Investigating exoskeletons applicability in manufacturing and logistics systems: state of the art and future research directions

Ashta G.*, Finco S.*, Persona A.*, Battini D.*

** Department of Management and Engineering, University of Padova, Stradella San Nicola, 3*
36100 - Vicenza - Italy (gjulio.ashta@phd.unipd.it , serena.finco@unipd.it ,
alessandro.persona@unipd.it , daria.battini@unipd.it)

Abstract: In modern industry, many activities, even repetitive, need high flexibility, perception, judgment and a series of skills that cannot be automatized and performed by robots. Several workers are employed in logistics, manufacturing and assembling activities requiring tasks that could lead to awkward postures and a high physical effort. The exposure to ergonomically risky activities could lead to overexertion and disorders of the musculoskeletal system and, consequently, a productivity and efficiency reduction. Work-related musculoskeletal disorders are serious concerns, especially in the actual aging workforce scenario. Since the modern industry is moving towards the philosophy of human-centred workplaces design and the operator 5.0 concept, there is a need to match real operators' characteristics by personalizing their workplaces and by providing personalized assistive equipment. New instruments and tools need to be used for improving workers' well-being and capabilities. In such a context, exoskeletons are candidates for human-focused intervention in improving work conditions. The interest in these devices grew up in the last years from a company and an academic perspective. Several devices have been designed and tested according to their application field. Moreover, previous works showed their potential in improving ergonomics and workers' safety. In this paper, several exoskeletons and their applications in manufacturing and logistics systems are investigated. Several contributions are classified according to the application field, the type of task analyzed, simulated or real, and instruments used for the assessment and findings. Even if there is not a standardized method for exoskeleton assessment, a trend in using electromyography, motion capture and questionnaires is detected. Finally, a future research agenda is proposed.

Keywords: Exoskeletons, Human Factor, manufacturing systems, logistics systems, Industry 5.0.

I. INTRODUCTION

The modern industry trend is mainly based on tasks automation, however, there are still many activities that need high flexibility, dexterity, judgment and other series of skills that cannot be automatized and performed by robots (de Looze et al., 2016; Spada et al., 2017). Recent developments in modern industry paradigms are pushing the transition from a fully technology-driven approach to a human-centric approach in which the workers have not to continuously adapt to the new technology, but the technology involved is needed to serve them and to be adapted to their needs and diversities (Breque et al., 2021). Romero et al., (2016) identified the operator 4.0 paradigm as a smart operator that creates trusted interaction-based relationships with machines. More recently, in 2021, Romero and Stahre introduced the resilient operator 5.0 based on the self- and system-resilience paradigms. Self-resilience for the workforce is created by overcoming human fragilities whilst system-resilience paradigms aim at creating conditions for reaching the optimal working conditions. One of the aspects composing the "self-resilience" is the "physical resilience" which can be reached using exoskeletons for improving the operator's endurance and wellbeing (Romero, 2021). Exoskeletons are wearable devices designed for empowering humans' biomechanical capabilities. According to de Looze et al., (2016) they are classified into two types:

- *Active:* motors and other actuators provide energy for the movement augmenting human strength.
- *Passive:* the structure is composed of elastic components (springs, elastics, etc.) which harvest energy from human movement and return that to the counter-movement.

Moreover, they can be classified according to the body part they support. Upper limb exoskeletons support the arms, generally the shoulder joint. Back support exoskeletons support the back region reducing efforts on back erector muscles mainly working on the joint between the lower lumbar vertebrae and the upper sacral one. Then, lower limb exoskeletons provide supporting torques at the knee and hip level. In the last years, several exoskeletons have been designed and tested and their interest grew up from both academic and industrial fields showing the potential to improve workers' biomechanics, ergonomics and safety by reducing muscle activity for certain tasks. Passive exoskeletons are the most accessible for large industrial use due to their lower complexity, cost and easiness to use, the passive exoskeletons (Voilqué et al., 2019). In this work, several passive exoskeletons used in manufacturing, assembly and logistics systems are classified according to the task type they are used to support. Moreover, we cluster them according to the application field, the type of analysis and the method used to evaluate their benefits. Finally, we answer the following research questions: 1) What impacts have the exoskeletons on task execution times? 2) How are the benefits evaluated from a managerial point of view?

The remainder of the paper is structured as follows: Section 2 presents the research methodology; Section 3 reports results and the clusterization; Section 4 presents a final discussion and a future research agenda.

II METHODOLOGY

The research is conducted by using the Scopus database. No limitation has been applied on the publication year since passive exoskeletons as well as their application in the industry field is recent (deLooze et al., 2016). The first identification query was built to identify scientific contributions about exoskeletons in the abovementioned fields (see Table 1). Then, all papers written in the English language and related to the fields of engineering, material science, social sciences, multidisciplinary, business, decision sciences and economics are selected according to our research scope. Since, as stated by Voilqué et al., (2019), passive exoskeletons are the most accessible for large industrial use, the screening phase restricted the records to only the studies regarding these types of devices by title and abstract reading. If the content was not enough delivered by title and abstract, the full paper was analysed. Simulations and methodology proposal papers are also included. Articles from trade journals are excluded from the search due to their low scientific value.

TABLE I. PAPERS SELECTION PROCESS

Step	Process	# Papers
Database	Scopus	
Query	TITLE-ABS-KEY (("exoskeleton") AND ("logistic*" OR "manufacturing" OR "industry" or "assembly" or "production"or "warehous*"))	1089
Field limitations	English+ engineering, material science, social sciences, multidisciplinary, business, decision sciences and economics	629
Content selection	Passive exoskeletons (title, abstract, full article)	63
Scientific selection	Paper reading and exclusion if out of topic	60

III. RESULTS ANALYSIS

The main insights coming from the selection process are reported and classified in this section. Firstly, Figure 1 shows the publications distribution during the years. The graph shows an increasing interest since de Looze et al., (2016) reviewed previous works identifying active and passive exoskeletons that could be suitable for industrial deployment. In the early months of the current year, 2022, already 4 articles have been published. The different focuses of the studies are shown in Figure 2. More than half of the contributions (34 out of 60) focus on the physical testing of exoskeletons behaviour in different tasks.

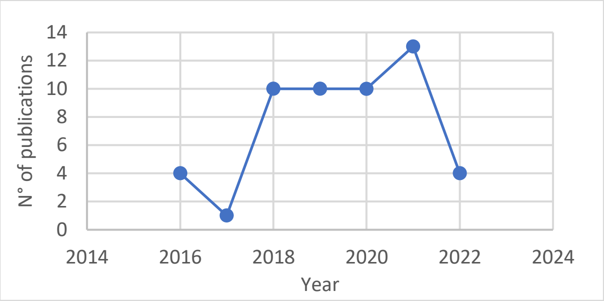

Fig. 1 Publications distribution over the years

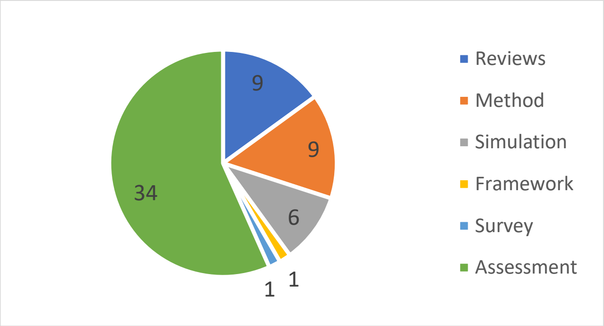

Fig. 2 Categorization of previous studies based on passive exoskeleton

As well, interest is also posed in methodological studies and simulations with 9 and 6 works respectively. Finally, the panorama is completed by 9 reviews or overviews, a framework for investigating user acceptance (Elprama et al., 2022) and a survey on the potential adoption of industrial exoskeletons in small and medium enterprises (Schwerha et al., 2021). Finally, 20 of the studies have a reported application industry on which the exoskeleton is aimed to be deployed (Figure 3). The automotive industry leads the classification with 13 studies confirming it in a driving role due to its growing interest in improving workers’ well-being while executing tasks (Gilotta et al., 2019).

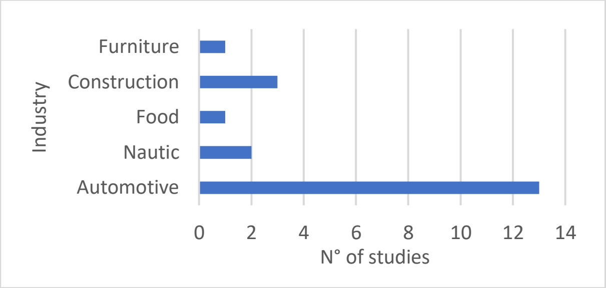

Fig. 3 Industry-based clustering of studies

By focusing on previous reviews, De Looze et al., (2017, 2016) reviewed early-stage industrial exoskeleton studies finding 26 different exoskeletons: 19 of them have been classified as actives while 7 as passives. The reviews show the outcomes mainly in terms of muscle activations. An overview of the development of robotic exoskeletons is provided by Bogue, (2018), while

Voilqué et al., (2019) proposed a classification of 62 exoskeletons. Devices are classified according to the region they support, if they are active or passive, the energy source and their potential adoption in different automotive use cases. Kuber and Rashedi, (2020) identified some design features which could be linked to the acceptance of these devices and proposed new technologies for future improvements. Then, Fox et al., (2020) conducted a multivocal literature review finding eight different families of exoskeletons and classified each according to enhancements and limitations it brings to industrial tasks. Zhu et al., (2021) reviewed passive and active material handling exoskeletons and discussed their potential deployment in the construction industry. Pesenti et al., (2021) reviewed 23 articles and reported the technical characteristics of each exoskeleton. Moreover, they underlined the lack of standardization and proposed a framework for back-support exoskeletons' functional validation for industrial purposes. Finally, Ali et al., (2021) reviewed 34 active and passive exoskeletons providing a classification of their technical features, kinematic compatibility and their ability to reduce the load on spinal structure.

The current review differentiates from previous ones by clustering the previous study according to different industrial applications and analysing the performance results for the different categories. Importance is given to the discussion of managerial key features of exoskeletons deployment in the industry like their impact on process times and the evaluation of their cost-effectiveness. In the next sub-section, the 34 scientific contributions in the assessment are clustered according to the task type the worker is asked to perform and the type of exoskeleton used in performing the task. Moreover, we provide a classification of the remaining papers according to their main topic. Finally, methodologies and technologies used for the assessment, industry of application, dynamicity and reality of tasks are discussed.

A. Assessment clusterization

In this section, for each paper, the type of assessment is classified according to the following clusterization: assembly, overhead assembly, construction, drilling and screwing, material handling, picking and generic tasks.

Assembly tasks

Candidates for exoskeletons deployment are assembly tasks. Six of the 34 assessment works studied assembly tasks both in real and simulated scenarios. Bosch et al., (2016) studied the impact of the Laevo exoskeleton in two different static task configurations: pick and place operation with trunk bent 40° forward and 40° forward bending position. They found a 38% decrease in low back muscle activity and a nearly triplicated endurance time in the forward bent position (from 3.2 to 9.7 minutes). Amandels et al., (2019) tested a Laevo exoskeleton in a real car assembly task finding a 12% reduction in erector spinal muscle activity and a 15% decrease in total task time while discomfort is reported in chest and thighs contact areas. Their study differs from Bosch et al., (2016) due to the variability of conditions and positions characteristic of a real work scenario. A lower-limb exoskeleton, the Chairless Chair, is assessed by Luger et al., (2019) in simulated car assembly tasks. Relative stability decreased by 27% while the device unloaded 64% of users' weight. Gastrocnemius activity decreased by 25% but a 135% increase is detected in quadriceps with general discomfort reported while using the exoskeleton. Kim et al., (2020); Madinei et al., (2020) studied the "expected" and "undesired" effects of two passive back-support exoskeletons (BackX, Laevo) in a Pegboard simulated quasi-static assembly task in different positions. They reported a decrease of up to 47% and 24% in trunk muscle activity with, respectively, BackX and Laevo while completion time increased by up to 1.2s over a mean 30s task time duration. The "undesired" effects reported are discomfort in reaching far positions and a decrease of 14° in lumbar flexion. Pacifico et al., (2022) compared MATE, an upper limb exoskeleton, in a simulated and a real version of enclosures assembly for construction. While the muscle activity decrease is lower in the in-field respect to the simulation due to the unavoidable variability, the technology's perception improved.

Assembly overhead tasks

In overhead assembly 4 studies have been carried out using upper limb exoskeletons. All these studies have been dealt with in the automotive industry. Spada et al., (2018) tested a Levitate Airframe in both simulated and real tasks. Increased holding time and quality improvements were achieved in simulated tasks. For real tasks, users raised concerns about interference of the exoskeleton with the car frame but judging positively at all its adoption with resulting lower physical and mental load. Moreover, in real assembly tasks, a decrease of 34% of deltoids and 18% of trapezius activities have been detected. Muscular activities are also classified in Johnson's acceptance areas: operators' deltoids activity remains in acceptance for 50% of the time when not wearing the exoskeleton and that time increases to 70% when wearing it (Iranzo et al., 2020). The other two different upper limb exoskeletons (Skelex and Crimson Dynamics) were tested in the assembly of the exhaust under the car body after the powertrain merged with the chassis. The questionnaire on the perceived strain showed a reduction of above 20% (Hefferle et al., 2021). Carnazzo et al., (2021) tested Levitate and then MATE in different plants based across world regions. 135 workers were involved in real tasks which have over 20% of the time with hands above shoulder height, no interferences of the exoskeleton with car structure and high variability of actions. Potential benefits are recognized by workers when working above shoulder height, but concerns are raised on fit, ease of use, freedom of movement and wearing comfort.

General construction tasks

Four studies come from the construction and naval industry all with general construction tasks. Three of them were conducted in real tasks. Moyon et al., (2018) investigated the cardiac cost evolution in overhead sanding operations of boat body construction when using a Skelex (upper limb exoskeleton). A 13.5% reduction in cardiac cost is detected when using the exoskeleton. In the same field, another study involved Skelex and ShoulderX (Mouzo et al., 2022) on simulated ceiling and welding tasks. Muscular activity, kinematics, driving torques, metabolic cost, donning, doffing and execution times, were compared for both operators without and with the two exoskeletons in three assistance levels. Improvement is achieved with both exoskeletons in most indicators although the total time to perform the task is not always reduced. In the construction industry, Gonsalves et al., (2021) studied the behaviour of the BackX, a back support exoskeleton, in rebar work tasks. Task completion times decreased up to 50% but no significant difference was found in muscle activity. Perceived discomfort decreased in the back region but increased in the chest region, where the supportive force is transferred to the body by the chest pad. Peláez et al., (2021) reported an analysis of the deployment of an upper limb exoskeleton conducted in high voltage electrical lines. Non-significant reductions in muscle activity are detected. A RULA and REBA analysis of the tasks without the exoskeleton showed that it was mandatory to redesign the activity instead of deploying it.

Drilling and screwing tasks

All the studies for drilling and screwing tasks (clustered together since tools are very similar) are conducted in simulated laboratory tasks and with the hands at shoulder height or above. Kim et al., (2018) tested an upper limb exoskeleton, the Eksovest, in overhead drilling and wiring showing a reduction of up to 50% in shoulder muscle activity and a decrease in completion time by 18.9%. Instead, errors increased suggesting the authors' changes in proprioception that could be restored with more practice and a speed-precision trade-off since users were able to work faster. Van Engelhoven et al., (2018) studied the impact of a ShoulderX, an upper-limb exoskeleton, in static and dynamic drilling tasks with heavy and light tools and with different exoskeleton support levels. Beyond the activity reduction of shoulder elevator muscles (up to 70%), they also showed an increase in triceps activity raising according to the exoskeleton’s support level. Alabdulkarim et al., (2019) and Alabdulkarim and Nussbaum, (2019) tested two tool-carrying exoskeletons, Fortis and Fawcett Exovest with ZeroG arm, and compared them with two classical passive upper-limb as Eksovest and ShoulderX. A higher maximum acceptable frequency was achieved with the ZeroG arm while for ShoulderX was comparable to the without exoskeleton condition and Fortis led to a lower one. Errors with Fortis, ZeroG and Eksovest increased while decreased with ShoulderX. In 2019, Hyundai designed an upper limb passive exoskeleton for its industrial plants, the H-VEX. They achieved up to 70% activity reduction in shoulder muscles but an increase of 97% in the erector spine (back erector muscle) in overhead drilling (Hyun et al., 2019). Remaining in the automotive industry, Pinho et al., (2020a, 2020b) tested ShoulderX, Paexo Shoulder and MATE for screwing with screwdriver laboratory tasks. Reductions in shoulder muscle activations were between 32% to 41% and were lower in the tasks with fully extended shoulders due to decreasing supportive torque of the exoskeletons. Vibrations to the shoulder were also measured resulting in different spectrums through the no exoskeleton and the 3 exoskeletons conditions.

Material handling tasks

By focusing on material handling tasks, four studies out of seven were conducted in the automotive industry. Gilotta et al., (2019); Spada et al., (2019b, 2017) tested two upper-limb exoskeletons, Levitate and IUVO, in laboratory material handling tasks. The three tasks analysed are static holding of an object with a shoulder at 90° and full extended elbow, repetitive lifting of an object from hip height to shoulder height, precision drawing at shoulder height with a shoulder at 90° and full extended elbow. With the tasks of static holding and precision drawing, which requires a holding action of the shoulder, the performance increased respectively by 31% and 33.6% for Levitate and 56% and 26.5% with IUVO. This shows an increase in static holding time for the static position. Concerning the repetitive lifting, no improvement was detected. Users well accepted the technology and reported less perceived discomfort while performing tasks with the exoskeletons but underlined that their use should be non-mandatory and that they could not always fit real work tasks. The other study from automotive is only questionary based and was conducted in real tasks with a Laevo back support exoskeleton (Flor et al., 2021). Tasks that have at least 30% of cycle time with trunk bent in the range 20°-60° with a 5% over 60° and more than 3kg weight of the object handled. Participants reported that, generally, the device helped them to perform the task. Another work on Laevo tested it in repetitive lifting tasks performed in a laboratory environment. EMG, heart rate and joint angles were tracked during the tests on 36 volunteers. The hip extensor decreased by 28% while the trunk extensor only 6. Heart rate decreased 1,6% (105-110bpm) with exoskeleton. The joint angles sensor showed a slight increase in knee and hip flexion (Luger et al., 2021). Schmalz et al., (2021) assessed the newly introduced Paexo Back in material handling tasks examining oxygen consumption, activation of back and thigh muscles, and compression forces at low back. Results report a general reduction in oxygen consumption, back and thigh muscle activity, and peak and mean compression forces at L4/L5 and L5/S1. Another type of exoskeleton with no supporting capabilities but designed to limit the user’s range of motion when he tries to perform incorrect movements is the Flx Ergoskeleton. Ogunseiju et al., (2021) studied this device in terms of a range of motion (ROM), pain, discomfort and completion time. Reduced back and increased hip ROM demonstrates the adaptation of the users to the feedback of the device. Completion time increased by 20% and back pain during the tasks did not reduce.

Picking tasks

For the picking tasks, three out of four studies were real-scenarios based. Laevo back support exoskeleton was deployed in all the works below mentioned. Motmans et al., (2019) studied the effect of the exoskeleton in order picking activities in a cheese factory detecting a 9-12% reduction in the erector spine. The physical workload was well perceived by the workers but they also reported the necessity of higher energy for performing the downward movement. Moreover, collisions between the rods and the pallet jack are detected while executing picking tasks. Laevo exoskeleton also resulted well perceived in the study on simulated picking tasks from Kinne et al., (2020). NASA TLX subdimensions resulted lower when using the exoskeleton except for the mental workload resulting slightly higher. The task was perceived also easier with exoskeleton support. Well-perceived support resulted also in the study of Cardoso et al., (2020) who tested the exoskeleton in the furniture industry. The reduction of back muscles’ activity was minimal (3.8%) and users also reported interference, movement limitations and discomfort in the neck, shoulder, thoracic region, hips and thighs. Finally, a questionary-based survey on supermarket picking activities was performed by Siedl et al., (2021). They tested Laevo, Daedalus (lower-limb support), Atlas (upper-limb support), Rakunie (full body elastic slings) and the Paexo Soft Back (back lumbar support band) from 0.5 to 7 hours. Results of the questionnaire showed that the soft ones had better scores from the users.

Generic tasks

Three studies performed exoskeleton assessment in generic tasks. Näf et al., (2018) designed a flexible beam back-support exoskeleton. They compared it to the Laevo by considering generic tasks (e.g., lifting, forward bending, walking, sitting, trunk rotation, squat) and they demonstrated better-perceived respect for Laevo with a 25% increased range of motion. Proposing a new standard for benchmarking, Hartmann et al., 2021 built a cheap test bench for mechanically assessing upper limb exoskeletons. They tested the MATE upper-limb exoskeleton in both static and dynamic loading on the test bench mapping the device mechanical responses.

B Methodological studies

Nine contributions focused on trying to give methodological standards for selecting and assessing the exoskeletons. Greater importance is given to the selection process which has to be based on the workplace, the appropriation to the task and the impacts it has on the production system as well as an ergonomic index approach (C. Dahmen et al., 2018; Christian Dahmen et al., 2018; Dahmen and Constantinescu, 2020; di Pardo et al., 2022; Masood et al., 2019). Grazi et al., (2019) and Hefferle et al., (2020) underlined the importance of having common evaluation methods for lumbar exoskeletons by overviewing the technologies adopted by different studies through the years. Impacts on production systems could be evaluated through digital simulation after collecting enough data on parts, tools and cycle time for preparing and running it. (Constantinescu et al., 2019b). Then, if simulation results are satisfying the final recommendations as layout or production schedule could be provided (Ippolito et al., 2020).

C Simulation studies

Importance in the studies has also been given to digital simulation processes. The simulations could support the decisions on exoskeletons deployment by digitally building the “as is” and the “to be” scenarios (Constantinescu et al., 2016b). Constantinescu et al., (2016) presented the concept of a modified Siemens Classical Jack with a RoboMate exoskeleton attached and simulated three simple car assembly tasks (Constantinescu et al., 2016a). Spada et al., (2019a) built a biomechanical model in AnyBody software simulating the interactions between the human body and a lower-limb exoskeleton: the Chairless Chair. Constantinescu et al., (2019a) focused on the challenges of making digital twins o of exoskeleton-centred workplaces. The exoskeletons digital model must be kinematically and dynamically paired to the Classical Jack by modifying its source code instead of manually updating geometrical and force parameters as usually done. Rusu et al. (2021) highlighted the necessity to modify Classical Jack or Delmia to directly consider exoskeletons impact on forces and torques. Up to now, exoskeletons are only graphically paired to the humanoid and their effects are simulated through reducing manually the carried load. This approach poorly affects the joints non-involved in the exoskeleton support and results in a non-realistic simulation. Rivera et al., (2021) proposed a virtual automated mannequin with simple instructions, a well-known behaviour and a realistic musculoskeletal system model aiming to calculate forces. Using positions as input to the virtual exoskeleton should be possible to calculate forces to apply to the mannequin and calculate new derived postures with a back loop.

IV. FINAL DISCUSSION AND FUTURE RESEARCH AGENDA

In this section main findings of the reviewed works, their investigation methods and research questions are discussed. The balance between real-based scenarios and simulated task studies is inclined towards the second one. Only 13 assessment studies involved at least a real task while 21 were on laboratory simulated tasks. Muscle activity reductions in real tasks may be lower concerning laboratory tasks due to the natural variability of conditions and movements in a real environment (Amandels et al., 2019). In fact, in the real scenario studies, the muscle activation reductions result overall lower. Since the aim is to deploy exoskeletons in an industrial environment, further in-field research could enable us to better understand their impact on activities and to identify limitations that could not be observed in simulated tasks. Then, 15 out of 34 assessment studies are dynamic with only 7 of them performed in real scenarios highlighting again the impossibility to intercept the behaviour with natural variabilities in activity. Coming to the research questions, here below are discussed the answers given by the analysis of the studies involved in this review.

What impacts have the exoskeletons on task execution times?

There are only 10 assessments that consider this topic and only 3 of them are evaluated in real tasks. Four of the studies measured performance related to static holding endurance time. In other words, the human joint supported by the exoskeleton is maintained in static position while the user performs a task and the time performance is related to the increased endurance time in holding the position which was triplicated with exoskeleton support (Bosch et al., 2016). Kim et al., (2018) showed a decrease of 18.9% on completion time for simulated drilling tasks but with errors increasing. Madinei et al., (2020) measured a 15% reduction on a car assembly task while using a Laevo. In precision simulated manual assembly task, Madinei et al., (2020) found 7.6% increased completion time for females while no changes are measured for men in an average task time of 30s. Most time performance enhancements are found in construction with 7-50% reductions on rebar work aided by BackX exoskeleton (Gonsalves et al., 2021). Time performance non always increased in the work proposed by Mouzo et al., (2022) in overhead exoskeleton-assisted ceiling and welding. Ogunseiju et al., (2021) recorded a 20% increase in completion time for material handling while using Flx Ergoskeleton. Mixed results are found for time performance and very few studies focused on real tasks. Further investigation is necessary to support in the future the decision-making on exoskeletons deployment.

How are the benefits evaluated from a managerial point of view?

From the managerial point of view, cost-effectiveness was not considered in any of the studies found. It could be affected directly by time performance but mixed and few results are found until now on this topic. Additionally, no study covers an entire work shift for assessing the overall productivity impacts of exoskeletons including also donning and doffing or adjustments. Another way exoskeletons could impact overall industrial cost is their presumed ability to reduce work-related musculoskeletal disorders (WRMSD) and mitigate absence from work due to injuries. Even if the majority of studies introduce the exoskeletons as devices capable of reducing WRMSD no investigations have been performed to directly measure that capability. Future research could be performed to better understand exoskeletons' effects on task completion times and their capability of reducing injury-related absenteeism enabling managers to evaluate these devices from their point of view. 22 passive exoskeletons emerged from the different studies. Different aspects are studied for each of these wearable devices giving them different maturity levels. Even for a highly studied exoskeleton such as Laevo, gaps are detected in few data for time performance and no study focused on oxygen consumption which can be related to metabolic cost, nor on simulation which can be useful for decision-making support. Furthermore, EMG results between different laboratory studies and different exoskeletons showed consistency and muscle activation reduction could be considered established for exoskeleton families.

Finally, here below are briefly proposed open points for future research: 1) *In-field studies*: further investigation is needed to study the impact of the exoskeletons in a real industrial scenario for covering the natural variability of tasks that cannot be considered in laboratory studies. 2) *Time performances in real tasks*: a decisive topic for the future will be the study on exoskeletons productivity impact determined by task completion time variations or holding time enhancements in awkward positions (eg. Overhead work). 3) *WRMSD and absenteeism reduction rate*: these data studied according to the tasks for each exoskeleton will be useful for cost-effectiveness evaluations and decision-making. 4) *Cost-effectiveness on exoskeleton deployment in a real scenario*: evaluating cost and benefits in different industries could support decision-making. 5) *Predictive biomechanical models for muscle activations' reductions for different exoskeletons*: muscle activations are the direct effect of exoskeletons' support on the human musculoskeletal system and efforts could be spent in modelling and simulation for predicting muscular loads instead of measuring them by EMG. 6) *Long-term physical effects of using exoskeletons*: long-term effects of prolonged use of exoskeletons are unknown and data about that aspect will be very important to drive their future development.

The reference list here below is not complete. For space reasons some references were omitted. For the full list contact the authors.

REFERENCES

[1] Alabdulkarim, S., Kim, S., Nussbaum, M.A., 2019. Effects of exoskeleton design and precision requirements on physical demands and quality in a simulated overhead drilling task. Applied Ergonomics 80, 136–145. https://doi.org/10.1016/j.apergo.2019.05.014

[2] Alabdulkarim, S., Nussbaum, M.A., 2019. Influences of different exoskeleton designs and tool mass on physical demands and performance in a simulated overhead drilling task. Applied Ergonomics 74, 55–66. https://doi.org/10.1016/j.apergo.2018.08.004

[3] Ali, A., Fontanari, V., Schmoelz, W., Agrawal, S.K., 2021. Systematic Review of Back-Support Exoskeletons and Soft Robotic Suits. Frontiers in Bioengineering and Biotechnology 9. https://doi.org/10.3389/fbioe.2021.765257

[4] Amandels, S., het Eyndt, H.O., Daenen, L., Hermans, V., 2019. Introduction and testing of a passive exoskeleton in an industrial working environment, Advances in Intelligent Systems and Computing. https://doi.org/10.1007/978-3-319-96083-8_51

[5] Bogue, R., 2018. Exoskeletons – a review of industrial applications. Industrial Robot 45, 585–590. https://doi.org/10.1108/IR-05-2018-0109

[6] Bosch, T., van Eck, J., Knitel, K., 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. https://doi.org/10.1016/j.apergo.2015.12.003

[7] Breque, M., de Nul, L., Petridis, A., 2021. Industry 5.0 : towards a sustainable, human-centric and resilient European industry. European Commission, Directorate-General for Research and Innovation. https://doi.org/doi/10.2777/308407

[8] Cardoso, A., Colim, A., Sousa, N., 2020. The Effects of a Passive Exoskeleton on Muscle Activity and Discomfort in Industrial Tasks, Studies in Systems, Decision and Control. https://doi.org/10.1007/978-3-030-41486-3_26

[9] Carnazzo, C., Spada, S., Ghibaudo, L., Eaton, L., Fajardo, I., Zhu, S., Cavatorta, M.P., 2021. Exoskeletons in Automotive Industry: Investigation into the Applicability Across Regions, Lecture Notes in Networks and Systems. https://doi.org/10.1007/978-3-030-74608-7_50

[10] Constantinescu, C., Muresan, P.-C., Simon, G.-M., 2016a. JackEx: The New Digital Manufacturing Resource for Optimization of Exoskeleton-based Factory Environments, in: Procedia CIRP. pp. 508–511. https://doi.org/10.1016/j.procir.2016.05.048

[11] Constantinescu, C., Popescu, D., Muresan, P.-C., Stana, S.-I., 2016b. Exoskeleton-centered Process Optimization in Advanced Factory Environments, in: Procedia CIRP. pp. 740–745. https://doi.org/10.1016/j.procir.2015.12.051

[12] Constantinescu, C., Rus, R., Rusu, C.-A., Popescu, D., 2019a. Digital twins of exoskeleton-centered workplaces: Challenges and development methodology, in: Procedia Manufacturing. pp. 58–65. https://doi.org/10.1016/j.promfg.2020.01.228

[13] Constantinescu, C., Todorovic, O., Ippolito, D., 2019b. Comprehensive modelling and simulation towards the identification of critical parameters for evaluation of exoskeleton-centred workplaces, in: Procedia CIRP. pp. 176–179. https://doi.org/10.1016/j.procir.2019.02.040

[14] Dahmen, C., Constantinescu, C., 2020. Methodology of employing exoskeleton technology in manufacturing by considering time-related and ergonomics influences. Applied Sciences (Switzerland) 10. https://doi.org/10.3390/app10051591

[15] Dahmen, C., Hölzel, C., Wöllecke, F., Constantinescu, C., 2018. Approach of Optimized Planning Process for Exoskeleton Centered Workplace Design, in: Procedia CIRP. pp. 1277–1282. https://doi.org/10.1016/j.procir.2018.03.185

[16] Dahmen, Christian, Wöllecke, F., Constantinescu, C., 2018. Challenges and Possible Solutions for Enhancing the Workplaces of the Future by Integrating Smart and Adaptive Exoskeletons. Procedia CIRP 67, 268–273. https://doi.org/10.1016/J.PROCIR.2017.12.211

[17] de Looze, M.P., Bosch, T., Krause, F., Stadler, K.S., O’Sullivan, L.W., 2016. Exoskeletons for industrial application and their potential effects on physical work load. Ergonomics 59, 671–681. https://doi.org/10.1080/00140139.2015.1081988

[18] de Looze, M.P., Krause, F., O’Sullivan, L.W., 2017. The potential and acceptance of exoskeletons in industry, Biosystems and Biorobotics. https://doi.org/10.1007/978-3-319-46532-6_32

[19] di Pardo, M., Monferino, R., Gallo, F., Tauro, F., 2022. Exoskeletons Introduction in Industry. Methodologies and Experience of Centro Ricerche Fiat (CRF), Biosystems and Biorobotics. https://doi.org/10.1007/978-3-030-69547-7_81

[20] Elprama, S.A., Vanderborght, B., Jacobs, A., 2022. An industrial exoskeleton user acceptance framework based on a literature review of empirical studies. Applied Ergonomics 100. https://doi.org/10.1016/j.apergo.2021.103615

[21] Flor, R., Gaspar, J., Fujão, C., Nunes, I.L., 2021. How Workers Perceive LAEVO Exoskeleton Use in Non-cyclic Tasks, Lecture Notes in Networks and Systems. https://doi.org/10.1007/978-3-030-79816-1_19

[22] Fox, S., Aranko, O., Heilala, J., Vahala, P., 2020. Exoskeletons: Comprehensive, comparative and critical analyses of their potential to improve manufacturing performance. Journal of Manufacturing Technology Management 31, 1261–1280. https://doi.org/10.1108/JMTM-01-2019-0023

[23] Gilotta, S., Spada, S., Ghibaudo, L., Isoardi, M., Mosso, C.O., 2019. Acceptability beyond usability: A manufacturing case study, Advances in Intelligent Systems and Computing. https://doi.org/10.1007/978-3-319-96071-5_95

[24] Gonsalves, N.J., Ogunseiju, O.R., Akanmu, A.A., Nnaji, C.A., 2021. Assessment of a passive wearable robot for reducing low back dIsorders during rebar work. Journal of Information Technology in Construction 26, 936–952. https://doi.org/10.36680/J.ITCON.2021.050

[25] Grazi, L., Chen, B., Lanotte, F., Vitiello, N., Crea, S., 2019. Towards methodology and metrics for assessing lumbar exoskeletons in industrial applications, in: 2019 IEEE International Workshop on Metrology for Industry 4.0 and IoT, MetroInd 4.0 and IoT 2019 - Proceedings. pp. 400–404. https://doi.org/10.1109/METROI4.2019.8792877

[26] Hartmann, V.N., Rinaldi, D.M., Taira, C., Forner-Cordero, A., 2021. Industrial upper-limb exoskeleton characterization: Paving the way to new standards for benchmarking. Machines 9. https://doi.org/10.3390/machines9120362

[27] Hefferle, M., Lechner, M., Kluth, K., Christian, M., 2020. Development of a Standardized Ergonomic Assessment Methodology for Exoskeletons Using Both Subjective and Objective Measurement Techniques, Advances in Intelligent Systems and Computing. https://doi.org/10.1007/978-3-030-20467-9_5

[28] Hefferle, M., Snell, M., Kluth, K., 2021. Influence of Two Industrial Overhead Exoskeletons on Perceived Strain – A Field Study in the Automotive Industry, Advances in Intelligent Systems and Computing. https://doi.org/10.1007/978-3-030-51758-8_13

[29] Hyun, D.J., Bae, K.H., Kim, K.J., Nam, S., Lee, D. hyun, 2019. A light-weight passive upper arm assistive exoskeleton based on multi-linkage spring-energy dissipation mechanism for overhead tasks. Robotics and Autonomous Systems 122, 103309. https://doi.org/10.1016/J.ROBOT.2019.103309

[30] Ippolito, D., Constantinescu, C., Riedel, O., 2020. Holistic planning and optimization of human-centred workplaces with integrated Exoskeleton technology, in: Procedia CIRP. pp. 214–217. https://doi.org/10.1016/j.procir.2020.05.038

[31] Iranzo, S., Piedrabuena, A., Iordanov, D., Martinez-Iranzo, U., Belda-Lois, J.-M., 2020. Ergonomics assessment of passive upper-limb exoskeletons in an automotive assembly plant. Applied Ergonomics 87. https://doi.org/10.1016/j.apergo.2020.103120

[32] Kim, S., Madinei, S., Alemi, M.M., Srinivasan, D., Nussbaum, M.A., 2020. Assessing the potential for “undesired” effects of passive back-support exoskeleton use during a simulated manual assembly task: Muscle activity, posture, balance, discomfort, and usability. Applied Ergonomics 89. https://doi.org/10.1016/j.apergo.2020.103194

[33] Kim, S., Nussbaum, M.A., Mokhlespour Esfahani, M.I., Alemi, M.M., Alabdulkarim, S., Rashedi, E., 2018. Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part I – “Expected” effects on discomfort, shoulder muscle activity, and work task performance. Applied Ergonomics 70, 315–322. https://doi.org/10.1016/j.apergo.2018.02.025

[34] Kinne, S., Kretschmer, V., Bednorz, N., 2020. Palletising Support in Intralogistics: The Effect of a Passive Exoskeleton on Workload and Task Difficulty Considering Handling and Comfort, Advances in Intelligent Systems and Computing. https://doi.org/10.1007/978-3-030-27928-8_41

[35] Kuber, P.M., Rashedi, E., 2020. Product ergonomics in industrial exoskeletons: potential enhancements for workforce efficiency and safety. Theoretical Issues in Ergonomics Science 22, 729–752. https://doi.org/10.1080/1463922X.2020.1850905