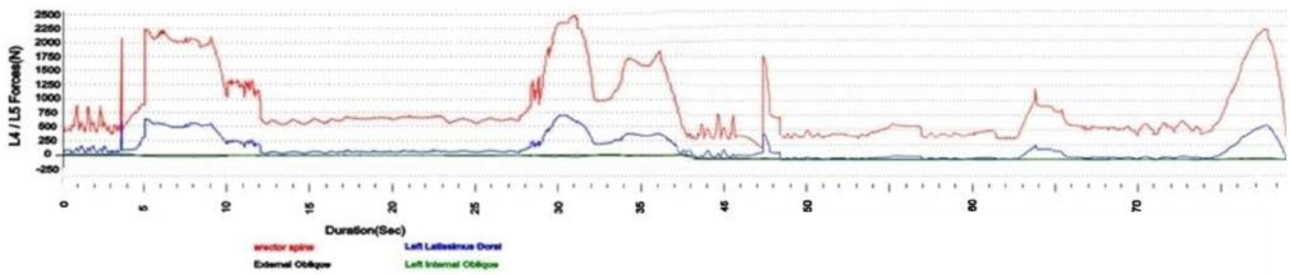


Figure 35: Evaluation of the of the L4/L5 compression forces when the worker uses an exoskeleton for the INDRA test case, where the driver's seat is removed from the end-of-life vehicle

The methodology is ultimately an important tool in the decision process when considering the integration of an exoskeleton into a production step.

4. IMPACT

When Robo-Mate issued its first press release at the start of the project it received a staggering amount of attention from the media – attention for a project which did not even have a rudimentary prototype to show. For example, the project was featured on the BBC technology website (on second position, beaten only by the new iPhone). Some of these articles featured the potential benefits for workers appropriately while other media spiced up their articles on Robo-Mate with references to the “Terminator” movies and wondered whether this was the first step to developing a “cyborg”. Receiving too little attention was thus not the main problem for Robo-Mate. Therefore, Robo-Mate could focus on getting the *right kind* of attention *from the right people* and making best use of this attention.

To achieve this, **Robo-Mate** defined for the following **dissemination and exploitation strategy** to be implemented throughout the project lifespan:

- Dissemination focussed on communicating and spreading the project results to those stakeholders who can help promote their exploitation. Robo-Mate dissemination activities thus primarily aimed to generate contacts with organisations who have an interest to either participate in follow-up R&D projects or to invest in a pilot implementation of one or several Robo-Mate modules on their shop floors.
- Results were exploited on two levels: by partners individually and on the project level. On the project level, exploitation concentrated on few, but promising exploitation contacts: From all the potential exploitation contacts established through dissemination activities, Robo-Mate selected the most promising ones and invested time to discuss future collaboration opportunities. In addition, Robo-Mate contributed to standards development by participating at meetings of relevant standardisation bodies.

This strategy was implemented through the following main **dissemination activities**:

- Distribution of print communication material, ranging from project factsheets to product brochures, at events and within partner networks.
- Creation of online/digital information material, such as infographics and videos of use cases.
- Robo-Mate modules were demonstrated to companies at 2 industry workshops (Stuttgart, DE, and Sibiu, RO).
- Representatives of Robo-Mate attended 7 technology fairs to inform about the modules and attract companies’ attention for exploitation.
- 5 demonstrations of prototypes at international conferences were organised to show Robo-Mate’s results to representatives from both science and industry.
- Scientific publications (3 articles, 1 book chapter)
- Presentation at scientific conferences (15 presentations at 9 conferences)

These and other dissemination activities (e.g. Robo-Mate website, conference presentations, and newsletters) led to valuable contacts to industry, primarily from the logistics sector, warehousing, manufacturing and automotive.

Thanks to this high number of contacts, we could pick the most promising contacts for **exploitation activities**:

- **4 company visits to interested industry companies** in Germany, Switzerland and the Netherlands where arranged to analyse relevant tasks on the shop floor and to identify the best suitable Robo-Mate modules for possible piloting.

- **8 company visits from interested companies** to the Institute of Mechatronic Systems (IMS) at the Zurich University of Applied Science, Robo-Mate's coordinator in Switzerland, were arranged. Company representatives had the opportunity to try on the prototype modules and discuss possible use scenarios.
- **A Brokerage and Pitching Event** was organised in Amsterdam, where around 50 representatives of 5 other exoskeleton projects and external stakeholders from academia and industry met to discuss business and research opportunities.

Together, dissemination and exploitation activities increased the long-term sustainability of the Robo-Mate project. The following facts illustrate the high potential and impact of Robo-Mate's work:

- **5 companies** have expressed interest to rent Robo-Mate module(s) after the project end under commercial terms and conditions.
- More than **100 contacts** of potential customers, distribution partners and R&D partners have been established based on direct enquiries via the Robo-Mate website, indirect requests via the partners' networks and meetings.
- **Start-up company preparations** have started in 2016.
- **Further EU funding opportunities** with project partners have been discussed.
- F**ollow-up EU funded projects** have been proposed or started.

The following sections describe some of the dissemination and exploitation highlights of the project.

4.1. Dissemination

Throughout the duration of the Robo-Mate project, dissemination activities were performed in order to disclose results to the public in order to maximize impact. Robo-Mate participated in several scientific conferences and published in scientific journals. The main dissemination activities with the non-scientific community started once the first functional prototypes had been produced. The 2 industry workshops and the numerous demonstrations led to an increase of interest from various organizations around the globe and could be seen as the stepping stones towards acceptance of exoskeletons in the workplace. The highlights of the main dissemination activities are described in the following sections.

4.1.1. Scientific conferences and publications

Robo-Mate delivered presentations at scientific conferences to show the advances of the project and exchange ideas with related projects. In sum, Robo-Mate gave 15 presentations at 9 conferences, some of them attracting attention not only from academia but from companies as well (such as VDI-Konferenz or WEROB). Robo-Mate also published 3 articles in peer-reviewed journals and one book chapter on the Robo-Mate modules (for details, see Robo-Mate website).

4.1.2. Industry Workshops

Industry workshop in Stuttgart (12 June 2015)
The Fraunhofer Institute for Industrial Engineering organised the first exoskeleton demo for industry on Friday, 12 June 2015. The aim of the workshop was to present the progress of the prototypes developed during the first 18 months of the project. This industry workshop was the first on-site demonstration of the Robo-Mate trunk and arm modules, as well as the modelling, simulation and 3-D visualisation of advanced manufacturing environments integrating exoskeletons.

Several of Robe-Mate's experts as well as experts from outside the consortium held presentations to industry representatives (see below).

Figure 36: List of industry workshop speakers

17 company representatives attended the event. Their contact details were collected and later used to disseminate updates and results on the project.

The workshop was also an opportunity to take pictures of the modules (see figure 2) and produce a short video with subtitles in English and German, which were used for dissemination measures throughout the course of the project.

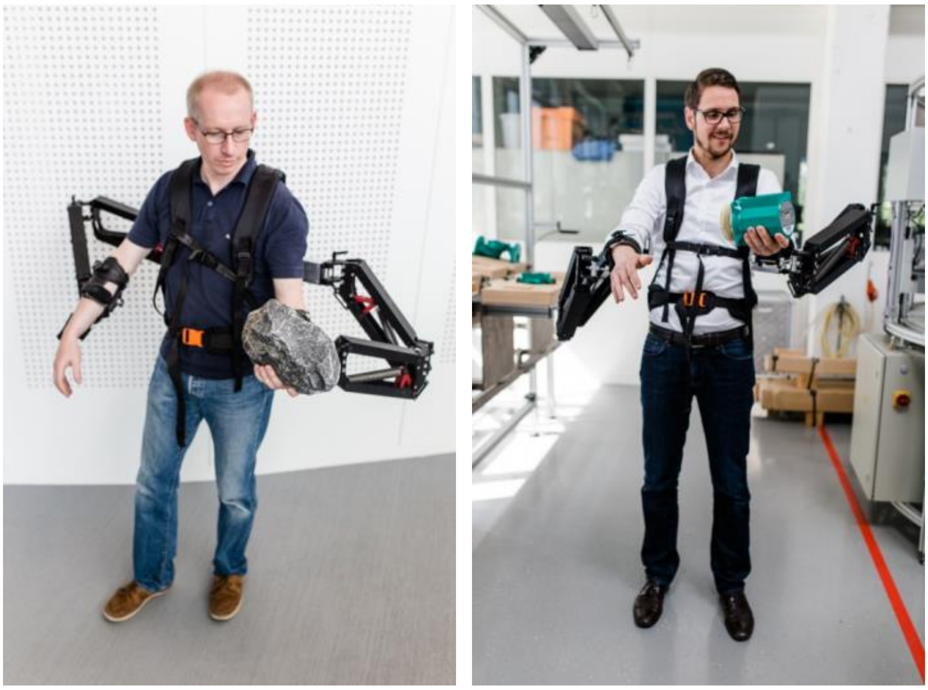


Figure 37: The passive arms modules in action during the Stuttgart industry workshop

Industry Workshop in Sibiu (30 August 2016)
After the M36 meeting in Sibiu, COMPA, ROPARDO and IAO invited companies from the region to Sibiu, Romania, to show them Robo-Mate's modules. In total, 12 representatives from 10 companies participated in the workshop on 30 August 2016. The industry workshop consisted of presentations from Robo-Mate partners, live demonstrations and sessions which allowed the company representatives to try on and test the Robo-Mate modules. For some impressions of the industry workshop see Figure 5.

Figure 38: Demonstration of the Robo-Mate active arm module

4.1.3. Demonstrations

Demonstration at Logistica
Logistica is the leading logistics trade fair in the Benelux and took place from 10 to 13 November 2015 in Jaarbeurs Utrecht (NL). The event features not only an exhibition, but seminars, presentations – and demonstrations. Robo-Mate partner TNO was invited to one of these demonstration sessions and presented the prototype of Robo-Mate's passive parallelogram arm module.

Demonstration at VDI Workshop
Robo-Mate was invited to the specialized VDI conference "Assistive robots in production" from 9 to 10 December 2015 in Berlin, Germany. VDI stands for "Verein Deutscher Ingenieure" and is Germany's biggest association of engineers. The conference covered current applications of human-robot collaboration in the industry and was chaired by Robo-Mate's coordinator Hans Wernher van de Venn.

The conference was complemented by two special days: The first one on "Exoskeletons for industrial applications" was chaired by Robo-Mate's technical coordinator Konrad Stadler and was visited by 25 persons, mainly decision-makers and innovation managers from the German automotive industry. The second was titled "Humans, robots and security" chaired by Robo-Mate's partner MRK. During the conference and its special days, experts and users from the industry reported on how to optimally make use of human-robot collaboration and how to overcome the most frequent challenges. The conference was aimed at employees, engineers and leaders in the area of robotics and automation as well as at producers of robots.

Cybathlon

Cybathlon was an event organized by ETH Zurich on 8 October 2016 in Kloten (CH). It was promoted as "a championship for racing pilots with disabilities using advanced assistive devices including robotic technologies". One of Cybathlon's aims was to facilitate conversation between academia and industry and to attract the interest of the general public to robotic assistive devices.

Robo-Mate was present at the event with its active arm module. The Swiss public service broadcaster SRF featured Robo-Mate in two items connected to this event:

- Live broadcast: A journalist tried the active arms live during the event and Dr. Konrad Stadler (ZHAW) explained how it worked and how exoskeletons like Robo-Mate can help Europe's industry (broadcast available on SRF website)
- Pre-produced item: Before the event, SRF produced an item on the industry tests of the Robo-Mate prototypes (trunk module and passive and active arms) at CRF, FIAT`s research facility, in Italy (item available on SRF website).

WEROB 2016

WEROB is conference conducted every two years aimed at academia, government, industry, medical centres and end users to report on innovations and exchange ideas in all fields of wearable robotics. At WEROB 2016 (18–21 October, Segovia, ES) Robo-Mate was one of the wearable robotics projects that was given the opportunity to demonstrate a prototype. IIT used this opportunity to present the latest trunk module prototype. In addition, Robo-Mate was present at the EU projects booth with a video, a flyer and a poster on the three Robo-Mate modules.

hub conference

The hub conference (22 November, Berlin, DE) is a showcase for technology trends and brings together industry, SMEs, investors, policy-makers and scientist in one place. One of the key topics of the 2016 conference was "Working in the Digital Age". Robo-Mate was invited to attend this conference, demonstrate the trunk module and give a presentation.

4.2. Exploitation

The exploitation activities started at the beginning of 2016 and focused on increasing the interest and commitment of companies and leads which had been building up over the duration of the project through dissemination activities. The most promising contacts from the high number of contacts were picked for exploitation activities which best suited their needs. This included industry and shop floor visits, creating a business plan and preparing for a start-up as well as brokerage and pitching event. IP was protected mainly through publications (passive protection).

4.2.1. IP Protection

Patent searches have shown that the IP landscape for exoskeleton components is very extensive with many patents close to the Robo-Mate technology. Hence patent registration was not deemed a suitable measure for IP protection. Additionally, many patents are related to application areas outside the Robo-Mate operating area. Most common examples are: teleoperation, military applications and medical applications. The Robo-Mate consortium concluded a different strategy was needed. Components would only be patented if they sufficiently differentiated from existing components. IP protection of the Robo-Mate modules focussed mainly on passive protection through scientific publications.

4.2.2. Industry visits

Starting in January 2016, ACCEL, ZHAW and IAO started inviting companies to demonstrations in ZHAW's labs in Winterthur (CH). In sum, 8 companies visited ZHAW and saw the Robo-Mate modules. The visits usually took 5 hours, starting with an overview presentation, continued with a hands-on demonstration of modules and concluded by a discussion on potential application areas, weaknesses, strengths, opportunities and threats.

4.2.3. Shop floor visits

Robo-Mate used shop floor visits to assess the needs of end-users and explore collaboration options for follow-up projects or pilot tests of the Robo-Mate modules. In total, Robo-Mate partners visited 4 companies in order perform on-site analysis of the tasks workers have to perform. The Robo-Mate partners spent on average a day at the companies in order to introduce Robo-Mate, to discuss problems with management as well as directly observe workers on the shop floor. The aim was to define tasks and potential application areas on-site in order to support workers and define who could benefit from using which Robo-Mate module. The Robo-Mate team also produced a short presentation with the key insights they gained during observation.

4.2.4. Business Plan & start-up company preparations

A Business Plan was set up to highlight the key functions and benefits of Robo-Mate to project stakeholders. It has been used as a tool to introduce, inform and attract possible prospects in the industry, in one-to-one meetings, in presentations during conferences and workshops. The business plan was also the beginning of start-up company preparations (ongoing as of November 2016).

4.2.5. Brokerage and Pitching event

Around 50 people visited the **Brokerage and Pitching Event** on 28 November 2016 in Amsterdam. The event was initiated by Robo-Mate and facilitated by the Common Exploitation Booster. 5 other EU-funded exoskeleton projects were present and showed their work (AXO-SUIT, Symbitron, SPEXOR, BALANCE and MovAiD). The event also attracted potential customers, an investor, engineers and representatives from 3 exoskeleton companies.

4.3. Outlook

The Robo-Mate project officially ended on the 30th November 2016. However, some measures have already been implemented and others are currently being prepared to ensure the sustainability of newly generated knowledge and of the Robo-Mate modules. These include the following:

- Pilot tests for different tasks and in selected companies from different sectors.
- Industry-academia collaboration to adapt selected module(s) for specific tasks.
- Follow-up research projects to advance the current Technology Level 6 of the most promising module(s)
- Start-up company, cooperation partners or joint venture(s) exploiting the technologies developed during the projectto deliver future products and solutions to industry.

The experience, knowledge, prototypes and contacts built up during the 39-month project implementation will thus continuously be used for follow-up projects and companies, research in adjacent fields and industry-academia collaboration.

5. CONTACT

During the last months of the Robo-Mate project, the project website has been redesigned to present the outcomes of the project. The website will remain online and present outcomes, contacts, follow-up projects and offers to industry.

www.robo-mate.eu

6. REFERENCES

[1] K. S. Stadler, W. J. Elspass and H. W. Van de Venn, "Robo-Mate: Exoskeleton to Enhance Industrial Production," in *Mobile Service Robotics*, World Scientific, 2014, pp. 53-60.

[2] T. R. Waters, V. Putz-Anderson, A. Garg and L. J. Fine, "Revised NIOSH equation for the design and evaluation of manual lifting tasks," *Ergonomics,* vol. 36, no. 7, pp. 749-776, 1993.

[3] European Parliament and of the Council, *Directive 90/269/EEC - manual handling of loads,* 1990.

[4] S. Bevan, "The impact of back pain on sickness absence in Europe," The Work Foundation, 2012.

[5] A. Gerfin, "Rückenreport Schweiz," Rheumaliga Schweiz, 2011.

[6] K. Summers, K. Jinnett and S. Bevan, "Musculoskeletal Disorders, Workforce Health and Productivity in the United States," The Workfoundation, 2015.

[7] B. W. Koes, M. W. van Tulder and S. Thomas, "Diagnosis and treatment of low back pain," *British Medical Journal,* vol. 332, pp. 1430-1434, 2006.

[8] E. Westkämpfer, D. Spath, C. Constantinescu and J. Lentes, Digitale Produktion, Springer Vieweg, 2013.

[9] M. P. de Looze, T. Bosch, F. Krause, K. S. Stadler and L. W. O'Sullivan, "Exoskeletons for industrial application and their potential effects on physical work load," *Ergonomics,* vol. 59, no. 5, pp. 671-681, 2015.

[10] J. Van der Vorm, L. O`Sullivan, R. Nugent and M. de Looze, "White Paper - Considerations for developing safety standards," www.robo-mate.eu, 2015.

[11] ISO, *ISO 18646 Performance criteria and related test methods for service robots,* International Organization for Standardization, 2016.

[12] ISO, "ISO 10218 Robots and robotic devices -- Safety requirements for industrial robots," International Organization for Standardization, 2011.

[13] ISO, *ISO/TS 15066:2016 Robots and robotic devices -- Collaborative robots,* International Organization for Standardization, 2016.

[14] ISO, *ISO 13482 Robots and robotic devices -- Safety requirements for personal care robots,* International Organization for Standardization, 2014.

[15] European Commission, *Commission communication in the framework of the implementation of the Directive 2006/42/EC of the European Parliament and of the Council on machinery and amending Directive 95/16/EC,* 2016.

[16] J. Van der Vorm, M. de Looze, M. Hadziselimovic and P. Heiligensetzer, “White Paper - Risk assessment of Robo-Mate, an exoskeleton for workers,” www.robo-mate.eu, 2016.

[17] L. O'Sullivan, R. Nugent and J. van der Vorm, “Standards for the safety of exoskeletons used by industrial workers performing manual handling activities: A contribution from the Robo-Mate project to their future development,” *Procedia Manufacturing,* vol. 2015, no. 3, p. 1418 – 1425, 2015.

[18] R. Altenburger, D. Scherly and K. S. Stadler, “Design of a passive, iso-elastic upper limb exoskeleton for gravity compensation,” *ROBOMECH Journal,* vol. 3, no. 12, 2016.

[19] K. S. Stadler, R. Altenburger, E. Schmidhauser, D. Scherly, J. Ortiz, S. Toxiri, L. Mateos and J. Masood, “Robo-Mate an Exoskeleton for Industrial Use – Concept and Mechanical Design,” in *Advances in Cooperative Robotics: Proceedings of the 19th International Conference on Clawar 2016*, London, 2016.

[20] S. Toxiri, J. Ortiz, J. Masood, J. Fernndez, L. A. Mateos and D. G. Caldwell, “A wearable device for reducing spinal loads during lifting tasks: Biomechanics and design concept,” in *IEEE Conference on Robotics and Biomimetics*, Zhuhai, China, 2015.

[21] ISO, *ISO9241 Ergonomics of human--system interaction,* International Organization for Standardization.

[22] ISO, *ISO 6385 Ergonomics principles in the design of work systems,* International Organization for Standardization, 2016.

[23] ISO, *ISO/TR 16982 Ergonomics of human-system interaction -- Usability methods supporting human-centred design,* International Organization for Standardization, 2002.

[24] A. Bangor, P. T. Kortum and J. T. Miller, “An Empirical Evaluation of the System Usability Scale,” *International Journal of Human-Computer Interaction,* vol. 24, no. 6, p. 574–594, 2008.

[25] SIEMENS, “Process Simulate Human,” [Online]. Available: www.siemens.com/tecnomatix. [Accessed 5 February 2017].