

OCCUPATIONAL EXOSKELETONS: WEARABLE ROBOTIC DEVICES TO PREVENT WORK- RELATED MUSCULOSKELETAL DISORDERS IN THE WORKPLACE OF THE FUTURE

Introduction

This discussion paper was developed as part of the collaboration agreement signed by the Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro (INAIL) with EU-OSHA related to the provision of research services in the area of musculoskeletal disorder (MSD) prevention, and presents results of a joint INAIL/Italian Institute of Technology (IIT) project on collaborative exoskeletons.

In recent years, new assistive devices worn by the worker, known as exoskeletons, have been introduced in the workplace. The growing interest in exoskeletons indicates that wearable robotic devices will possibly represent one of the next changes in many occupational scenarios (e.g. in economic sectors such as automotive and aerospace manufacturing, logistics, construction and agriculture).

The idea of supporting human activities with automation and mechanisation such as robots and robotic devices is not recent. Robots and robotic devices, such as exoskeletons, typically perform or support the performance of tasks to improve the quality of life of intended users, irrespective of age or capability.

In particular, manual material handling (MMH) is a common physically demanding activity in many occupational contexts (e.g. in economic sectors such as manufacturing, logistics, construction and agriculture). MMH includes tasks such as dynamic lifting and prolonged stooped postures, can generate considerable compressive pressure on the lumbar spine and is one of the main risk factors for work-related musculoskeletal disorders (WRMSDs). WRMSDs not only increase the costs sustained by companies but, most importantly, have a severe impact on workers' quality of life (Peters and Wischniewski, 2019). Safety and ergonomic guidelines for the workplace aim to reduce the workload on workers, often resulting in very strict limitations on MMH operations in terms of object weights and movement frequency (Garg, 1995).

With the use of technical devices, such as external manipulators, which unload all or part of the weight to be handled, the physical workload on workers can be reduced.

Nevertheless in some circumstances, such devices and other technical and organisational measures to design workplaces can be impractical or infeasible, and therefore it becomes necessary to consider the use of exoskeletons.

As a matter of fact, there are many workplaces that are not tied to a specific location (e.g. in logistics, construction, agriculture), where ergonomic design measures cannot be implemented because of the changing environmental requirements (Schick, 2018). Furthermore, in other scenarios overexertion of the musculature, frequent lifting or incorrect postures can increase the risk of physical overstrain. In all these contexts, exoskeletons may offer a number of possibilities to improve working conditions and help prevent WRMSDs.

In this perspective, this article tries to define the state of the art of occupational exoskeletons and to illustrate what needs must be met and what requirements this typology of exoskeleton must possess in order to maximise the user benefits and minimise potential negative impacts, through a human-centred design (HCD) process.

Definition of occupational exoskeletons

Exoskeletons can be defined as personal assistance systems that affect the body in a mechanical way (Liedtke and Glitsch, 2018), and are normally classified as active or passive systems.

Active exoskeletons use actuators (mechanical drive components) to support human movements. Most active exoskeletons use electric motors, but examples of pneumatic actuation exist (Aida, Nozaki & Kobayashi, 2009; Inose et al., 2017). A computer program based on sensor information controls the action of the actuators during operation.

In contrast, *passive exoskeletons* use the restoring forces of springs, dampers or other materials to support human movement.

The movements of the user generate the energy stored in a passive exoskeleton (de Looze et al., 2016). Furthermore, forces are redistributed to protect specific body regions. The change in user performance results not from additional physical strength but from the ability to maintain exhausting positions over a longer period of time, for example in overhead working conditions.

In order to frame the exoskeleton product more specifically and above all to define its characteristics more specifically, we start by analysing what is currently meant by 'robot' and 'robotic device'.

International Standard ISO 8373:2012 (ISO, 2012) specifies vocabulary used in relation to robots and robotic devices operating in both industrial and non-industrial environments. It provides definitions and explanations of the most commonly used terms, which are grouped into classes by main topics of robotics, and so it helps to clarify the differences among these.

Generally speaking:

1. A *robot* is an actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks. A robot includes the control system and interface with the control system.
2. A *robotic device* is an actuated mechanism fulfilling the characteristics of robot, but lacking either the number of programmable axes or the degree of autonomy (e.g. power assist device, teleoperated device, two-axis industrial manipulator).

The standard classifies robots and robotic devices as:

- *industrial applications*, which can be either fixed in place or mobile for use in industrial automation applications such as manufacturing, inspection, packaging and assembly;
- *service applications*, for personal use for a non-commercial task (e.g. domestic servant robot, automated wheelchair, personal mobility assistance robot, pet-exercising robot) or professional service robots used for a commercial task ⁽¹⁾.

This overview helps to introduce the definition and technical characteristics of a device that can be considered an *active exoskeleton*.

For this purpose, the draft standard ISO/CD 18646-4 – Robotics – Performance criteria and related test methods for service robots – Part 4: Lower-back support robots (ISO/CD 2019), defines:

- a *wearable robot* as a device that provides an assistive force or torque for supplementation or augmentation of personal capabilities while attached to the human during use [wearable robots are referred to as restraint-type physical assistant robots in ISO 13482:2014 (ISO 2014)];
- a *lumbar support robot* as a wearable robot to reduce the load in the lower back of the user by its assistive force or torque (Figure 1).

In a narrower sense, *active exoskeletons are wearable service robot devices* that modify internal or external forces acting on the body to enhance or support the strength of the user.

⁽¹⁾ Professional service robots are usually operated by a properly trained operator (e.g. cleaning robots for public places, delivery robots in offices or hospitals, fire-fighting robots, rehabilitation robots and surgery robots in hospitals).

Figure 1: Examples of lumbar support robot



Source: XoTrunk – INAIL/Italian Institute of Technology (IIT) project on collaborative exoskeletons

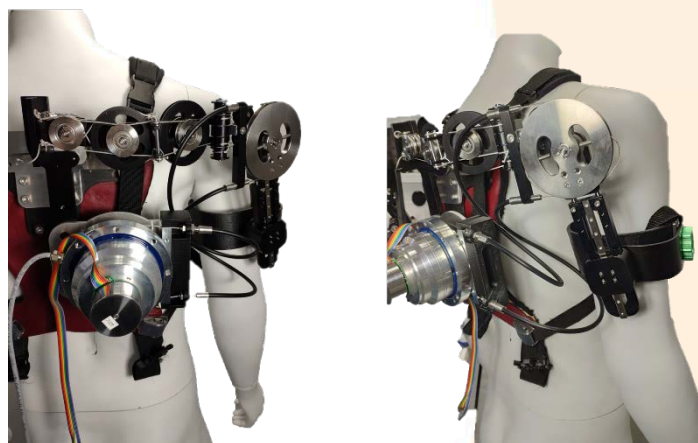
There are many possible applications of exoskeletons, which include physical therapy for clinical motor rehabilitation (Colombo et al., 2000), assistance for people with motor impairments (Ortiz, Di Natali & Caldwell, 2018) or those in the military (Kazerooni et al., 2005), and even protective or enhancing gear for sports (RoamRobotics, 2018).

Recently, there has been increasing interest in employing exoskeletons to reduce the physical load on workers carrying out demanding activities in several occupational sectors, because these devices may offer an alternative to existing solutions, when the latter are not practicable. These exoskeletons are referred to as *occupational exoskeletons*.

In recent years, the landscape of occupational exoskeletons has expanded substantially, including several new research prototypes as well as products by existing or new companies. More recently, a white paper by Sugar et al. (2018) listed the newest 'lift assist wearables' and their applications, with a particular focus on devices for reducing lumbar loading.

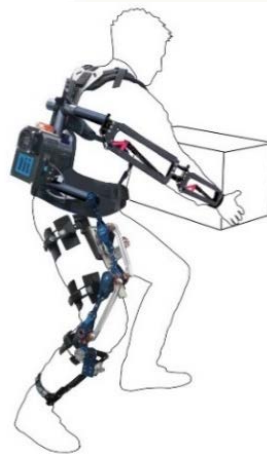
In general, occupational exoskeletons, like other applications, can be classified into three groups: lower, upper (Figure 2) and full body exoskeletons. These last offer support to the upper body and lower body at the same time (Figure 3).

Figure 2: Example of occupational upper active exoskeleton



Source: Park, Ortiz & Caldwell, 2018

Figure 3: Concept of occupational full body active exoskeleton



Source: INAIL/Italian Institute of Technology (IIT) project on collaborative exoskeletons

Occupational exoskeletons: difficulty of acceptance by workers

Despite the high interest in exoskeletons with an occupational application, large-scale implementation of this type of exoskeletons has still a long way to go, mainly because there is little knowledge of these wearable service robot devices and their real preventive effects on WRMSDs, and because of some technical and user acceptability issues.

Although the potential benefit of exoskeletons preventing WRMSDs could be significant, it is important to take into consideration several specific safety issues, which need to be addressed to promote more widespread use of exoskeletons in the workplace.

For workers wearing occupational exoskeletons (both active and passive), several risk scenarios can be defined relating to their prolonged use (EU-OSHA, 2019).

In this regard, the French National Research and Safety Institute for the Prevention of Occupational Accidents and Diseases (INRS) has published an overview of the new risk factors encountered in the workplace while using exoskeletons (INRS, 2019). On the one hand, exoskeletons can be an opportunity to reduce muscular, joint, ligament and bone stress at work by physically assisting workers and potentially preventing WRMSDs or supporting workers with physical impairments. On the other hand, new potential health risks could occur because of the redistribution of stress to other body regions. The use of exoskeletons also affects motor control, joint stability and altered kinematics (INRS, 2018).

There are also some technical, safety and ergonomic issues that need to be considered and solved first to imagine large-scale implementation of occupational exoskeletons.

One reason might be, for example, the level of discomfort associated with wearing the exoskeleton (e.g. Abdoli-E, Agnew & Stevenson, 2006; Abdoli-E et al., 2007). After establishing the biomechanical advantage, the elimination of discomfort at the physical user interface with the equipment could be the next challenge in the design of exoskeletons, bearing in mind that even a minimal level of discomfort might hinder acceptance by users.

Another concern regarding passive devices is related to the potentially increased activity of leg or arm muscles. This aspect certainly needs consideration in further developments towards final ready-to-use products. Active exoskeletons may have greater potential to reduce physical loads than passive exoskeletons, lightening the load on many joints throughout the body. However, with increasing numbers of joints and their actuators, and power supply, the weight of the exoskeleton will increase. To relieve the worker from this constant weight burden, an extension of the exoskeleton to the ground would be beneficial, but would increase the complexity of the design.

The use of *anthropomorphic exoskeletons* can be helpful to overcome these issues.

Anthropomorphic exoskeletons have a similar skeletal structure to the human body, involving a series of many actuated joints. This architecture presents some advantages compared with that of non-anthropomorphic exoskeletons, which does not follow the same kinematics of the human body. For example, the footprint becomes relatively small, as it attaches directly to the body, and consequently reduces the size.

The exoskeleton replicates the movements of the worker, i.e. the limbs of the human and the exoskeleton are aligned during motion. This requires the exoskeleton to detect how the human intends to move so that the actuators can respond appropriately. Distinguishing intended from unintended movements is often difficult and results in systems with many different kinds of sensors and complex signal processing.

Yang et al. (2008) address the necessity for improved control strategies to enable smooth movements at a normal to fast pace, human-machine information exchange, real-time motion planning and safety control are the difficulties faced in building such a control strategy.

It remains a challenge for *anthropomorphic active exoskeletons* to reflect the human anatomy, kinematics and kinetics to enable natural and comfortable movements. Moreover, rotational movement in any joint requires movement between the skin and skeletal structure. To accommodate this during movement, the exoskeleton should ideally extend or shorten.

Another concern is that international safety standards for occupational application of exoskeletons do not yet exist. This is a significant barrier to their adoption.

To date, only the previously mentioned ISO/DIS 18646-4, which provides performance criteria and related test methods for lower-back support robots, and general standards such as EN ISO 10218-1:2011 (ISO, 2011) and ISO/TS 15066:2016 (ISO/TS, 2016), which give safety requirements for industrial robots and collaborative robots, exist.

In addition to the above technical challenges, and the safety and regulatory aspects of large-scale implementation of occupational exoskeletons, user acceptability is a crucial factor for the real implementation of these devices in the workplace.

Recent publications looking at the barriers to acceptance and utilisation of wearable technology noted that the device must not only be safe, comfortable, useful and usable but, just as importantly, must be desirable to the end user (Reid et al., 2017; Schall, Seseck & Cavuoto, 2018; Jacobs et al., 2019). For this reason, it is advisable to resort to a user-centred design approach to involve the users (companies and workers) directly in the exoskeleton design process.

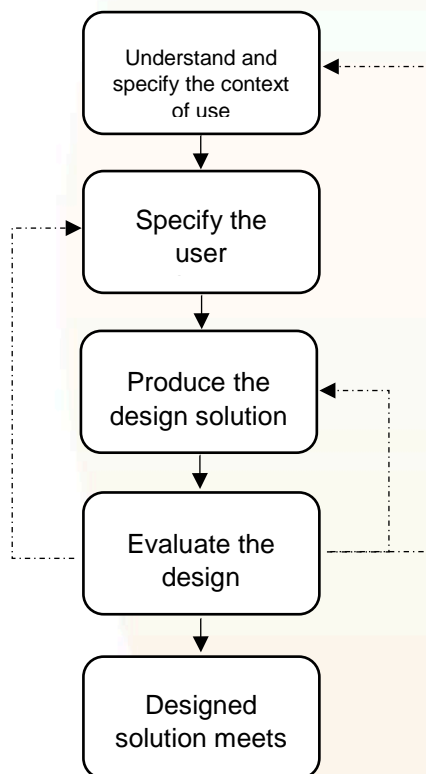
Human-centred design and occupational exoskeletons

Human-centred design is an approach to interactive development that aims to make systems usable and useful by focusing on the users, their needs and their requirements, and by applying human factors/ergonomics, and usability knowledge and techniques.

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.

There is a substantial body of human factors/ergonomics and usability knowledge about how HCD can be organised and used effectively. EN ISO 9241-210:2019 (EN ISO, 2019) aims to make this information available to help to develop systems following an interactive process, where appropriate (Figure 4). This standard is specifically for managing hardware and software design and redesign processes to identify and plan effective and timely HCD activities, but the approach can also be useful for other complex systems such as the design of an occupational exoskeleton or other technical safety measures.

Figure 4: Plan of the human-centred design process



Source: authors' elaboration of EN ISO, 2019, figure 1

In the literature, there are some applications of HCD to optimise the design of robotic exoskeletons, especially for rehabilitation purposes (Zhou, Li & Bai, 2017) or for general investigation (Davis et al., 2020).

Another useful standard for the scope of HCD is EN 614-2:2000+A1:2008 (EN, 2008), which focuses on the interactions between the design of machinery and work tasks. This standard is a harmonised standard published in the *Official Journal* for the Machinery Directive (2006/42/EC), and establishes the ergonomic principles and procedures to be followed during the design process of machinery and operator work tasks. In general, an exoskeleton can be defined as a machinery in the field of the regulations of the Machinery Directive of the European Union.

The next section provides an overview of the critical issues presented in the literature, addressed by a two-stage HCD approach as defined by EN ISO 9241-210:2019 (EN ISO, 2019). This information is helpful to guide designers of occupational exoskeletons before wearable devices can be fully adopted. The section indicates some ergonomic harmonised standards on machinery that are already published and can indicate ways to address these issues.

Design characteristics of a safe occupational exoskeleton

When adopting the HCD process, understanding and describing the user context is the first step to take. Therefore, for occupational exoskeletons it is of great importance to define the characteristics of the workplace and the MMH activities to be carried out by the worker.

In this case it is useful to refer to the ISO/TR 12295:2014 technical report on the manual handling of loads and the evaluation of static working postures (ISO/TR, 2014) to define the intended use of exoskeletons in the process and the specifications of the work activity.

Based on this procedure, a risk assessment relating to a specific job must begin by defining the tasks performed by the worker, such as:

- lifting and carrying weights,
- pushing and pulling weights,
- moving light weights at high frequency,
- static working postures.

Other aspects to consider at this stage, based on information about the activity to carry out in relation to the surrounding conditions and the work environment, relate to:

- the handling load (e.g. mass, size/dimension, grip/handles),
- environmental aspects (e.g. temperature, outdoor/indoor activity, restricted spaces, work space features),
- production conditions (e.g. times and working methods, price of the device),
- workers' characteristics (e.g. gender, age, qualifications, skill).

The second stage of the HCD process is specifying user requirements. In general, in the literature, the following main requirements have been identified:

- freedom of movement (e.g. body postures, dimensions of the device),
- comfort (e.g. postural and physiological comfortable angle),
- environmental conditions (e.g. interaction between operators, caloric/metabolic expenditure),
- wearability (e.g. material, shape of the device, adaptability),
- intuitiveness of use (e.g. cognitive resources required),
- biomechanical aspects (e.g. force/pressure in the different parts of the body, vibrations, noise, distribution of the weight on the operator's body),
- physiological aspects and effects (e.g. right balance between activity and inactivity).

Furthermore, other secondary aspects can encourage the acceptance of the system, such as the aesthetics of the occupational exoskeleton.

The guidance on the application of the essential health and safety requirements on ergonomics set out in Section 1.1.6 of Annex I to the Machinery Directive gives several standards that are useful to define some of these aspects.

In Table 1 below, the ergonomic standards useful for designing safe occupational exoskeletons are listed.

Table 1: International standards for the design characteristics of safe occupational exoskeletons

Operator's variability	Physical dimension	EN 547-3:1996+A1:2008 – Safety of machinery – Human body measurements — Part 3: Anthropometric data EN 614-1:2006+A1:2009 – Safety of machinery – Ergonomic design principles – Part 1: Terminology and general principles EN 894-1:1997+A1:2008 – Safety of machinery – Ergonomics requirements for the design of displays and control actuators – Part 1: General principles for human interactions with displays and control actuators EN 1005-1:2001+A1:2008 – Safety of machinery – Human physical performance – Part 1: Terms and definitions EN 1005-4:2005+A1:2008 – Safety of machinery – Human physical performance – Part 4: Evaluation of working postures and movements in relation to machinery access into machinery EN ISO 14738:2008 – Safety of machinery – Anthropometric requirements for the design of workstations at machinery EN ISO 15536-1:2008 – Ergonomics – Computer manikins and body templates – Part 1: General requirements EN ISO 7250-1:2017 – Basic human body measurements for technological design – Part 1: Body measurement definitions CEN ISO/TR 7250-2:2011+A1:2013 – Basic human body measurements for technological design: Statistical summaries of body measurements from national populations
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	Strength	EN 614-1:2006+A1:2009 EN 1005-1:2001+A1:2008 EN 1005-2:2003+A1:2008 – Safety of machinery – Human physical performance – Part 2: Manual handling of machinery and component parts of machinery EN 1005-3:2002+A1:2008 – Safety of machinery – Human physical performance – Part 3: Recommended force limits for machinery operation EN ISO 15536-1:2008
Space for movement	Posture	EN 614-1:2006+A1:2009 EN 1005-1:2001+A1:2008 EN 1005-2:2003+A1:2008 EN 1005-3:2002+A1:2008 EN 1005-4:2005+A1:2008 – Safety of machinery – Human physical performance – Part 4: Evaluation of working postures and movements in relation to machinery access into machinery EN ISO 14738:2008 EN ISO 15536-1:2008
	Dynamics	EN 614-1:2006+A1:2009 EN 1005-1:2001+A1:2008 EN 1005-4:2005+A1:2008 EN ISO 14738:2008 EN ISO 15536-1:2008
Work rate	Pace	EN 1005-3:2002+A1:2008
	Speed	EN 894-1:1997+A1:2008
Concentration	Mental operation	EN 614-1:2006+A1:2009 EN ISO 10075-1:2017 – Ergonomic principles related to mental work-load – Part 1: General terms and definitions EN ISO 10075-2:2000 – Ergonomic principles related to mental workload – Part 2: Design principles EN ISO 10075-3:2004- Ergonomic principles related to mental workload – Part 3: Principles and requirements concerning methods for measuring and assessing mental workload
	Cognitive performance	EN 614-1:2006+A1:2009 EN ISO 10075-1:2017 EN ISO 10075-2:2000 EN ISO 10075-3:2004
Human/machine ry interface	Interaction	ISO 6385:2004 – Ergonomic principles in the design of work systems EN ISO 9241-910:2011 – Ergonomics of human–system interaction – Part 910: Framework for tactile and haptic interaction
	Visual	EN 614-1:2006+A1:2009 EN ISO 14738:2008
	Auditory	EN 614-1:2006+A1:2009
	Sensitivity	EN ISO 7730:2005 – Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria ISO 7933: 2004 – Ergonomics of the thermal environment – Analytical determination and interpretation of heat stress using calculation of the predicted heat strain EN ISO 8996:2004 – Ergonomics of the thermal environment – Determination of metabolic rate

Source: Authors' elaboration

After understanding and specifying the user context and specifying user requirements, the HCD approach of EN ISO 9241-210:2019 gives other structured steps that the designer has to follow to target the design solutions to meet context and user requirements. In the literature, one ideal choice for some of the abovementioned aspects is to develop anthropomorphic occupational exoskeletons (Figure 5) to reflect the human anatomy, kinematics and kinetics to enable natural and comfortable movements.

Figure 5: Example of anthropomorphic occupational exoskeleton



Source: FleXo – INAIL/Italian Institute of Technology (IIT) project on collaborative exoskeletons

Gender-related considerations have to be taken into account in exoskeleton design. Examples of gender-related research aspects include considerations of female anthropometry.

Other ideas that can address the need for design solutions to meet the context and user requirements for an active exoskeleton could be:

- Power supplies with batteries and not cables. This choice increases the weight of the exoskeleton, but guarantees freedom of movement for the worker. It is therefore a possibility that should be considered in relation to the type of activity to be carried out.
- Reduce the weight of the exoskeleton by the use of customised motors. This makes the device lighter than using commercial engines, but increases its price.
- Decrease the price of the device. The development of specific commercial components for occupational exoskeletons should be guaranteed by the suppliers.
- Increase the adaptability. Produce more adaptable exoskeletons, to also allow large-scale production, which obviously would reduce the cost of the product.

The last step of the HCD process is the evaluation of the gap between the design context and user requirements, reiterated as many times as necessary.

Furthermore, as solutions evolve (e.g. lighter materials, smaller devices, more integrated devices, wearable computing, artificial intelligence), the designer, with the help of users, will continue to work on making a device acceptable and, more importantly, ensuring that it will be used.

Conclusions

As shown in this article, exoskeletons can support workers in performing specific tasks in some working environments, and therefore can help prevent WRMSDs. Nevertheless, for a number of reasons the use of occupational exoskeletons in the workplace is still rather limited. On the one hand, there is little knowledge about these devices and their real preventive effects on WRMSDs. On the other, technical challenges and user acceptability issues explain the current state of diffusion of these wearable service robot devices in the workplace.

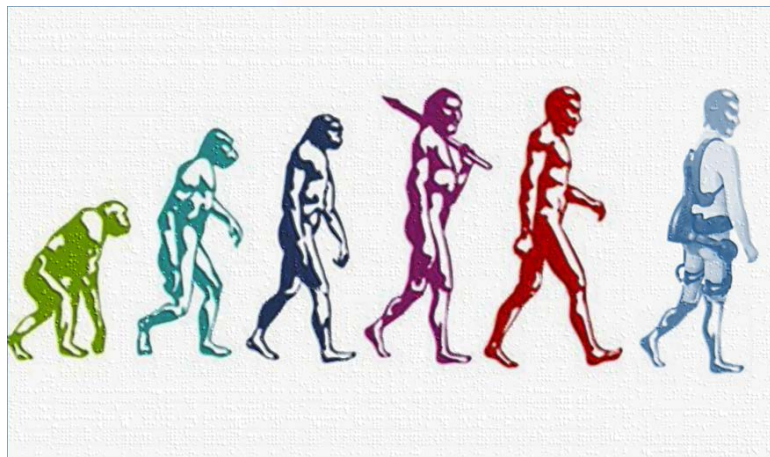
The HCD approach can be a tool to guarantee ever more widespread diffusion of these systems, responding more and more precisely to the real needs that users manifest.

The information in this article can be identified as a potential foundation for future occupational exoskeleton human user research and provide critical insights that will ensure that occupational

exoskeletons and their many potential benefits are here to stay instead of becoming merely the next ergonomic trend (Figure 6) in the workplace of the future for the prevention of WRMSDs.

Furthermore, the use of active and passive exoskeletons makes it necessary to develop new methodologies for biomechanical risk assessment. The redistribution of forces applied to the body and the changes in kinematics and motor systems that the use of exoskeletons entails do not allow the application of existing biomechanical risk assessment methodologies.

Figure 6: Exoskeletons as the next step in a hypothetical Darwinian theory of evolution



Source: authors' elaboration of Darwin's theory of evolution

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