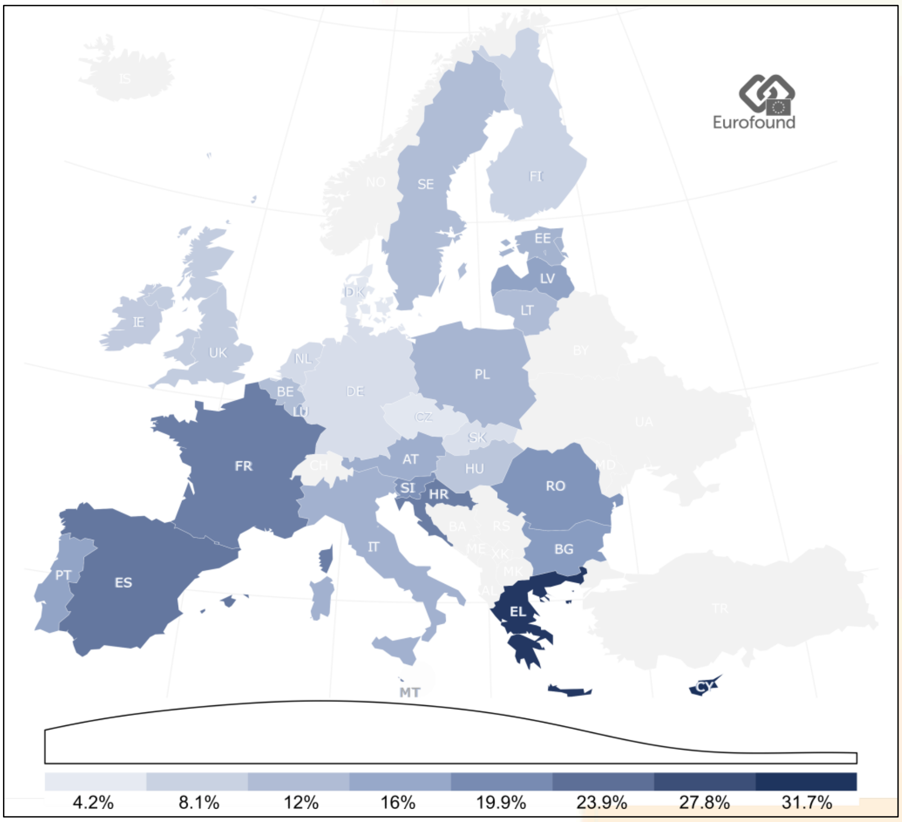
THE IMPACT OF USING EXOSKELETONS ON OCCUPATIONAL SAFETY AND HEALTH

Introduction

In recent years, new body-worn assistive devices — so-called exoskeletons — have been introduced in the workplace. Their use is expected to become more commonplace in the future, since prototypes of exoskeletons have proven to be beneficial in areas such as medical care. In particular, exoskeletons appear to be a new approach to addressing the issue of work-related musculoskeletal disorders (WRMSDs). WRMSDs are one of the most challenging problems for workplaces in Europe. [1] Figure 1 shows the percentages of workers working in tiring and painful positions, which can be associated with poor workplace design, as working conditions are still a major problem all across Europe. Exoskeletons have been developed to address this problem.

Figure 1 The percentages of all employees in Europe working in tiring or painful positions (adapted from Eurofound 2019)



Exoskeletons are wearable devices that can support the musculoskeletal system using various mechanical principles. With regard to WRMSDs, they can reduce muscular stress in frequently affected body regions, such as the lower back or shoulders. Although the potential benefit of exoskeletons preventing WRMSDs could be significant, it is also necessary to take into account that such assistive

[1] Over 40 % of workers in Europe suffer from lower back pain or shoulder complaints. Furthermore, 63 % of workers perform repetitive tasks or frequently work (46 %) in potentially hazardous positions (Eurofound, 2012). The annual costs arising from health-related issues due to these working conditions amount to about 2 % of the gross domestic product of the European Union (EU) (Bevan, 2015). Many of these issues are caused by manual material handling (MMH) tasks, which include lifting, lowering, holding or carrying loads (Zurada, 2012; Collins and O'Sullivan, 2015). Twisting, bending and overhead work also increase the risk of a work-related disorder. WRMSDs are therefore not only a health-related problem, but also of central economic relevance.

devices raise new questions in relation to occupational safety and health (OSH). 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 seen as a chance to reduce muscular 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. It also affects motor control, joint stability and altered kinematics (INRS, 2018). In addition, the ergonomic design of workplaces, focusing the principles of a human-centred design, may be neglected. Nevertheless, there are many workplaces that are not tied to a specific location, for example those concerning furniture delivery or emergency services, where ergonomic design measures cannot be implemented because of the changing environmental requirements (Schick, 2018). Furthermore, overexertion of the musculature, frequent lifting, incorrect postures or heavy personal protective equipment (PPE) can increase the risk of physical overstrain in these professions. In this context, exoskeletons may offer a number of possibilities to improve working conditions.


Inc/MONOPOLY919, ©Shutterstock

The most important concern is that caution should be exercised when using technology so close to the human body. Technical and organisational measures should be taken into account when designing workplaces, before employees are equipped with exoskeletons. In general, using exoskeletons to improve the ergonomic design of workplaces should always be the last resort. Currently, there is little scientific evidence on exoskeletons in ergonomics and work science. One challenge is accessing the long-term effects of exoskeletons on human biomechanics and physiology, which is difficult to do in practice (Liedtke and Glitsch, 2018), since the type of exoskeleton, work tasks and application periods have to be considered. In addition, investigating health effects related to physiological or biomechanical aspects has just begun, since human interaction with exoskeletons is complex and time-consuming to examine. However, new approaches must be developed to demonstrate the effectiveness of exoskeletons, to better estimate the advantages and disadvantages of this technology. This article provides an overview of the current discussion on the use and evaluation of exoskeletons in terms of OSH.

Exoskeletons

Definition

An exoskeleton can be defined as a personal assistance system that affects the body in a mechanical way (Liedtke and Glitsch, 2018). In a narrower sense, exoskeletons are portable robot technologies that modify internal or external forces acting on the body. In short, exoskeletons are wearable devices that enhance or support the strength of the user. Owing to the large number of applications and different functionalities, there is still no common definition. In the literature, there is general agreement that exoskeletons can be defined as on-body external mechanical structures (Herr, 2009; De Looze et al., 2016). It is possible to classify them as active or passive systems.

Active exoskeletons use actuators (mechanical drive components) to support human movements. These mechanical components consist of electrical motors but can also be hydraulic or pneumatic driven (Gopura and Kiguchi, 2009). With this support, they provide additional strength and thus increase the performance of a worker. In contrast, passive exoskeletons use the restoring forces of springs, dampers or other materials to support human movement. The energy stored in a passive exoskeleton is generated exclusively by the movement of the user (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.

Hybrid exoskeletons, which can be active or passive systems, remain an exception so far. They use brain wave activities (EEG signals) or muscle activation to initiate movements. However, their use in industry is currently unlikely, so they will not be discussed further in this paper.

Types of exoskeletons

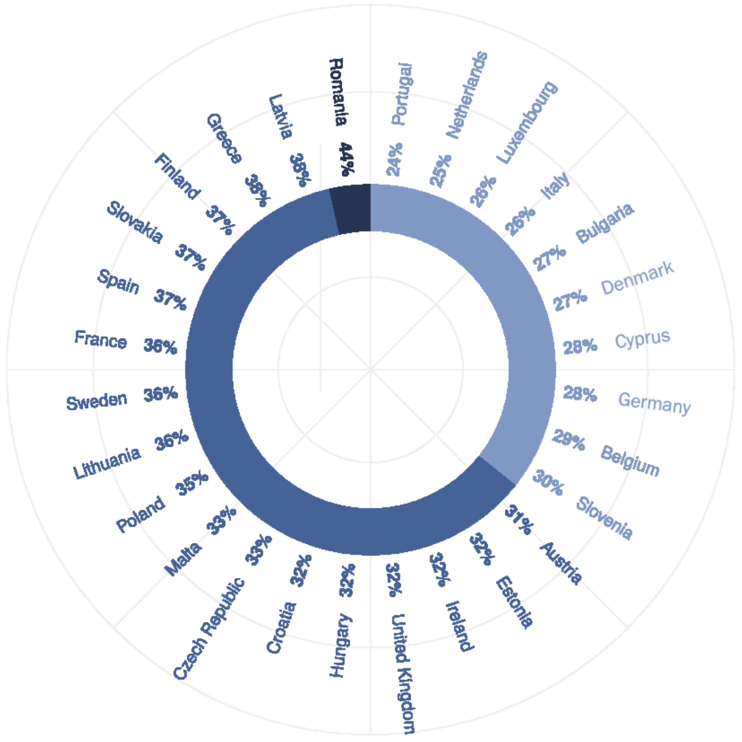
Exoskeletons can be classified into three groups: lower, upper and full body exoskeletons. Single-joint exoskeletons have been mentioned in the literature (Gams et al., 2013), but they will not be discussed further in this article because of their highly individual aspects and single case applications. Exoskeletons for the upper body usually use solid mechanical structures to redistribute body forces applied to the upper extremities and torso (e.g. upper arms, lower arms, shoulders or lower back). In this case, the redistribution of forces means that other body regions, such as hip or legs, take on additional loads. Lower body exoskeletons are able to transfer forces to the ground and thereby reduce the load on the musculoskeletal system. However, it is important to note that these principles strongly depend on the design and the functionality of the exoskeleton. Assistive systems that offer support to the upper body and lower body at the same time can be defined as full body exoskeletons.

Fields of application in workplaces

The idea of supporting human movements with technical devices is not a recent development. Portable assist the devices like exoskeletons have been used in medical care for a long time, for example the use of orthoses for rehabilitative purposes to support injured patients restore their physical health (Viteckova et al., 2013). Nevertheless, orthoses can be differentiated from exoskeletons, since they serve to support people with musculoskeletal morbidity. Exoskeletons were also developed for military applications (De Looze et al., 2016). However, the use of exoskeletons to maintain or protect the physical health of workers is new. Although improving ergonomic working conditions with assistance devices such as exoskeletons is currently a subject of controversy, they still provide new possibilities for the safety and health of employees (Schick, 2018). Furthermore, the requirements for ergonomic workplaces will play a major role in the future in ensuring the physical health of an ageing workforce brought about by demographic change. From this perspective, it is essential to develop new ergonomic tools, since the options are currently limited (Hensel et al., 2018; Schick, 2018).

The fields of application for exoskeletons to reduce WRMSDs are numerous. Throughout Europe, over 30 % of working tasks are associated with manual material handling (MMH) (Eurofound, 2012), which represents a major health risk. Work that involves repetitive tasks, handling of heavy loads, overhead work or hazardous body positions offers various possibilities for the use of exoskeletons. Figure 2 shows that, in every European country, moving and carrying heavy loads is a significant part of work. In Romania in particular, almost half of employees (44 %) sometimes handle heavy loads. In this context, industrial workplaces, furniture delivery services, emergency services and hospitals are of interest. However, it is important to recognise that ergonomic design namely in stationary workplaces. As long as technical or organisational measures provide possibilities for improving ergonomic design, the use of exoskeletons should not be preferred (Schick, 2018). Nevertheless, it seems that focusing on exoskeletons that increase the performance of workers might be of greater interest than focusing on the human-centred design of workplaces (Baltrusch et al., 2018).

Figure 2 Percentage of employees of all ages in Europe spending a quarter of their time carrying or moving heavy loads (Eurofound, 2019)



Owing to technical issues, active exoskeletons have little practical relevance. Several reports point out issues concerning the weight, mechanical structure, battery support and design of the drive mechanics of active exoskeletons (Yang et al., 2008; Herr, 2009; De Looze et al., 2016). In contrast, some passive exoskeletons are already commercially available. Nevertheless, the support of these passive systems is limited, as initially only some parts of the body can be relieved. Assistance during heavy lifting tasks is still restricted.

The intended use of exoskeletons strongly depends on their field of application. Besides their use as a technical measure, exoskeletons could also be used as personal protective devices or medical products. Depending on the intended applications, different certifications must be obtained. These certifications are strongly related to OSH issues.

Certifications of exoskeletons

Owing to their wide range of application in the field of rehabilitation, industry and the military and their different construction types, there is still no uniform regulation or certification of exoskeletons. To fill this gap, their functional design and intended use have to be considered first. In this regard, an exoskeleton can be classified as a technical device, which supports a worker in fulfilling his or her work task. Furthermore, it can be defined as PPE. In this case, the exoskeleton protects the worker from physical loads that may lead to work-related diseases, such as overuse injuries. There is currently no consensus that exoskeletons can protect against MSDs, which makes classification more difficult.

The practical application of exoskeletons is strongly related to the specific certification. As already mentioned, an exoskeleton can be defined as a technical aid as a result of the regulations of the Machinery Directive of the European Union (2006/42/EC). Active systems can be further defined with the international regulation of robots and robotic devices (ISO 10218-1:2011) and the safety requirements for personal care robots (ISO 13482:2014).

If an exoskeleton is certified as PPE, based on European Regulation 89/686/EEC, it can be used for preventive purposes to avoid work-related or overuse injuries. It should be mentioned that Regulation 89/686/EEC is gradually being transferred to the new Regulation (EU) 2016/425 on personal protective equipment.

Finally, an exoskeleton can be considered a medical device according to the corresponding European regulation (93/42/EEC). Medical products have to meet high standards for their safety and performance. A challenge is the clinical evaluation of medical efficacy, which is still difficult to prove. However, all these requirements are necessary to use exoskeletons for rehabilitation purposes or medical applications, or to make use of them within the scope of inclusion (Schick, 2018).

Workplace risk assessment with exoskeletons

Employers have a general duty to provide a safe and healthy working environment, and limit potential risks during work. Workplace risk assessments, which take all possible occupational hazards into account, are mandatory and have to be performed by all employers in Europe. According to the European guideline that was purposed to address the duties of risk assessment of the Framework Directive (89/391/EEC), specific measures are described. Such measures include the prevention of occupational risks, the provision of information and training for workers and organisations, and the means to implement the necessary measures. Based on these regulations, possible risks linked to exoskeletons in specific workplaces have to be considered.

The potential risks of exoskeletons in working environments are numerous and relate to their design and functionality. Active systems might include mechanical and technical defects. In this case, malfunctioning can lead to injuries, since the drive mechanism of active exoskeletons can exert additional forces on the body of the worker. Currently, it is difficult to classify forces of on-body devices and their connection to injuries. As a general reference, biomechanical threshold values of collaborative robots (ISO/TS 15066:2016) can be considered (Schick, 2018). It is conceivable that exoskeletons can increase the risk of injuries during a slip, trip or fall incident. However, their influence is currently assessed as low when exoskeletons for the upper body are worn during level walking (Kim et al., 2018). Nevertheless, depending on the construction and weight of the exoskeleton, workers may be restricted in their natural freedom of movement. This makes it difficult to restore balance through compensating movements in the event of a fall. The consequences could be more severe than without an exoskeleton. In addition, possible collisions between an exoskeleton and work equipment, robots or construction machines must be considered. In this context, computer simulations were performed to investigate the practical applications of exoskeletons in virtual factory environments (Constantinescu et al., 2016). In conclusion, several limitations have been mentioned concerning the redesign of workplaces with integrated exoskeletons. In the event of emergency, buildings must be evacuated quickly to ensure the safety and health of all employees. The quick removal of an exoskeleton is therefore essential. Designers should also consider situations in which the workers may be on their own.

In summary, the safety and health hazards of exoskeletons can be estimated in scenarios but not yet specified. One reason for this is the limited scientific evidence (Schick, 2018) and a lack of practical experience. In particular, the long-term effects of exoskeletons on the musculoskeletal system are unknown. As a result, there is still a need for comprehensive studies that take person-related, physiological, medical and biomechanical aspects of exoskeletons into account.

Evaluation of exoskeletons

The advantages and disadvantages of exoskeletons are currently the subject of controversy in the literature. In general, they represent a promising opportunity for research groups to improve ergonomic working conditions and reduce WRMSDs that are often associated with MMH (Hensel et al., 2018). However, physical demands concerning the musculoskeletal system are not the only aspects that should be considered. Exoskeletons may also affect social environments or influence other physiological parameters, such as blood pressure, oxygen consumption and heart rate.

Physiological aspects

Putting an external structure such as an exoskeleton on a worker’s body might have negative physiological effects. In the literature, it has already been shown that the additional weight of an exoskeleton possibly increases cardiovascular demands (Theurel et al., 2018), although the effects are still poorly known. A previous investigation revealed the impacts of weight on energy demands during movement: higher oxygen consumption was shown corresponding to the weight being carried.

Nevertheless, energy expenditure depends to a great extent on sex, walking speed and body weight (Holewijn et al., 1992). In contrast, Whitfield et al. (2014) were able to prove that an ergonomic lifting aid does not increase oxygen consumption during repetitive tasks, although the additional mass of the lifting device was included. In addition, these results are in line with the findings of different research groups, which showed no changes in the heart rate of subjects wearing a personal lifting device (Godwin et al., 2009; Lotz et al., 2009). As a conclusion for industrial applications, Whitfield et al. (2014) suggested that personal lifting devices should not be used to increase the scope of working tasks. These different conclusions could be based on the diversity of exoskeletons that have been previously studied. Besides the mechanical structure and function of an exoskeleton, working tasks e.g. dynamic or static conditions also have an impact on metabolic costs and make it even more difficult to make general statements. However, in specific conditions, exoskeletons can reduce muscle fatigue and therefore offer great potential for the health of workers, since it is assumed that muscle fatigue increases the risk of injury (Godwin et al., 2009; Lotz et al., 2009). Permanent support can also have negative long-term effects on the skeletal muscle system. It is conceivable that a reduction in muscle mass and consequently a reduction in body strength will occur, but these effects are strongly related to the amount of muscle support of the exoskeleton.

Furthermore, pressure points could occur in those areas where the exoskeleton is attached to the body. This may lead to discomfort over time. In addition, it is conceivable that external pressure on blood vessels, caused by straps or belts, will reduce the blood flow in the corresponding body part. Furthermore, heart rate and blood pressure might be modified by the use of an exoskeleton in repetitive overhead working conditions. Finally, skin irritation due to friction or allergic reactions is possible. However, these factors are speculative and can be considered only with caution.

User acceptance and psychosocial effects

It must be taken into account that, although the physical effects of exoskeletons can influence the worker, user acceptance can also play a major role in the working environment. Acceptability of an exoskeleton is essential if they are to be used for a long time. At present, some research taking subjective evaluations of exoskeletons into account has been performed to address the acceptance of technology (Gilotta et al., 2018; Hensel et al., 2018). Although tough exoskeletons are judged positively by many users, Hensel et al. (2018) showed that their acceptance can decrease over time and is strongly related to discomfort and usability. Discomfort is one of the most challenging aspects and may impede a wide application of exoskeletons in industrial workplaces (Bosch et al., 2016). Again, it has to be mentioned that these evaluations are strongly related to specific tasks and exoskeletons and therefore cannot be generalised. Nevertheless, the findings indicate that developers should take functionality and weight, as well as the ergonomic design of exoskeletons, into account. In addition, workers may feel inferior when using an exoskeleton to fulfil their daily tasks, since the physical aspect of performance is also linked to the device. Gilotta et al. (2018) mentioned social aspects as a factor that might reduce acceptability. Wearing exoskeletons can also lead to stigmatisation in the workplace, as it may appear that workers are dependent on their support.

Biomechanical aspects

Currently, there are numerous studies showing that exoskeletons can reduce physical stress in local body areas, such as the shoulder joints or lower spine (Abdoli-E et al., 2006; Graham et al., 2009; Bosch et al., 2016; De Looze et al., 2016; Theurel et al., 2018; Weston et al., 2018). However, at the same time, it may be relevant that the redistribution of physical stress leads to higher amounts of stress in other body regions if forces are not transferred to the ground (Theurel et al., 2018; Weston et al., 2018). In this context, Weston et al. (2018) found out that an exoskeleton for the upper body increases the load on the lumbar spine. Theurel et al. (2018) showed that an upper body exoskeleton is able to reduce muscle activity in shoulder joints. Nevertheless, physical consequences have been mentioned, including higher levels of muscle activity in other body regions or different movement patterns. Furthermore, the additional weight of an exoskeleton not only affects cardiovascular demands, but also shifts the centre of body mass, which influences the wearer’s muscle activity. It is important to mention that the effects of exoskeletons on the human body cannot be generalised. Biomechanical research questions are often related to very specific movements and muscle activities and do not consider all possible cases of use and types of exoskeletons. Nevertheless, they can address the lack of functionality due to mechanical effects of specific exoskeletons and their consequences on body stress and strain.

Challenges for occupational safety and health

Implementing new technologies in the workplace always involves a critical assessment of OSH for stakeholders. In general, a human-centred design, according to the Framework Directive (89/391/EEC), is a basic prerequisite. In a narrower sense, this implies that standard workplaces do not require additional measures. However, owing to the current work situation in Europe and new technologies' connection to musculoskeletal diseases, ergonomic conditions are not self-evident. To ensure good working environments, technical, organisational and individual measures, in accordance with the Framework Directive (89/391/EEC), should be considered. In terms of their impact on OSH, a hierarchical application is mandatory. When all technical measures have been exhausted, for example the use of lifting aids or the redesign of a workplace, organisational aspects such as the rearrangement of work processes have to be taken into account. Finally, personal measures can be considered to protect workers.

As discussed earlier, exoskeletons can be described as technical or medical devices and can also be defined as protective equipment. Their classification is strongly dependent on their application, design and intended use. Thus, exoskeletons can currently be assessed only using a case-by-case approach. In practice, it is conceivable that exoskeletons are used as technical devices to facilitate work processes. However, if they are used to improve the design of a workplace in which ergonomic measures are needed to protect workers from overuse injuries, they must be considered PPE.

In future, the evaluation of exoskeletons should be integrated with the traditional ergonomic approach (human-centred design), since they have an impact on work situations and organisational aspects.

Workers

The user requirements for workers are dependent on the specific classification of the exoskeleton in question. If certified as a technical device, exoskeletons are bound to workplaces and cannot be used in every conceivable work situation, unless they have been considered for this application. However, technical devices are not personal measures and their use is voluntary. If an exoskeleton is certified as PPE, use of it is legally required. In this case, an employee must be equipped with an exoskeleton as long as he or she is exposed to an increased workload.

Employers

During the implementation and course of operation, employers have to take different aspects into account. In comparison with technical aids, the hygienic requirements for PPE are more comprehensive. In this regard, the use of an exoskeleton becomes mandatory. To fulfil these demands, at least every worker who operates in a workplace that requires an exoskeleton in the form of PPE must be equipped with an exoskeleton, which can cause storage problems. Furthermore, chronic adaptations, MSDs, cardiovascular responses and aspects of performance should be considered. In addition, sufficient cleaning agents or washing machines must be available to meet hygiene standards. Exoskeletons that are defined as technical aids are optional and do not have to be made available to every employee in the workplace. However, when they are used, they should be seen as an aid (support), and not a way to increase the performance or the efficiency of workers.

Policy-makers

In future, policy-makers should take into account the regulation of exoskeletons regarding technical aspects and their application, to facilitate the certification of the new technology. This enables manufacturers to classify their products more clearly and allows employers to use exoskeletons for their intended purpose. However, it must be mentioned that the intended use of the product and the corresponding certification are always the responsibility of the manufacturer.

Summary

The topic of exoskeletons is currently receiving considerable attention. However, despite their apparent promising potential, the application of exoskeletons in a wide range of fields should be questioned. It remains to be seen whether or not exoskeletons will be used extensively in the future to protect workers from overload injuries or to economise work processes. Depending on technical developments, exoskeletons may become a standard tool for manual work processes or remain a niche product for very specific applications. However, the current commercial interest in exoskeletons may also pose a problem for future development, as performance-oriented or economic approaches may be prioritised, causing occupational safety to be neglected. Nevertheless, exoskeletons can be applied as technical, medical or personal protective devices, depending on their intended use in the workplace. However, because of the variety in functionality, design and application, no uniform definition is available, which complicates their implementation in practice with regard to their certification. Even though there are numerous studies on exoskeletons that take different aspects of usability and functionality into account, effects on the health of employees are currently poorly understood. In particular, long-term effects of exoskeletons on physiological, psychosocial and biomechanical parameters are unknown. Future studies should address practice-oriented long-term effects of exoskeletons in the workplace for more reliable results. It should be mentioned that the use of exoskeletons to improve the ergonomic design in stationary workplaces cannot be recommended, but there are also a vast number of non-stationary or mobile workplaces in which ergonomic measures are not possible. In this context, exoskeletons may offer a promising approach to reduce WRMSDs in future.

Authors: Peters, M. and Wischniewski, S. (2019). Federal Institute for Occupational Safety and Health, Friedrich-Henkel-Weg 1-25, 44149 Dortmund, Germany.

Project management: Annick Starren, Emmanuelle Brun, European Agency for Safety and Health at Work (EU-OSHA), 2109

We thank Dr Lars Adolph, Professor Dr Ute Latza and the group of EU-OSHA focal points for their critical reviews and useful suggestions. We would also like to thank EUROFOUND for the use of the illustrations in this paper.

References

89/391/EEC. Council Directive of 12 June 1989 on the introduction of measures to encourage improvements in the safety and health of workers at work. The Council of the European Communities.

89/686/EEC. Council Directive of 21 December 1989 on the approximation of the laws of the Member States relating to personal protective equipment. The Council of the European Communities.

93/42/EEC. Council Directive 93/42/EEC of 14 June 1993 concerning medical devices. The Council of the European Communities.

2006/42/EC. Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast). The European Parliament and the Council of the European Union.

2016/425. Regulation (EU) 2016/425 of the European Parliament and of the Council of 9 March 2016 on personal protective equipment and repealing Council Directive 89/686/EEC. The European Parliament and the Council of the European Union.

Abdoli-E, M., Agnew, M. J. and Stevenson, J. M. (2006). An on-body personal lift augmentation device (PLAD) reduces EMG amplitude of erector spinae during lifting tasks. *Clinical Biomechanics*, *21* (5), 456-465.

Baltrusch, S. J., van Dieën, J. H., van Bennekom, C. A. M. and Houdijk, H. (2018). The effect of a passive trunk exoskeleton on functional performance in healthy individuals. *Applied Ergonomics, 72*, 94-106.

Bevan, S. (2015). Economic impact of musculoskeletal disorders (MSDs) on work in Europe. *Best Practice & Research in Clinical Rheumatology, 29* (3), 356-373.

Bosch, T., van Eck, J., Knitel, K. and de Looze, M. (2016). The effects of a passive exoskeleton on muscle activity, discomfort and endurance time in forward bending work. *Applied Ergonomics, 54*, 212-217.

Collins, J. D. and O'Sullivan, L. W. (2015). Musculoskeletal disorder prevalence and psychosocial risk exposures by age and gender in a cohort of office based employees in two academic institutions. *International Journal of Industrial Ergonomics, 46*, 85-97.

Constantinescu, C., Muresan, P.-C. and Simon, G.-M. (2016). JackEx: the new digital manufacturing resource for optimization of exoskeleton-based factory environments. Procedia CIRP, 50, 508-511.

De Looze, M. P., Bosch, T., Krause, F., Stadler, K. S. and O'Sullivan, L. W. (2016). Exoskeletons for industrial application and their potential effects on physical work load. Ergonomics, 59 (5), 671-681.

INRS. (2018). Exosquelettes au travail: impact sur la santé et la sécurité des opérateurs – état des connaissances. Paris: Institut National de Recherche et de Sécurité. Retrieved from INRS: http://www.inrs.fr/media.html?refINRS=ED%206311

INRS. (2019). Acquisition et integration d'un exosquelette en entreprise: Guide pour les préventeurs. Paris: Institut National de Recherche et de Sécurité. Retrieved from INRS: http://www.inrs.fr/media.html?refINRS=ED%206315

Eurofound. (2012). *Fifth European Working Conditions Survey*. Luxembourg: Publications Office of the European Union.

Eurofound. (2019). *European Working Conditions Survey 2015*. Brussels: Eurofound. Retrieved from *Eurofound*: https://www.eurofound.europa.eu/data/european-working-conditions-survey.

Gams, A., Petrič, T., Debevec, T. and Babič, J. (2013). Effects of robotic knee exoskeleton on human energy expenditure. *IEEE Transactions on Biomedical Engineering, 60* (6), 1636-1644.

Gilotta, S., Spada, S., Ghibaudo, L., Isoardi, M. and Mosso, C. (2018). *Acceptability beyond Usability: A Manufacturing Case Study.* Paper presented at the Congress of the International Ergonomics Association.

Godwin, A. A., Stevenson, J. M., Agnew, M. J., Twiddy, A. L., Abdoli-Eramaki, M. and Lotz, C. A. (2009). Testing the efficacy of an ergonomic lifting aid at diminishing muscular fatigue in women over a prolonged period of lifting. *International Journal of Industrial Ergonomics, 39* (1), 121-126.

Gopura, R. A. R. C. and Kiguchi, K. (2009). *Mechanical Designs of Active Upper-limb Exoskeleton Robots: State-of-the-art and Design Difficulties.* Paper presented at the, ICORR 2009: IEEE 11th International Conference on Rehabilitation Robotics.

Graham, R. B., Agnew, M. J. and Stevenson, J. M. (2009). Effectiveness of an on-body lifting aid at reducing low back physical demands during an automotive assembly task: assessment of EMG response and user acceptability. *Applied Ergonomics, 40* (5), 936-942.

Hensel, R., Keil, M., Mücke, B. and Weiler, S. (2018). Chancen und Risiken für den Betrieblichen Einsatz von Exoskeletten in der betrieblichen Praxis. *ASU Zeitschrift für medizinische Prävention, 53*, 654-661.

Herr, H. (2009). Exoskeletons and orthoses: classification, design challenges and future directions. Journal of Neuroengineering and Rehabilitation, 6 (21).

Holewijn, M., Hens, R. and Wammes, L. (1992). Physiological strain due to load carrying in heavy footwear. European Journal of Applied Physiology Occupational Physiology, 65 (2), 129-134.

ISO 10218-1:2011. Robots and robotic devices — safety requirements for industrial robots — part 1: robots. Geneva: International Organization for Standardization.

ISO 13482:2014. Robots and robotic devices — safety requirements for personal care robots. Geneva: International Organization for Standardization.

ISO/TS 15066:2016. Robots and robotic devices — collaborative robots. Geneva: International Organization for Standardization.

Kim, S., Nussbaum, M. A., Mokhlespour Esfahani, M. I., Alemi, M. M., Jia, B. and Rashedi, E. (2018). Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: part II — 'unexpected' effects on shoulder motion, balance, and spine loading. Applied Ergonomics, 70, 323-330.

Liedtke, M. and Glitsch, U. (2018). Exoskelette — Verordnung für persönliche Schutzausrüstung. *sicher ist sicher, 3*, 110-113.

Lotz, C. A., Agnew, M. J., Godwin, A. A. and Stevenson, J. M. (2009). The effect of an on-body personal lift assist device (PLAD) on fatigue during a repetitive lifting task. *Journal of Electromyography Kinesiology, 19* (2), 331-340.

Schick, R. (2018). Einsatz von Exoskeletten in der Arbeitswelt. *Zentralblatt für Arbeitsmedizin, Arbeitsschutz und Ergonomie, 68* (5), 266-269.

Theurel, J., Desbrosses, K., Roux, T. & Savescu, A. (2018). Physiological consequences of using an upper limb exoskeleton during manual handling tasks. *Applied Ergonomics, 67*, 211-217.

Viteckova, S., Kutilek, P. and Jirina, M. (2013). Wearable lower limb robotics: a review. *Biocybernetics and Biomedical Engineering, 33* (2), 96-105.

Weston, E. B., Alizadeh, M., Knapik, G. G., Wang, X. and Marras, W. S. (2018). Biomechanical evaluation of exoskeleton use on loading of the lumbar spine. *Applied Ergonomics, 68*, 101-108.

Whitfield, B. H., Costigan, P. A., Stevenson, J. M. and Smallman, C. L. (2014). Effect of an on-body ergonomic aid on oxygen consumption during a repetitive lifting task. *International Journal of Industrial Ergonomics, 44* (1), 39-44.

Yang, C., Zhang, J., Chen, Y., Dong, Y. and Zhang, Y. (2008). A review of exoskeleton-type systems and their key technologies. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 222* (8), 1599-1612.

Zurada, J. (2012). Classifying the risk of work related low back disorders due to manual material handling tasks. *Expert Systems with Applications, 39* (12), 11125-11134.