



Framework for the adoption, evaluation and impact of occupational Exoskeletons at different technology readiness levels: A systematic review

Jamil Ahmad^{a,b,*}, Vasco Fanti^{a,b,1}, Darwin G. Caldwell^a, Christian Di Natali^a

^a Department of Advanced Robotics (ADVR), Istituto Italiano di Tecnologia (IIT), 16163 Genova, Italy

^b Department of Informatics, Bioengineering, Robotics and Systems Engineering (DIBRIS), Università degli Studi di Genova (UniGe), 16145, Genova, Italy

ARTICLE INFO

Keywords:

Musculoskeletal disorders
Occupational exoskeletons
Technology readiness level
Exoskeleton evaluation
Exoskeleton assessment
Wearable robotics

ABSTRACT

Work-related Musculoskeletal Disorders (WMSDs) are the most common occupational diseases caused by the prolonged performance of strenuous work, such as manual handling of loads or long-term maintenance of incongruous postures. Different safety protocols are implemented to reduce WMSDs and optimize the working environment, but one of the most promising solutions is using occupational exoskeletons (OEs). However, to truly acknowledge the benefits of OEs and be able to introduce them into daily business use, devices must pass several development and testing stages that determine the Technology Readiness Level (TRL). This review study aims to present an up-to-date collection of the most advanced assessments of exoskeletons for upper and back support, ranging from laboratory real-task simulations to operational scenarios in industrial sites. To identify relevant studies, we conducted comprehensive searches across different electronic databases, i.e., PubMed, Scopus, and Web of Science. Different keywords were used for the literature search, e.g., occupational exoskeleton, industrial exoskeleton, etc. Studies were included if they investigated the assessment of exoskeletons in the laboratory with real tasks or an industrial environment. We identified 45 research articles that fulfilled this selection criterion. Several features are compared and discussed in detail, such as industrial environment, experimental protocol, task performed, and exoskeleton typology. These data allowed us to formulate results that report the correspondence or discrepancy between the number of papers testing exoskeletons and WMSDs in different industrial sectors, the type of assessment performed, and the impact of exoskeletons on workers and industries at different TRLs. Among the results, the incidence of WMSDs in the manufacturing industry is 21.13%, while the adoption of exoskeletons in the same field is the highest with respect to the other industrial fields, at 44.45%. Electromyography (EMG) and Questionnaires were the most evaluated typologies across all development and testing stages (with an incidence of 64% across the selected articles). Additionally, an average reduction of EMG activity was reported, with 24% for Upper Limb and 20% for Back Support. Regarding the subjective assessment reported in the questionnaires, 68% of the studies reported a positive evaluation. Based on these outcomes, this work provides a framework for an effective evaluation process for the OEs to raise TRL with recommendations for future research activities.

1. Introduction

The International Labor Organization (ILO) has identified that the risk of developing occupational diseases correlates with performing strenuous work, defined as “a disease contracted as a result of exposure to risk factors arising from work activity” [1]. To limit or better prevent this risk, it is good practice to apply engineering control by monitoring not only the task performed by the worker but also the work environment around the worker [2]. Of all occupational diseases, the most common are work-related musculoskeletal disorders (WMSDs), i.e., disorders of the soft tissues and their surrounding structures not

resulting from an acute or instantaneous event [3]. The European Agency for Safety and Health at Work estimates that 60% of work-related health problems affect the musculoskeletal system [4], and the most affected body sections are the back and the upper limbs, with 43% and 41% of incidence, respectively, and then the lower limbs with 29%, which also includes numbers from cumulative WMSD. These events noticeably worsen the worker's health and lifestyle, leading to severe economic consequences that spill over into personal, corporate, and national turnovers. The estimated financial cost associated with WMSD in Europe was 240 billion euros in 2007 [5]. To ensure adequate safety,

* Corresponding author at: Department of Advanced Robotics (ADVR), Istituto Italiano di Tecnologia (IIT), 16163 Genova, Italy.
E-mail address: jamil.ahmad@iit.it (J. Ahmad).

¹ J. Ahmad and V. Fanti equally contributed to this work.

the activities that fall into the category of strenuous work require a first step of risk analysis. Standard assessment methods are based on the nature of the task (TACOS [6], NIOSH [7–9], OCRA [10]). After the risk evaluation, the second step is optimizing the workstation's reorganization and redesigning it to mitigate risk factors. Although best practices are in place, a US study underlined that the best solution to reduce Manual Material Handling (MMH) related hazards is implementing appropriate engineering changes and mechanical assists [11]. Moreover, factors such as an aging workforce, pension crisis, growing burden of chronic diseases, and increasing health inequalities [12] make the risk of WMSDs worse. Therefore, developing exoskeletons for industrial applications as a possible preventive solution for the WMSD [13] is strongly motivated.

Exoskeletons are wearable devices that can assist, rehabilitate, or augment human body capabilities [14]. These devices have been widely implemented in medical [15] and military [16] environments and are becoming increasingly common in industry [17]. When applied in the industrial field, they are called Industrial or Occupational Exoskeletons (OEs) [17]. OEs are mobile exoskeletons that can be active or passive based on the actuation mechanism. An active exoskeleton [18] operates utilizing actuators, generally electric motors, but other drive systems are possible, whereas a passive exoskeleton [19] operates employing springs, elastic bands, or other energy storage systems. In addition, exoskeletons can be distinguished according to their mechanical structure, which is rigid and soft. Rigid exoskeletons consist of a solid frame with actuators attached to it, whereas soft exoskeletons (often called exosuits) consist of garments and soft actuators that transmit assistive forces without rigid mechanical transmissions [20]. Also, different exoskeletons assist different body sections, e.g., upper limbs, lower limbs, back support, and full body exoskeleton. Upper limb exoskeletons are used to support and assist one or more of the shoulder, elbow, and wrist movements. A common example of an application for upper limbs exoskeletons to assist with overhead working tasks [21,22]. Similarly, back support exoskeletons are commonly implemented for assisting the back during MMH activities [23].

A debate that is still very current in the literature concerns which exoskeleton and actuation type (active/passive) is best suited to specific work tasks (dynamic/static). Developers compete to show continuously improved results. Toxiri et al. [24] reported that passive exoskeletons are very suitable for tasks that involve static or very limited dynamic movements, whereas active exoskeletons are better for more dynamic tasks but are currently less suited for static tasks. Tasha et al. [25] reported that to prevent WMSDs during overhead work (a mostly static task), it is better to consider passive upper limb exoskeletons rather than active upper limb exoskeletons. Tommaso et al. [26] conducted a preliminary research study to determine the difference between active and passive back-support exoskeletons during static and dynamic tasks. In this work, it was concluded that the active back-support exoskeleton performed better during dynamic tasks on both back muscle activation reduction and user experience than the passive back-support exoskeleton. In the static tasks, although the muscle activation was reduced with the active device, the passive back-support exoskeleton performed better in terms of comfort. Since there are few comparative tests between active and passive OEs, the collection of more data is essential.

To truly evaluate the benefit of OEs and their impact in the “real world”, industrial tests are essential. These experimental sessions, conducted in industrial environments, can have a strongly defining effect on the final acceptance of the devices, generating new needs and highlighting real problems that can be addressed as part of the design and development process [27]. In fact, a recent study underlined the discrepancies between laboratory and field evaluation of a passive shoulder-support exoskeleton [28]. Another critical factor is the interaction of the exoskeletons with the workers. This interaction introduces essential considerations such as comfort, breathability, user experience,

ergonomics, etc. [29], that impact the acceptance and lead to the development of new solutions that enhance user uptake.

Although numerous other papers in the literature have reviewed the state of the art of OEs in recent years [13,17,24], few are relevant and complementary to this work. Kuber et al. [30] undertook a review study to examine and contrast the methods, strategies, and results employed in field evaluations of exoskeletons designed to support the shoulders and back. De Bock et al. [31] provides an overview of protocols assessing the effect of OEs on users and formulating recommendations to benchmark their effects, which are distinguished into “validation”, “evaluation”, and “field” studies. To conclude, Crea et al. [32] conducted a study to evaluate the effectiveness of OEs in laboratories and fields to promote large-scale adoption of these devices. Hence, with the current and predicted growth in interest in occupational exoskeletons, this paper aims to systematically investigate the state of the art in industrial-oriented exoskeletons and determine the market readiness of this technology. The paper highlights the most traveled sectors of exoskeleton assessment in factories and vitally identifies areas not yet explored. This paper also identifies the key benefits and needs in moving from basic laboratory testing to field validation.

This review paper systematically analyzed the state of the art in occupational exoskeletons targeting industrial setups. We studied research articles with Technology Readiness Levels (TRL) 5, 6, and 7 (lab testing with industrial tasks reproduction, real task simulated in industrial environment and operational setup, respectively). To the best of the authors' knowledge, this is the first review article that devotes a significant amount of attention to exoskeleton evaluation across TRLs. The division of the research papers into distinct TRLs adds innovation to this study because the publications do not specifically indicate the TRL. The paper is divided into the following sections: “Methodology” where the selection criteria to include/exclude the papers from this work are reported, “Technology Readiness Level (TRL)” where the technical maturity of the devices included in this work is defined, “Results and Discussions” which is divided into subsections that separately address the adoption, evaluation, and impact of exoskeletons in industry, “Framework for the Assessment of Industrial Exoskeletons” where are the recommendations and suggestions to guide future researchers, “Study Implications” where the significance of this study is stated, and finally “Conclusion” where the principal aspects that characterize this paper and its limitations are reported.

2. Methodology

We adopted the methodology to perform the systematic review in accordance with the PRISMA guidelines [33]. The methodology involves several stages as shown in Fig. 1 and are explained as follow:

2.1. Identification and search strategy

The research to find relevant articles to include in this paper was performed by two authors on three different electronic databases, i.e., Web of Science, Scopus, and PubMed. The authors used a keyword-based search where different keywords were used along with OR and AND operators, i.e., (occupational exoskeleton OR industrial exoskeleton) AND (automotive OR construction OR hospital OR agriculture OR logistics OR food) to identify all the possible papers. The two authors performed the search and selected the papers independently. The search resulted in 982 research articles in total. After selecting research articles, 422 duplicate records were removed using Zotero software, and 22 were removed by authors.

2.2. Screening of research articles

The research articles identified as a result of keyword-based search were screened by two authors based on titles and abstracts. The authors analyzed a total of 538 studies. Articles that were relevant to the theme of the review paper were selected. If the two authors disagreed on selecting a specific article, the complete article was analyzed. Still, if the disagreement persisted, a third reviewer made the decision.

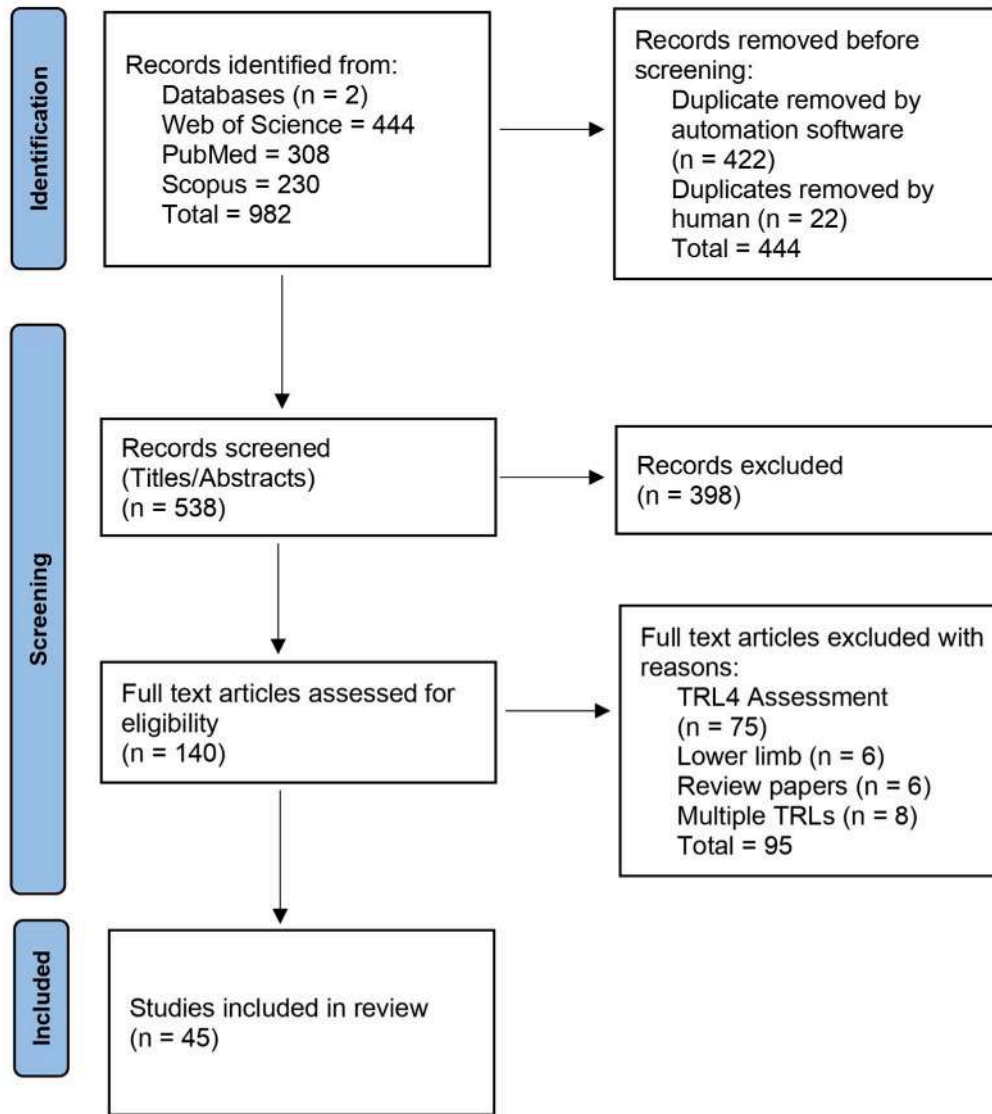


Fig. 1. Flow chart of the methodology adopted to select the papers included in this work using PRISMA guidelines.

2.3. Eligibility for selection

In order to select relevant papers for the review, an eligibility criterion was developed. The eligibility criterion is as follows :

- The paper must assess the exoskeleton in the lab or the field.
- The article should not be a rehabilitation-based study.
- The study should involve practical work rather than software simulations.
- The study should be performed with healthy subjects (novice subjects/experienced workers)

2.4. Data extraction

The selected 140 papers were assigned an ID number for the “blind procedure” process. Associating an ID number with each article aims to avoid bias with respect to individual researchers or research groups. During this stage, the main characteristics of each paper, i.e., industrial application, target work task, exoskeleton, methodology of the experiment, type of subject, and results, were reported in a specific analysis table. After filling all the columns in the table except TRL, the analysis table was revised by a third reviewer who did not participate

Table 1

TRL values with experimental protocol characteristics that identify them.

TRL-4	Assessment performed with generic motions in laboratory
TRL-5	Reproduction of industrial tasks in laboratory
TRL-6	Reproduction of industrial tasks in industrial environment
TRL-7	Assessment performed in real industry and during operational activity

in the assignment of the ID and, therefore, had no knowledge about the authors and titles of the research articles. The third reviewer assigned the TRL (4, 5, 6, and 7) values to each paper based on the experimental protocol (i.e., according to the task performed and the surrounding environment). Since the TRL was not mentioned in any article, this association was a critical aspect of the review. Table 1 below shows different TRL values and the characteristics required for their assignment.

3. Technology Readiness Level (TRL)

Technology Readiness Level is a process for determining the technical maturity of a technology. It is divided into several steps ranging from TRL-1 to TRL-9. TRLs make it possible to discuss technical maturity consistently and uniformly [34,35]. The different levels of TRL

are traditionally divided into 3 phases: TRL-1 to TRL-3 is the research phase, TRL-4 to TRL-6 is the development phase, and TRL-7 to TRL-9 is the deployment phase. In this paper, we are interested in reviewing and evaluating the paths to industrial uptake and how developers interpret and address the relevant steps of TRL-5 to TRL-7, which are defined as:

- TRL-5 is the validation of the exoskeleton on a reproduced work task in laboratories with novice subjects.
- TRL-6 is the simulation of the task in a relevant environment with the exoskeleton by expert workers.
- TRL-7 is the demonstration of the use of the exoskeleton in an operational environment with experienced workers.

The fundamental goal of moving through these TRL levels (from 5 to 7) is to experience each level's unique obstacles and unforeseen circumstances. Numerous challenges are there at every one of these selected TRL levels, and these challenges get more demanding as we go up the levels. The whole process aims to evaluate the technology as whole but also the possibility of guiding the redesign to fill gaps and challenges.

The primary objective of TRL-5 is to examine the exoskeleton biomechanical effects on the user's physical exertion and the amount of assistance they can offer the user while performing target activities. It can find possible inefficiencies, limitations, and detrimental effects of device usage.

The main goal of TRL-6 is to evaluate the device in non-laboratory testing, with real workers, but still not in the wild. It focuses on the impact of the workers and the environment rather than the device's technical performance.

TRL-7 seeks to evaluate the technical and user acceptance in a real setting and include factors such as usability, comfort, discomfort, and longer-term fatigue compared to laboratory tests.

Fig. 2 shows the relative importance of the three main aspects (technical performance, application evaluation, and technology acceptance) in TRL-5 to TRL-7 assessments. "Technical performance" refers to how effectively the exoskeleton supports the target body section. "Application evaluation" refers to how the exoskeleton is suitable for specific tasks and industrial sectors. Finally, "technology acceptance" is the level of appreciation of the exoskeleton provided by the end user. Fig. 2 is based on our hypothesis and understanding of the objectives associated with the TRLs and the authors' experiences in assessing industrial exoskeletons at various TRLs. The percentages in each bar plot represent the weight of the three main assessment categories: "technological assessment", "application evaluation", and "technical performances" for the three TRLs. We believe that TRL-5 should be more focused on verifying the "technical performance" of the industrial exoskeleton than the other two parameters. TRL-6 should place equal emphasis on "application evaluation" and "technical performance". Finally, TRL-7 should place more emphasis on "technology acceptance" and "application evaluation".

4. Results and discussions

In this review, 140 research publications were ultimately chosen using our selection criteria. Of these 140 papers, 6 were review papers that helped us in identifying other research articles that were relevant to our review [17,30,32,36–38], 75 were TRL-4 and hence were dropped because they were below these TRL threshold (TRL 5, 6 and 7). 6 studies utilized lower limbs exoskeleton as their foundation [39–44]. These publications were omitted so that we could concentrate on exoskeletons for the upper limbs and the back support. Additionally, the number of articles on lower limb exoskeletons was very low when compared to upper limb and back support articles. The remaining 53 papers were divided according to different TRL levels and the type of exoskeleton utilized. 14 papers were at TRL5, 8 papers were TRL6, and 31 papers were TRL7. Among the reviewed articles in different

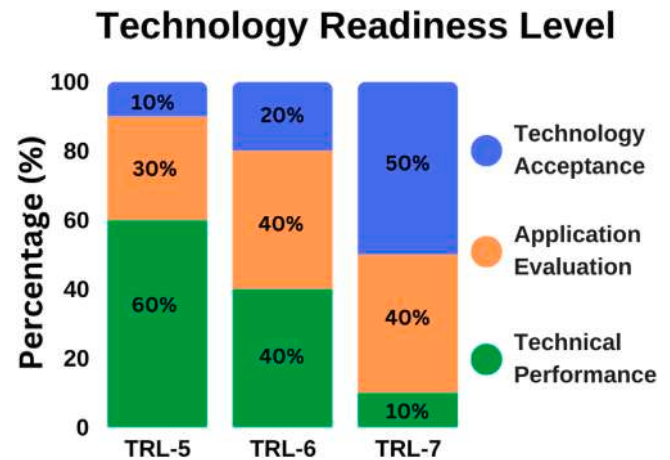


Fig. 2. Technology Readiness Level and evaluation of three aspects based on author's experience.

TRL (5, 6, 7) levels, 8 papers report tests performed in more than one evaluation environment, e.g., [45] is both TRL5 and TRL7 assessment, so they fall into multiple TRLs. However, we avoided the replication of a single article in different TRLs. Thus, we subtracted 8 from the total number of articles, yielding 45 papers in total. Similarly, out of the 45 papers, 18 papers were based on back support exoskeletons, 23 focused on upper limb exoskeletons, and 4 papers addressed both upper limb and back support exoskeletons. Some of the OEs from the selected papers are displayed in Fig. 3.

This section is divided into multiple sub-sections. Each sub-section analyzes a specific theme, including a dedicated discussion as follows: Exoskeletons Across Industrial Sectors and WMSD Incidence, Tasks and Exoskeletons Among Industries, Type of Assessment, Duration and Testing Subjects, Impact of Industrial Exoskeletons and Pathway to Effective Industrial Assessment.

4.1. Adoption of exoskeletons across industrial sectors and WMSD incidence

In this subsection, the selected 45 papers were further divided according to different industrial sectors and different TRL levels in each sector. Additionally, the incidence of WMSD specific to each industrial sector is also examined. The results are shown in Figs. 4 and 5, respectively.

According to Fig. 4, three studies focus on the Manufacturing industry: one study was at TRL-5 [53], one was assigned TRL-7 [54], and one was classified both TRL-6 and 7 because this paper presents a simulation and an operational test in the industry [55]. Although manufacturing clearly includes the Automotive and Shipbuilding industries, which represent 44.45% of the sector, we have kept this separate. Hence, the Automotive industry has the highest number of publications, corresponding to 35.56%. Within the Automotive studies, two were TRL-5 [48,56] and two were TRL-6 [57,58], eleven were TRL-7 [49,59–68], and one included both TRL-6 and 7 [28]. Ship construction has only one study at TRL-7 [69], while Health and social care includes two papers at TRL-5 [70,71] and one at TRL-6 and 7 [72]. Waste treatment and cleaning include two studies at TRL-7 [73,74]. Construction is the third most investigated sector for testing exoskeletons, with almost 8.89% of the papers. It has one paper at TRL-5 [75], one paper at TRL-6 [76], and two papers at TRL-7 [77,78]. Agriculture and also Transport and Storage are jointly ranked second in the list of the most investigated sectors with over 11.11% each. Agriculture consists of one paper at TRL-5 [79], one paper at TRL-7 [80], and three papers at both TRL-5 and 7 [81–83], while Transport and Storage, which includes Logistics, has two studies at TRL-5 [47,84], one paper at TRL-6 [85],



Fig. 3. Occupational exoskeletons used in different industries, (a) A medical operator performing a task while using an exoskeleton [46] (b) A luggage handling task while wearing the XoTrunk [47] (c) A worker using the ShoulderX V2 for an overhead task [28] (d) Operator performing a simulated automotive task using proto-MATE [48] (e) A worker performing assembly task with an exoskeleton [49] (f) A worker performing a manufacturing task with a back support exoskeleton [50] (g) A worker using the Laevo V2.5 while performing and order picking task [51] (h) Worker performing overhead task in automotive industry using Paexo [52].

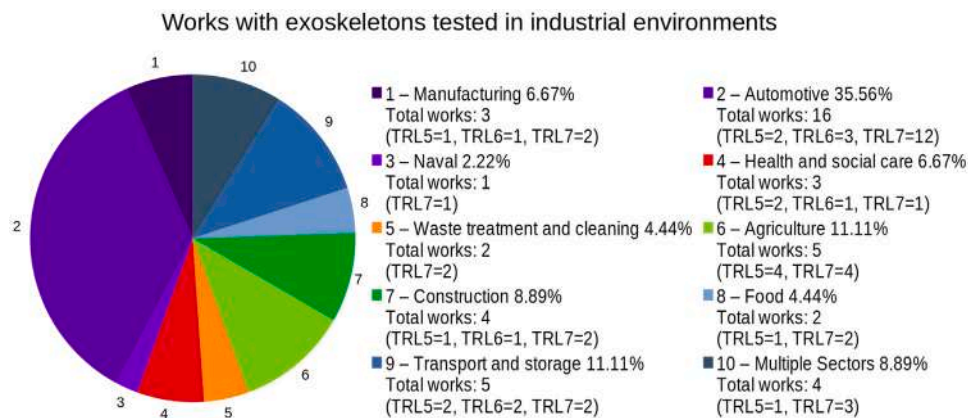


Fig. 4. Pie chart showing the percentage of articles collected for each industrial field, divided into TRL 5, 6, and 7.

one paper at TRL-7 [51] and one of both TRL-6 and 7 [86]. The Food industry reported two papers, one at TRL-7 [87], and the other at TRL-5 and 7 [45]. Four papers tested exoskeletons in Multiple heterogeneous sectors, i.e., different industrial fields that do not report the task in detail, thus preventing detailed categorization. We assigned TRL-5 to one of these papers [88], while TRL-7 was assigned to the remaining three [50,89,90].

To better understand the significance of the results in Fig. 4 in comparison with the industrial needs, we also analyzed the statistics on the incidence of WMSDs in Europe in 2019. By combining the data from [4,91], we were able to split the number of WMSDs according to the body section and industrial environment. In the sectors analyzed, the total number of workers affected by WMSDs of the back is almost 70 million, while those affected suffering upper limb WMSDs are almost 67 million. The results are shown in Fig. 5.

From Fig. 5, the highest percentage of WMSD occurs in the Manufacturing industry, with 21.13% of the total. Second, with 13.69%, is the Wholesale and retail trade industry, which has the highest gap between injuries on the back (16.52%) and on the upper limb (10.86%).

Third is the Health and Social Care industry with 14.6%, but also the Construction industry reports high values of WMSD, which is 10.44% on average. All the remaining industries report cases of WMSD that are under 10%.

Figs. 4 and 5 show industrial sectors that may offer an interesting field for the development and evaluation of occupational exoskeletons. For example, by additionally including Automotive and Naval in the Manufacturing industry, we noted a consistency between the high number of publications (44.45%, Fig. 4) and the incidence of disorders (21.13% for back and upper limb, Fig. 5). Similarly, Wholesale and retail report an average incidence of WMSD of 13.69% in Fig. 5, but does not appear in Fig. 4. In fact, this term also brings together very different activities and tasks that would be interesting to analyze further but are challenging to categorize. Some activities that could fall under this sector, for example, involved food handling, so they were included in Accommodation and Food, while others are part of the work included in Multiple Sectors. In any case, this industry offers vast opportunities for the analysis, development, and evaluation of exoskeletons, especially for back support. Also, Health and social care industries are certainly

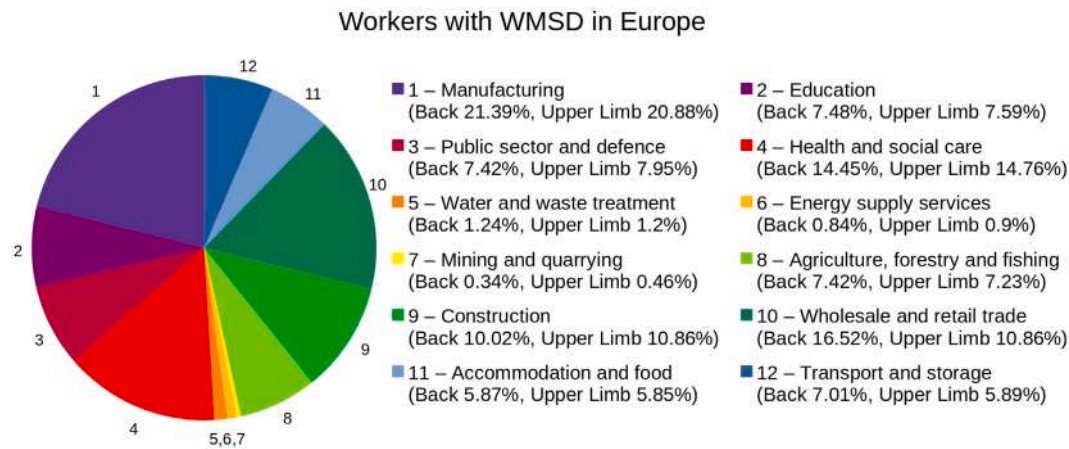


Fig. 5. Pie chart showing the percentage of work-related musculoskeletal disorders on the back and upper limb across the different industrial fields.

under-investigated compared to what they should be. In fact, they are the third largest industry sector for musculoskeletal injuries with an incidence of 14.6%, but looking at Fig. 4, there is only one assessment that exceeds TRL-5. Construction, Agriculture, and Transport and storage report a good alignment between the percentage of injuries, Fig. 5, and research studies, Fig. 4. However, other fields like Wholesale and retail trade and also Health and social care report high percentages of WMSDs compared to studies performed in these industries. In any case, the number of articles belonging to each of these industries does not exceed 5, so the continuation of these analyses in the above sectors is strongly encouraged. Additionally, we were unable to locate studies pertaining to some industries, such as the Public sector and defense, Education, Mining and quarrying, and Energy supply services. Hence, we highly encourage researchers to conduct studies in these sectors as well.

The reason why so few studies apply exoskeletons in some industries is an open question that needs to be investigated. Among the reasons that limit the testing of these devices in particular sectors is the cost at the front, which makes adoption difficult in some sectors. Another crucial aspect is the incompatibility of using some exoskeleton models in specific industrial environments due to constraints requiring dedicated customization and sector-specific OE development. The exoskeleton could interfere with workers' clothes, equipment, personal protective equipment (e.g., high-visibility suits, safety harnesses, etc.) or with the work environment (that due to confined spaces, the user's movement can be limited, presence of magnetic fields that can create interference, etc.). In these cases, research should move toward customizing exoskeletons to accommodate the end user's needs by offering tailored solutions suited to the specific work environment, as in [92]

4.2. Tasks and exoskeletons among the industries

This section analyses features of back-support (Table 2) and upper-limb support (Table 3) exoskeletons, respectively. The features analyzed are the nature of the test, the tested exoskeleton, actuation classification, and the TRL of the test. The test type is classified as static or dynamic [93,94] defined as:

- Static - Activities in which the assisted joint is either unmoving or makes small movements around the target position.
- Dynamic - Activities in which the assisted joint performs large movements around the target position or performs movements that are the combination of multiple simple tasks.

Table 2, on back support exoskeletons, shows that across the different industrial sectors, dynamic tasks are much more common than static ones. At the same time, the use of passive exoskeletons (P) is

markedly higher than active ones (A). In fact, of the 17 exoskeletons for back support that are shown in Table 2, only 3 devices provide active assistance, with the remainder using passive actuation. Laevo exoskeletons are the most commonly and widely tested (tested in all industries apart from Construction and Waste Treatment and Cleaning), with 32.14% of the trials. Additionally, it is the only exoskeleton to have been tested at all TRLs from 5 to 7. None of the other exoskeletons appear more than three times in Table 2. Another interesting finding is the recurrence of tests for each TRL. In fact, the TRL-5 column reports 10 ticks, the TRL-6 column reports 6 ticks, and the TRL-7 column reports 20 ticks, corresponding to 27.78%, 16.67%, and 55.55%, respectively. Thus, more than 50% of studies test exoskeletons in the operational environment (TRL-7), but less than 30% reproduce the task in the laboratory (TRL-5) or in industry (TRL-6). These results highlight that in most cases, researchers move on to performing the tests in the company without assuring the exoskeleton's performance and industrial environment sustainability with specific assessments in the laboratory and simulated industrial tasks. However, we should also consider the fact that publishing articles at TRL5 and 6 is very difficult because the exoskeleton does not change drastically, and there is nothing significantly new to report in a scientific journal. This can reduce the number of publications at TRL-5 and TRL-6. Moreover, TRL-6 can affect companies economically because the worker has to stop working in production and dedicate their time and effort to research.

Table 3 shows tasks and upper limb exoskeleton usage by industry. 59% of the papers analyze static tasks, and 41% analyze dynamic tasks. Interestingly, for upper-limb exoskeletons with TRL>4, only passive actuations have been reported, highlighting a possible technology gap. The three most used exoskeletons are Airframe (18.52%), Skelex (14.81%), and Mate (14.81%), with the latter being the only one used at TRL-5 to 7, although in different industries. TRL-5 column reports 6 ticks, TRL-6 reports 7 ticks, and TRL-7 reports 20 ticks, corresponding to 18.18%, 21.21%, and 60.61%, respectively. Again, as with back-support exoskeletons, the research's trend seems to be off balance, with the majority of exoskeleton tests carried out in production lines to the detriment of staged investigations in laboratories and simulations in a controlled environment.

A consideration that arose from these results, which deserves special attention, is the number of discrepancies between active and passive exoskeletons tested in TRLs from 5 to 7. Considering both back-support and arm-support exoskeletons, the number of passive exoskeletons is significantly higher than the number of active ones. Among the reasons for researchers conducting a high number of tests with passive exoskeletons is the ease of integrating these devices into the industrial process. But also, the device characteristics that do not require installation experts, wide commercial availability, and prices are certainly lower than those of the corresponding active exoskeletons [24]. The economic

Table 2

Industrial fields where Back-support exoskeletons have been tested. The table also reports the test typology, the name of the exoskeleton, its actuation classification, and the TRL associated with the test.

Back support							
Industrial Field	Task Typology	Exoskeleton	Actuation	TRL-5	TRL-6	TRL-7	Paper
Manufacturing	Dynamic	Laevo	P			X	[54]
	Static and Dynamic	Laevo	P	X			[53]
Waste treatment and cleaning	Dynamic	ErgoVest	P			X	[74]
Multiple sectors	Dynamic	BackX	P			X	[89]
	Static and Dynamic	Dynamic trunk orthosis-Japet	A			X	[50]
	Static and Dynamic	Laevo	P			X	[90]
	Static and Dynamic	BackX	P			X	[90]
	Static and Dynamic	NIST Exoskeleton	P	X			[88]
Automotive	Static	PLAD	P			X	[60]
	Static and Dynamic	Laevo	P			X	[59]
Construction	Dynamic	–	P	X			[75]
Health and social care	Dynamic	Flx Ergoskeleton	P	X			[70]
	Dynamic	V22 Ergoskeleton	P	X			[70]
	Dynamic	Laevo	P	X			[70]
	Static and Dynamic	Laevo	P		X	X	[72]
	Static and Dynamic	Corfor	P		X	X	[72]
	Static and Dynamic	BackX	P		X	X	[72]
	Static and Dynamic	CrayX	A		X	X	[72]
	Static and Dynamic	Laevo	P			X	[87]
Accommodation and food	Dynamic	XoTrunk	A	X		X	[45]
	Static and Dynamic	Laevo	P			X	[87]
	Static and Dynamic	Rakunie	P			X	[87]
	Static and Dynamic	Paexo Soft Back	P			X	[87]
Agriculture, forestry and fishing	Dynamic	CAE	A			X	[80]
	Static and Dynamic	Laevo	P	X		X	[81] [82]
Transport and storage	Dynamic	XoTrunk	A	X			[47]
	Dynamic	Laevo	P		X	X	[85] [51]
	Dynamic	HeroWear Apex	P		X	X	[86]
	Dynamic	Mile Bot	P	X			[84]

Table 3

Industrial fields where Upper-limb-support exoskeletons have been tested. The table also reports the test typology, the name of the exoskeleton, its actuation classification, and the TRL associated with the test.

Upper-Limb Support							
Industrial field	Task typology	Exoskeleton	Actuation	TRL-5	TRL-6	TRL-7	Paper
Manufacturing	Dynamic	Mate	P		X	X	[55]
Waste treatment and cleaning	Static	Mate	P			X	[73]
Multiple sectors	Static and Dynamic	Airframe	P			X	[89] [90]
	Static and Dynamic	EksoVest	P			X	[90]
	Static and Dynamic	NIST Exoskeleton	P	X			[88]
Automotive	Static	H-Vest	P	X			[56]
	Static	ShoulderX	P		X	X	[57] [67] [58]
	Static	Mate	P		X		[57]
	Static	Paexo Shoulder	P		X		[57]
	Static	EVO	P			X	[62]
	Static	Skelex	P			X	[67]
	Static	Airframe	P			X	[61] [67]
	Static	ProtoMATE	P	X			[48]
	Static and Dynamic	Crimson Dynamics	P			X	[65]
	Static and Dynamic	Skelex	P		X	X	[28] [65]
	Static and Dynamic	ShoulderX	P		X	X	[28]
	Static and Dynamic	Airframe	P			X	[63] [49]
	–	Airframe	P			X	[64]
	–	EksoVest	P			X	[66] [68]
Construction	Dynamic	Skelex 360	P		X	X	[76] [77]
	Dynamic	Exo01-Hilti	P			X	[78]
	Dynamic	EksoEvo	P			X	[78]
Health and social care	Static	Airframe	P	X			[71]
Accommodation and food	Static and Dynamic	Atlas	P			X	[87]
Agriculture, forestry and fishing	Dynamic	Prototype Exoskeleton	P	X			[79]
	Dynamic	PULE	P	X		X	[83]
Naval	Dynamic	Skelex	P			X	[69]

Assessment in different TRLs

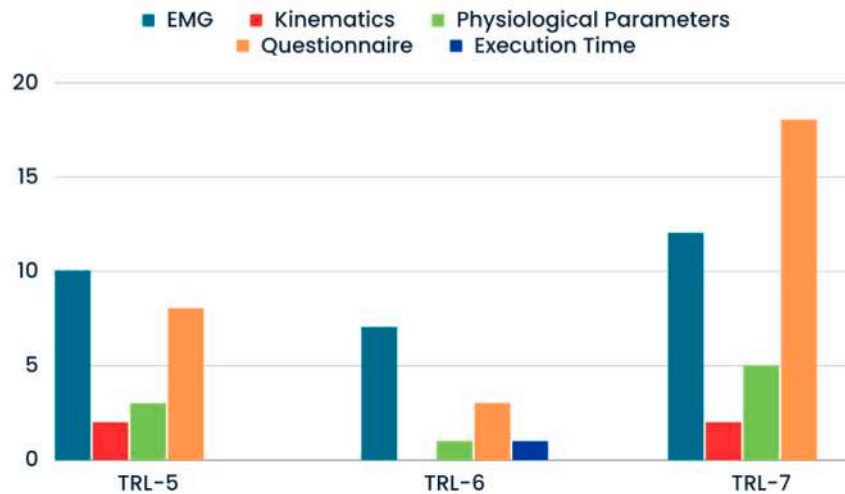


Fig. 6. Assessments performed in the different TRLs.

aspect is crucial because it allows companies and researchers to acquire them quickly and at affordable prices. Regarding active and passive exoskeletons' physical characteristics, it is worth underlining that active exoskeletons are generally heavier, bulkier, and more complex than passive ones, making their application in industrial environments, especially in places characterized by small spaces, challenging. Moreover, active exoskeletons rely on sensors and electronic components that could interfere with other industrial machinery, making compliance with industrial technical standards (e.g., ISO 12100) a requirement for device adoption. However, the versatility demonstrated by active exoskeletons is superior to passive exoskeletons [45], so the authors believe this technology deserves to be investigated more deeply.

4.3. Evaluation of industrial exoskeletons using various assessment typologies

During this study, a number of different assessment approaches were observed for both back and shoulder systems, i.e., electromyography, questionnaire, kinematics, physiological parameters, and execution time, as shown in Fig. 6.

4.3.1. EMG

Electromyography (EMG), involving recording muscle electrical activity, is a common assessment technique used with industrial exoskeleton [95,96]. However, EMGs are susceptible to noise and require careful set-up, e.g., skin preparation, sensor placement, signal processing, etc. [97].

At TRL-5, EMG was solely used in 7 papers while 3 papers measured EMG in combination with other assessment formats (10 of 14 papers — 71%) [45,47,48,53,56,70,75,79,82,83]. At TRL-6, EMG was solely used in 4 papers, with a further 3 papers reporting EMG along with other assessments (7 of 8 papers — 87%) [28,55,57,58,76,85,86]. Finally, at TRL-7, EMG was solely reported in 8 cases with 4 papers using some combination of assessment formats (12 of 31 papers — 38%) [28,49,54,55,60,61,63,64,67,73,82,83].

However, there are several limitations to this assessment approach. Zheng et al. [98] reported that the placement of EMG sensors often underlies the exoskeleton, and this can cause interference, which can affect the quality of the recordings and increase EMG signal noise [97]. Consequently, it is suggested that a controlled setting is required to

gather reliable and accurate data. Since EMG sites require a degree of preparation and calibration, this is very difficult to carry out in an operational environment (TRL-7). We advise using EMG measurement in a controlled setting (TRL-5). EMG can also be carried out in industrial settings (TRL-6), but extra safety precautions must be implemented. In the case of testing in the industrial sector (TRL-7), we suggest performing a long-duration experiment in which the worker becomes adapted to the exoskeleton. It can then be followed by a quick EMG analysis, such as one lasting for 10 min.

4.3.2. Questionnaire

Subjective user feedback is acquired from participants using questionnaires that can assess different aspects such as perceived exertion, pain scale, user interaction with OE, comfort/discomfort, performance using OE, and usability. Various protocols exist to assess subjective user feedback, i.e., Borg scale [99] and Visual Analogue Scale (VAS) [100]. Borg's scale is a scale for ratings of perceived exertion, whereas VAS is a pain rating scale. Moreover, questionnaires are also used to evaluate the interaction between humans and the exoskeleton and the user experience, i.e., comfort, acceptability, and system usability scale (SUS). Comfort means how pleasant the exoskeleton feels while performing activities. This depends on the fit of the exoskeleton, cushioning, and weight distribution. Acceptability is the willingness of users to integrate the exoskeleton into their everyday routine and job activities. It refers to the degree to which an exoskeleton fits the user's expectations. SUS is a standardized questionnaire that measures the subjective usability of the exoskeleton. SUS provides a quantitative measure of usability through a numerical score ranging from 0 to 100, with higher scores indicating improved/better usability [101]. Moreover, there are other questionnaires available for the evaluation of occupational exoskeletons [102].

Based on our review, at TRL-5, questionnaire is solely used in 2 papers with a further 6 papers using this approach in combination with other assessment techniques (8 of 14 papers — 57%) [47,53,70,71,75,81,84,88]. At TRL-6, questionnaires were solely assessed in 1 paper while a further 2 papers reported combined assessments (3 of 8 papers — 37%) [72,76,86]. Finally, at TRL-7, questionnaires only were used in 13 papers with 5 papers using a combination of assessment methods (18 of 31 papers — 58%) [45,50,51,54,59,60,65,66,68,72–74,77,81,86,87,89,90]. Questionnaires are most common at TRL-7.

Niclas et al. [101] reported that subjective assessments are the most frequently evaluated approach for the evaluation of exoskeletons. However, questionnaires and surveys can be prone to personal preferences [103]. We recommend using this technique at TRL-7 because it is simple to assess, is easily assessed in a work environment, and can be quickly transferred to workers without the need to use invasive equipment. Also, if an exoskeleton evaluation lasts for a longer duration, either in the field or in the laboratory, it is highly advisable to use questionnaires to gather relevant information.

4.3.3. Kinematics

Exoskeletons are mechanical structures that are physically aligned with the user's body, particularly with their joints; hence, mobility constraints must be avoided. This is an important feature in evaluating the interaction between the worker and the exoskeleton. Body kinematics and human motion can be measured using inertial measurement unit-based (IMU) sensors or optical cameras [104,105].

At TRL-5, only 2 papers assess kinematics at all, and this is in combination with other assessment techniques (2 of 14 papers — 14%) [47,53]. At TRL-7, 1 paper reported using kinematics solely, and 1 paper reported kinematics with other assessment methods (2 of 31 papers — 6%) [78,89]. At TRL-6, no papers were identified that assessed kinematics.

Clearly, while kinematic measurement forms part of the suite of assessment techniques, it is much less commonly used than other approaches as it is very challenging to implement in a working environment. Hence, it is best suited to the lab testing at TRL-5. We recommend using this technique in TRL-5 and eventually in TRL-6 because this test is crucial for determining whether the worker has to change the pattern of movement or is being hindered due to the exoskeleton.

4.3.4. Physiological parameters

Assessments like heart rate, metabolic rate, and VO2 are considered as physiological parameters. These parameters are good indicators of physiological loads. From this review, at TRL-5, 3 articles reported recording physiological parameters in combination with other evaluation methods (3 of 14 papers — 21% at TRL-5) [53,84,88]. Similarly, at TRL-6, 1 paper reported physiological parameters assessment combined with other techniques (1 of 8 papers — 12% at TRL-6) [28]. Finally, at TRL-7, 1 paper assessed only physiological parameters, and 4 assessed these parameters in combination (5 of 31 papers — 16% at TRL-7) [28, 69,74,80,89].

As with kinematics assessment, physiological parameter assessment (especially on its own) is less well regarded by researchers when evaluating exoskeletons. However, based on the analysis in [98,101], there is a case to be made that for the initial evaluation, i.e., TRL-5 and TRL-6, physiological parameters can be a very good assessment metric. Further, in a working environment, the less invasive and cumbersome nature of the sensors may make long-term testing more possible. Some issues with physiological parameter assessment are that the measurements could generate inconsistent results because several studies have shown that heart rate is affected by emotions and feelings [106], thus making it preferable to apply alternative assessment typologies that can demonstrate the exoskeleton's efficacy [107].

4.3.5. Execution time (& other work-related parameters)

Execution time is the time required to perform an activity. It provides important comparative information on the total time required to perform a task with and without an exoskeleton.

Based on our review, at TRL-6, only 1 paper evaluated this metric, and this was in combination with other methods (1 of 8 papers — 12% at TRL-6) [76]. No papers were found at TRL-5 and TRL-7. Execution time is the least commonly measured evaluation metric, although this is one of the most manageable parameters to measure, and we highly recommend including this assessment in all TRLs, particularly TRL-7. Further, by including this in all TRLs, we can find the difference between the execution time of experienced workers (TRL-7) and inexperienced subjects (TRL-5, and TRL-6).

4.4. Duration and testing subjects

Along with assessment protocols, we investigated the number of subjects and the assessment time in different TRLs. Table 4 shows details of the subjects and assessment time at each TRL.

4.4.1. Subjects in different TRLs

From the Table 4, it is apparent that the minimum number of test subjects in all TRLs is very low. Although it is technically possible to evaluate an industrial exoskeleton on a single subject, the value of a single (or small number) of test subjects is limited. On the contrary, the average number of subjects is satisfactory for TRL-5 and TRL-7. There are 2 studies [66,68] which reported a very high number of subjects in TRL-7, i.e., 198, compared to the rest of the studies in TRL-7. Apart from this, we believe that the average number of subjects in TRL-5 and TRL-7 is an adequate target for the evaluation of an industrial exoskeleton. However, the average number of subjects at TRL-6 is lower than TRL-5 and 7. One explanation might be the discrepancy in the number of studies at TRL-6 (8), which is very limited compared to TRL-5 (14) and TRL-7 (31).

When considering the design of an experimental protocol to evaluate the device's performance on a statistically relevant sample, the sample dimension depends on several factors [108]. The minimum number of subjects to conduct the analysis and achieve statistically significant results relies on the number of conditions to be compared, the evaluation scale, and the statistical power. The sample size can be two independent samples or paired samples [109]. The analysis implemented to estimate the sample size required for an experiment is known as Power Analysis. In order to find the sample size which can yield statistically significant results, certain parameters are adjusted in a pilot study beforehand, i.e., α (Type-I error), β (Type-II error), statistical power ($1 - \beta$), and effect size [110]. In general, α is set to 0.05, β is set to 0.2, and statistical power is set to 0.80.

Ideally, for exoskeleton assessment in TRL-5 where objective assessments are considered, paired samples are preferred. This means that the same sample is used as the control group (without exoskeleton) and experimental group (with exoskeleton). Additionally, in TRL-5, mostly a single variable, i.e., reduction in muscle activity, is considered. If we consider an effect size of 0.8, which indicates large practical significance based on Cohen's Convention [111], It will yield a paired sample size of 15 (JAMOV statistical software), which is the required number of subjects for evaluating an exoskeleton at TRL-5.

Similarly, for the TRL-7 assessment, where subjective techniques are very common and can have multiple variables for consideration, it will be required to calculate the effect size for each variable and then combine it into a single effect size to show an overall practical significance. If an overall effect size of 0.6 (medium practical significance) is considered, it will yield a paired sample size of 24. Overall, these values are set based on pilot studies and may vary for each study. It is possible that sometimes the calculated sample size may be too big, making the study completely unfeasible; in that case, these values need to be adjusted. However, for simplicity purposes, we tried to untangle this concept and would recommend researchers consider sample size calculation for future research activities.

4.4.2. Assessment time in different TRLs

The assessment time is the overall duration of the experiment, with and without the exoskeleton, and depends upon the experimental environment and the types of assessment that are under consideration. From Table 4, we can see that the average assessment time in TRL-5 is very low as compared to TRL-6 and TRL-7. This is because the most assessed form in TRL-5 is EMG, which requires some time for preparation and calibration, but the actual experiment usually lasts no more than 10 mins on average per subject with exoskeleton which is in accordance with our analysis. This can be seen from Table 4 where the minimum number of subjects is 2 in TRL-5, and the minimum duration

Table 4
Subjects and overall assessment time in different levels of TRLs.

Number of subjects			
	Minimum	Maximum	Average
TRL-5	2	36	15
TRL-6	2	11	7
TRL-7	1	198	24
Assessment Time With and Without Exoskeleton (minutes, hours, days, months)			
	Minimum	Maximum	Average
TRL-5	40 min	13 h	5 h
TRL-6	5 h	30 h	16 h
TRL-7	90 min	21 months	15 days

is 40 min, which translates into 20 mins per subject with and without the exoskeleton. Similarly, if we analyze the average number of subjects in TRL-5, i.e., 15, and the average duration, which is 5 h, it is 20 mins per subject with and without exoskeleton. However, this time can increase or decrease based on the number of activities that are under consideration. More activities correspond to more assessment time and vice versa. Also, the tasks performed at TRL-5 are replications of the original task, and the instructions are very precise and accurate about each task which makes it easy for the subjects to perform the tasks quickly. Similarly, the average time for TRL-7 is the highest because performing an experiment in an industrial setting encapsulates a lot of aspects, for example, to achieve acceptable evaluation the worker must adapt to the exoskeleton and adaption does require some time. Also, the tasks at TRL-7 are operational tasks and are very different from those that are replicated in the laboratory. The most common assessment technique at TRL-7 was the questionnaire, which is particularly suitable for studies that last for weeks or even months. However, although some assessments at TRL-7 do indeed last for months, the average assessment time for most TRL-7 trials is very much shorter (hours, days). We strongly advise future researchers to conduct long-term assessments of exoskeletons. Longer evaluation times give individuals more time to adapt to the exoskeleton, which makes this incredibly crucial. The likelihood that occupational exoskeletons will be accepted increases with successful exoskeleton adaption.

4.5. Impact of industrial exoskeletons

As previously mentioned, the implementation of occupational exoskeletons can reduce WMSDs in real-world scenarios, however, the adoption is still very limited. Deployment of industrial exoskeletons depends upon several metrics, i.e., reducing muscle activation, user's comfort/discomfort, size, usability, etc. This section includes a brief analysis of the findings from the 45 papers studying the impact of industrial exoskeletons in both "real-world" and simulated "real-world" settings. This will ultimately provide evidence for the large-scale adoption of industrial exoskeletons in the industrial sectors. This section is divided into the following subsections:

4.5.1. EMG impact in different TRL levels

Table 5 presents the average reduction in muscle activity for upper limb and back support exoskeletons used at TRL-5, 6, and 7. Although the papers report a number of different sets of muscles for back support and upper limb exoskeletons, we focus on activation of the Anterior Deltoid (AD) for upper limb exoskeletons and the Erector Spinae (ES) for back support exoskeletons. We chose these muscles because in upper limb exoskeletons, AD is most commonly reported, while in back support exoskeletons, ES is the most often recorded. Secondly, as both AD and ES are large muscle groups, they often register significant activation differences. 29 papers reported EMG at TRL-5, 6, and 7, and 26 of these papers (89%) showed significant reductions in EMG (both upper limbs and back support exoskeletons). These reduced EMGs suggest that exoskeletons can indeed lessen the risk of WMSDs and fatigue. However, large-scale adoption cannot be based on EMGs alone,

as a user's perception of the impact of using an exoskeleton may not agree with the outcome. Gilota et al. [112] found that for manual handling tasks, the physical performance investigation contradicted operators' perceptions of device benefits. For large-scale adoption of exoskeletons, other metrics should also be considered, i.e., questionnaires and surveys.

4.5.2. Questionnaire impact in different TRLs

In this section, we analyzed the results from all papers that evaluated exoskeletons based on subjective measures such as comfort, system usability scale, Borg's scale, and acceptability. Table 6 shows the analysis of the various subjective measures depending on TRL. Based on our analysis, a total of 29 papers evaluated subjective measures at TRL-5, 6, and 7 and 20 [47,50,51,60,65,66,68,70–72,72–77,86,86,87,89] of these articles (68%) reported that the exoskeleton is acceptable, comfortable, and useful. Among various subjective measures, only a single paper [72] reported comfort in TRL-6, and acceptability was reported by a single paper [47] in TRL-5. Still, these findings highlight the benefits of industrial exoskeletons even more and offer more proof for the large-scale adoption of OEs. However, in some studies [54,59,84], the participants reported discomfort while wearing an exoskeleton. There are several factors that can contribute to discomfort while wearing an exoskeleton, i.e., poor fit, restricted movement, weight, material and design, adjustability, and pressure points. Addressing these factors properly in future exoskeleton designs can significantly make the exoskeleton comfortable.

4.5.3. Kinematics and physiological parameters impact in different TRLs

Tables 7 and 8 show analysis of articles that evaluated kinematics and physiological parameters, respectively. Analysis of these parameters was less commonly recorded across studies at all TRLs, and as a result of the limited data, it is not possible to draw any definite conclusions. Clearly, in the future, these assessment formats need to be assessed more often at the different levels of TRL to verify their impact.

5. Framework for the assessment of industrial exoskeletons

This study has identified several significant features of industrial exoskeletons at high TRLs relating to assessment protocols, assessment format, and implementation of exoskeletons in different industrial fields.

Firstly, the automotive industry is the most active in its testing, use and implementation of industrial exoskeletons. This is fairly logical as Fig. 5 clearly shows that manufacturing has the highest rate of WMSDs. However, manufacturing also includes areas such as metallurgy, textiles, chemicals, etc., that are certainly at high risk of injury, but they are not so active in their use of exoskeletons. An important suggestion is, therefore, greater diversification of the research and testing across the full spectrum of activities involved in the macro sector of manufacturing. Beyond the manufacturing sector, we would also suggest focusing on other sectors with high incidences of WMSDs, such as health and social care, wholesale and retail trade, construction, etc.

Table 5
Analysis of EMG in different TRLs (Mean $\pm$ Standard deviation).

Assessment	Execution type	Muscle type	Reduction(%)
TRL-5	Upper Limb [48,56,79,83]	AD	31.4 $\pm$ 13.9
	Back Support [45,47,70,75]	ES	20.9 $\pm$ 10.3
TRL-6	Upper Limb [28,55,57,58,76]	AD	18.3 $\pm$ 17.1
	Back Support [85,86]	ES	10.25 $\pm$ 0.35
TRL-7	Upper Limb [28,49,55,61,63,64,67,73,83]	AD	23.1 $\pm$ 18.3
	Back Support [60,82]	ES	30.8 $\pm$ 22.6

Table 6
Analysis of subjective measures in different TRLs (Mean $\pm$ Standard deviation).

Comfort(%) - (Good=100%, Bad=0%)	
Assessment	Results $\pm$ SD
TRL-5	44.5 $\pm$ 19.02
TRL-6	80
TRL-7	61 $\pm$ 29.6
System Usability Scale (SUS)(%) - (Good=100%, Bad=0%)	
TRL-5	72.7 $\pm$ 9.2
TRL-7	72.9 $\pm$ 13
Reduction in BORG (with/without Exo) (%) - (Good=100%, Bad=0%)	
TRL-7	43.6 $\pm$ 21.8
Acceptability (%) - (Good=100%, Bad=0%)	
TRL-5	90
TRL-7	78.6 $\pm$ 15.1

Table 7
Analysis of kinematics in different TRLs.

Kinematics		
Assessment	Research article	Results
TRL-5	[53]	Increased hip and knee flexion with Exo by 31%
	[47]	Reduced hip and knee range of motion by 12%
TRL-7	[78]	Shoulder Flexion/Extension (ROMs) No Exo: 97.85% Average Reduction in ROMs: 89.5% Shoulder Abduction/Adduction (ROMs) No Exo: 36% Average: 35% (not significant)
	[89]	Reduction of mean step rate with Exo by 18.1%

Secondly, EMG measurement and questionnaires are the most common assessment formats for OEs. EMG, while valuable across all TRLs, can have placement and measurement problems, and this approach is currently best suited to the more controlled environments at TRL-5 and TRL-6, where the tasks are replications of industrial operations that typically only take tens of minutes to complete. Moreover, assessments at TRL-7 are meant to be done without any external interference to the workflow and unless EMG sensors are carefully designed into the exoskeleton structure, which is currently rare, employees should not wear these devices while performing regular duties because this could impair their performance, lead to inaccurate results and bias the acceptance of the device. We also recommend evaluating multiple assessment forms at TRL-5 and TRL-6 in combination with EMG, i.e., execution time, kinematics, physiological parameters, etc. Questionnaires and surveys are simple to distribute and do not interfere with a worker's performance. While valuable at all TRLs they are particularly suited at the higher TRL-7 where there is strong involvement of experienced workers who fully understand the aims and constraints in the specific work environment. We would strongly recommend this.

The analysis of objective and subjective measures also confirmed the hypothesis that we presented in Fig. 2. When observing Fig. 6, we can see that TRL-5 is more focused on technical performance (objective measures), whereas TRL-7 is more concerned with technology acceptance (subjective measures). TRL-6 follows a similar pattern; however, additional research is needed here. Regardless, the trend between

Figs. 2 and 6 is comparable, which proves our hypothesis. Additionally, some studies [84,89] revealed a mismatch of objective and subjective evaluations, with objective measures rated positively and subjective ones rated negatively. This outcome calls for both objective and subjective evaluations in conjunction. This is significant because a poor judgment of subjective assessment might impede the implementation of exoskeletons in industrial settings.

A further interesting observation is that there were 31 studies at TRL-7, but only 14 at TRL-5 and 8 at TRL-6. TRL-4, which is not specifically part of this study, on the other hand, had 75 studies. The reasons for the significantly reduced numbers at TRL-5 and TRL-6 are not clear, especially as laboratory trials would be shorter and easier to arrange than full workplace assessments. Further, it might be expected that at each stage of development, there might be some systems that do not achieve positive expectations, and their development is stopped. Hence, there might be expected to be fewer later-stage trials. Alternatively, the increased numbers at TRL-7 could arise as the same exoskeleton can be tested in a number of different work scenarios or simply that the higher TRL has more novelty, particularly in terms of user acceptance etc.

Nonetheless, the skipping of the reporting of stages at TRL-5 and TRL-6 does raise a number of issues, as the step-wise process can help evaluate the technical performance of the exoskeleton using complex assessment typologies (such as EMG, Kinematics, etc.) in a controlled environment, and then to evaluate the acceptance of the exoskeleton using simpler assessment typologies (such as questionnaires and surveys) in a complex environment. Fig. 7 shows the recommended framework and evaluation typologies for the assessment of OEs.

Table 4 shows that the number of test subjects is often small (often below statistically significant data). To drive the end-user (companies, workers, professional bodies), it is recommended that evaluations should involve a large number of subjects to assess the statistical significance of the results on a diverse range of participants.

Table 4 also showed the length of test periods and the variation from TRL-5, 6, and 7. Based on our observations, the duration of the test varies with the type of environment and the evaluation typology under consideration. The average test duration for exoskeleton evaluation in Table 4 approximates the time necessary for each TRL. However, it is strongly advised that investigations, particularly at TRL-7, be conducted for a longer period of time (hours, days, or weeks). This is critical in TRL-7 because workers may need to adapt to the system to evaluate it as useful and acceptable.

Finally, the analysis performed in the impact section showed a reduction in EMG activation in 89% of the papers and positive exoskeleton acceptance, comfort, and usefulness in 68% of the papers. Clearly, this indicates that the results are very encouraging and promising. They provide positive encouragement for companies to adopt (or at least start to investigate) the use of industrial exoskeletons in real-world scenarios to reduce WMSDs.

6. Study implications

The findings of this review study have important implications and significance for the widespread adoption of OEs in industrial sectors, as well as thorough OE assessment. This review study highlighted specific industries with a high incidence of WMSDs, and the implementation

Table 8
Analysis of physiological parameters in different TRLs.

Heart Rate (HR)		
Assessment	Exoskeleton Type	Results (HR, MR and EE in %)
TRL-5	Back Support [53]	No difference in HR with Exo and without Exo
TRL-6	Upper Limb [28]	10.6 increase in HR with Exo
TRL-7	Back Support [74,80,89]	4.3 $\pm$ 2.4 increase in HR with Exo
	Upper Limb [28,69]	4.1 $\pm$ 5.1 decrease in HR with Exo
Metabolic Rate (MR)		
TRL-5	Back Support [84]	28.1 decrease in MR with Exo
Energy Expenditure (EE)		
TRL-7	Back Support [74]	1.4 decrease in EE with Exo

Recommended Framework for the Evaluation of OEs

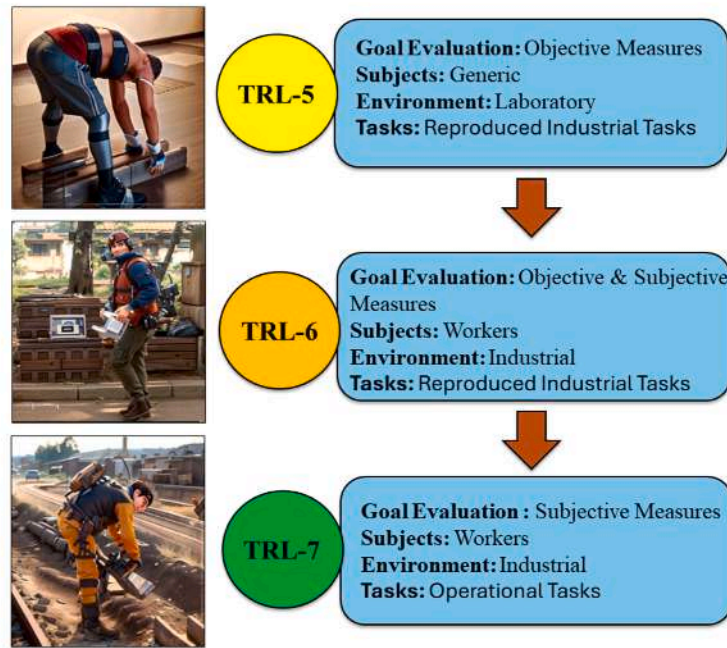


Fig. 7. Recommended Framework by the authors for the Assessment of OEs in different TRLs.

of exoskeletons in those sectors has been discussed, underlining an essential lack of OE in industries like wholesale and retail trade industry and health and social care industry, which has been compensated by the most popular industry that is automotive. This work also underlined the impact of OEs reported by several studies, providing end-users evidence of the benefit of these OEs in the industrial environment, such as reduction of muscle activity and positive evaluation of questionnaires, which emphasizes the fact that adoption of OEs in the industrial sector has the potential to considerably reduce WMSDs while also improving the lives of workers and the national economy. Furthermore, by taking advantage of the findings blended with the author's experience, this work proposes a framework for effectively conducting an experimental campaign by targeting appropriate objectives associated with the specific TRL for verification and assessment of OE. This framework provides guidelines and indications on how to raise the TRL-based assessment for the specific OE in the industrial sector by considering the application sector, an appropriate experimental protocol associated with the goal of the target TRL, the selection of the most appropriate level of assessment for the technology selected, and the sample dimension and test duration most suitable with the test. The step-by-step evaluation across different TRLs should also be supported by the scientific community in analyzing the OEs more systematically and designing OEs that are ergonomic, user-friendly, adaptable, and easy to use.

7. Conclusion

The field of industrial exoskeletons has expanded rapidly in recent years, driven by the need to provide better worker healthcare, the prevention of injuries, the need to retain older workers within the working population, and demands for greater efficiency within all aspects of the work process. However, to utilize an exoskeleton in an industrial environment, it has to pass through several phases of TRL levels. Each TRL level offers specific objectives during the evaluation of the exoskeleton, ranging from the type of subjects and assessment typology to the testing environment. It is very crucial to recognize these factors for an effective assessment of the exoskeleton. Several studies have been undertaken in recent years; however, no study has focused substantially on exoskeleton evaluation in different TRLs. This review paper investigates the state of the art regarding the adoption, evaluation, and impact of industrial exoskeletons across all sectors in different TRLs, with the selection of 45 papers entirely fitting this criteria. The analysis showed that the manufacturing industry has the highest rate of WMSDs and OEs adoption. It also revealed that EMG and questionnaires are the most assessed typologies for evaluating OEs. Furthermore, a reduction of EMG activity was demonstrated in back support and upper limb exoskeletons, and positive evaluation of questionnaires was also reported. Additionally, a framework was recommended for

the effective assessment of OEs at different levels of TRL which can help the scientific community in assessing OEs in a systematic way. Based on the outcome of this study we underline the need to further study and assess exoskeleton in industrial sectors that so far have been overlooked. In addition, active exoskeletons should be promoted to be assessed in higher TRL stages, particularly active shoulder exoskeletons. Moreover, studies conducted with lower limb exoskeletons can also be analyzed since they were not part of this review. However, the number of studies regarding lower limb exoskeletons was significantly low, which in return, should motivate future researchers to conduct studies on lower limb exoskeletons and also regarding the assessment of these exoskeletons. Additionally, it is advised to utilize alternative keywords to locate research that the authors may have overlooked. This will assist in creating a cumulative outcome that will be free of bias and based on the critical examination of several researchers.

Funding

This work was supported by the BEEYONDERS project funded by the European Union's Horizon Europe research and innovation program under grant agreement N° 101058548. Responsibility for the information and views expressed in the paper/article lies entirely with the authors.

CRediT authorship contribution statement

Jamil Ahmad: Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Vasco Fanti:** Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Darwin G. Caldwell:** Writing – review & editing. **Christian Di Natali:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Christian Di Natali reports financial support was provided by horizon 2020 research and innovation programme. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

- [1] E. Beres, Recording and notification of occupational accidents and diseases, 2002.
- [2] T. Scharf, C. Vaught, P. Kidd, L. Steiner, K. Kowalski, B. Wiehagen, L. Rethi, H. Cole, Toward a typology of dynamic and hazardous work environments, *Hum. Ecol. Risk Assess.* 7 (7) (2001) 1827–1841.
- [3] T.R. Hales, B.P. Bernard, Epidemiology of work-related musculoskeletal disorders, *Orthopedic Clin. North America* 27 (4) (1996) 679–709.
- [4] J. De Kok, P. Vroonhof, J. Snijders, G. Roullis, M. Clarke, K. Peereboom, P. van Dorst, I. Isusi, Work-related musculoskeletal disorders: Prevalence, costs and demographics in the EU, *Eur. Agency Saf. Health Work* 1 (2019).
- [5] R. Govaerts, B. Tassignon, J. Ghillebert, B. Serrien, S. De Bock, T. Ampe, I. El Makrini, B. Vanderborght, R. Meeusen, K. De Pauw, Prevalence and incidence of work-related musculoskeletal disorders in secondary industries of 21st century Europe: A systematic review and meta-analysis, *BMC Musculoskelet. Disord.* 22 (1) (2021) 1–30.
- [6] D. Colombini, E. Occhipinti, Working Posture Assessment: The TACOS (Time-Based Assessment Computerized Strategy) Method, CRC Press, 2018.
- [7] H.D. of Physical Sciences, NIOSH, Manual of Analytical Methods, US Department of Health and Human Services, Public Health Service, Centers ..., 1994.
- [8] T. Waters, E. Occhipinti, D. Colombini, E. Alvarez-Casado, R. Fox, Variable lifting index (vli) a new method for evaluating variable lifting tasks, *Hum. Factors* 58 (5) (2016) 695–711.
- [9] A. Garg, J.M. Kapellusch, The cumulative lifting index (CULI) for the revised NIOSH lifting equation: Quantifying risk for workers with job rotation, *Hum. Factors* 58 (5) (2016) 683–694.
- [10] E. Occhipinti, OCRA: A concise index for the assessment of exposure to repetitive movements of the upper limbs, *Ergonomics* 41 (9) (1998) 1290–1311.
- [11] V.P. Anderson, H. Chun, Workplace hazards and prevention options from a nonrandom sample of retail trade businesses, *Int. J. Occup. Saf. Ergonomics* 20 (1) (2014) 181–195.
- [12] S. Bevan, Economic impact of musculoskeletal disorders (MSDs) on work in Europe, *Best Pract. Res. Clin. Rheumatol.* 29 (3) (2015) 356–373.
- [13] J. Theurel, K. Desbrosses, Occupational exoskeletons: Overview of their benefits and limitations in preventing work-related musculoskeletal disorders, *IIESE Trans. Occup. Ergon. Hum. Factors* 7 (3–4) (2019) 264–280.
- [14] M. Tiboni, A. Borboni, F. Vèrité, C. Bregoli, C. Amici, Sensors and actuation technologies in exoskeletons: A review, *Sensors* 22 (3) (2022) 884.
- [15] T. du Plessis, K. Djouani, C. Oosthuizen, A review of active hand exoskeletons for rehabilitation and assistance, *Robotics* 10 (1) (2021) 40.
- [16] Z. Jia-Yong, L. Ye, M. Xin-Min, H. Chong-Wei, M. Xiao-Jing, L. Qiang, W. Yue-Jin, Z. Ang, A preliminary study of the military applications and future of individual exoskeletons, *J. Phys.: Conf. Ser.* 1507 (10) (2020) 102044.
- [17] M.P. De Looze, T. Bosch, F. Krause, K.S. Stadler, L.W. O'Sullivan, Exoskeletons for industrial application and their potential effects on physical work load, *Ergonomics* 59 (5) (2016) 671–681.
- [18] B.M. Otten, R. Weidner, A. Argubi-Wollesen, Evaluation of a novel active exoskeleton for tasks at or above head level, *IEEE Robot. Autom. Lett.* 3 (3) (2018) 2408–2415.
- [19] K. Huysamen, T. Bosch, M. de Looze, K.S. Stadler, E. Graf, L.W. O'Sullivan, Evaluation of a passive exoskeleton for static upper limb activities, *Appl. Ergon.* 70 (2018) 148–155.
- [20] M. Schwartz, J. Theurel, K. Desbrosses, Effectiveness of soft versus rigid back-support exoskeletons during a lifting task, *Int. J. Environ. Res. Public Health* 18 (15) (2021) 8062.
- [21] S. Kim, M.A. Nussbaum, M.I. Mokhespour Esfahani, M.M. Alemi, S. Alabdulkarim, E. Rashedi, 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, *Appl. Ergon.* 70 (2018) 315–322.
- [22] S. Kim, M.A. Nussbaum, M.I. Mokhespour Esfahani, M.M. Alemi, B. Jia, E. Rashedi, 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, *Appl. Ergon.* 70 (2018) 323–330.
- [23] T. Kermavnavar, A.W. de Vries, M.P. de Looze, L.W. O'Sullivan, Effects of industrial back-support exoskeletons on body loading and user experience: An updated systematic review, *Ergonomics* 64 (6) (2021) 685–711.
- [24] S. Toxiri, M.B. Näf, M. Lazzaroni, J. Fernández, M. Sposito, T. Poliero, L. Monica, S. Anastasi, D.G. Caldwell, J. Ortiz, Back-support exoskeletons for occupational use: An overview of technological advances and trends, *IIESE Trans. Occup. Ergon. Hum. Factors* 7 (3–4) (2019) 237–249.
- [25] T. McFarland, S. Fischer, Considerations for industrial use: A systematic review of the impact of active and passive upper limb exoskeletons on physical exposures, *IIESE Trans. Occup. Ergon. Hum. Factors* 7 (3–4) (2019) 322–347.
- [26] T. Poliero, V. Fanti, M. Sposito, D.G. Caldwell, C. Di Natali, Active and passive back-support exoskeletons: A comparison in static and dynamic tasks, in: 2022 9th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechanics, BioRob, IEEE, 2022, pp. 01–08.
- [27] M.P. De Looze, F. Krause, L.W. O'Sullivan, The potential and acceptance of exoskeletons in industry, in: *Wearable Robotics: Challenges and Trends: Proceedings of the 2nd International Symposium on Wearable Robotics, WeRob2016*, October 18–21, 2016, Segovia, Spain, Springer, 2017, pp. 195–199.
- [28] S. De Bock, J. Ghillebert, R. Govaerts, S.A. Elprama, U. Marusic, B. Serrien, A. Jacobs, J. Geeroms, R. Meeusen, K. De Pauw, Passive shoulder exoskeletons: More effective in the lab than in the field? *IEEE Trans. Neural Syst. Rehabil. Eng.* 29 (2020) 173–183.
- [29] S.A. Elprama, B. Vanderborght, A. Jacobs, An industrial exoskeleton user acceptance framework based on a literature review of empirical studies, *Appl. Ergon.* 100 (2022) 103615.
- [30] P.M. Kuber, M. Abdollahi, M.M. Alemi, E. Rashedi, A systematic review on evaluation strategies for field assessment of upper-body industrial exoskeletons: Current practices and future trends, *Ann. Biomed. Eng.* 50 (10) (2022) 1203–1231.
- [31] S. De Bock, J. Ghillebert, R. Govaerts, B. Tassignon, C. Rodriguez-Guerrero, S. Crea, J. Veneman, J. Geeroms, R. Meeusen, K. De Pauw, Benchmarking occupational exoskeletons: An evidence mapping systematic review, *Appl. Ergon.* 98 (2022) 103582.
- [32] S. Crea, P. Beckerle, M. De Looze, K. De Pauw, L. Grazi, T. Kermavnavar, J. Masood, L.W. O'Sullivan, I. Pacifico, C. Rodriguez-Guerrero, et al., Occupational exoskeletons: A roadmap toward large-scale adoption. Methodology and challenges of bringing exoskeletons to workplaces, *Wearable Technol.* 2 (2021) e11.

- [33] M.J. Page, J.E. McKenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, L. Shamseer, J.M. Tetzlaff, E.A. Akl, S.E. Brennan, et al., The PRISMA 2020 statement: An updated guideline for reporting systematic reviews, *Bmj* 372 (2021).
- [34] M. Héder, From NASA to EU: the evolution of the TRL scale in public sector innovation, *Innov. J.* 22 (2) (2017) 1–23.
- [35] E.H. Conrow, Estimating technology readiness level coefficients, *J. Spacecr. Rockets* 48 (1) (2011) 146–152.
- [36] C. Andrade, D. Nathan-Roberts, Occupational exoskeleton adoption and acceptance in construction and industrial work: A scoping review, in: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 66, (no. 1) SAGE Publications Sage CA: Los Angeles, CA, 2022, pp. 1325–1329.
- [37] E. Ozan, Back and shoulder exoskeletons for occupational use: A review, 2022.
- [38] A. De Vries, M. De Looze, The effect of arm support exoskeletons in realistic work activities: A review study, *J. Ergon* 9 (4) (2019) 1–9.
- [39] S. Spada, L. Ghibaudo, C. Carnazzo, M. Di Pardo, D.S. Chander, L. Gastaldi, M.P. Cavatorta, Physical and virtual assessment of a passive exoskeleton, in: *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018) Volume VIII: Ergonomics and Human Factors in Manufacturing, Agriculture, Building and Construction, Sustainable Development and Mining* 20, Springer, 2019, pp. 247–257.
- [40] D. Onofrejova, M. Balazikova, J. Glatz, Z. Kotianova, K. Vaskovicova, Ergonomic assessment of physical load in slovak industry using wearable technologies, *Appl. Sci.* 12 (7) (2022) 3607.
- [41] Y. Hasegawa, M. Muramatsu, Wearable lower-limb assistive device for physical load reduction of caregiver on transferring support, in: *2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, IEEE, 2013*, pp. 1027–1032.
- [42] Y.-K. Kong, C.-W. Park, M.-U. Cho, S.-Y. Kim, M.-J. Kim, D.J. Hyun, K. Bae, J.K. Choi, S.M. Ko, K.-H. Choi, Guidelines for working heights of the lower-limb exoskeleton (CEX) based on ergonomic evaluations, *Int. J. Environ. Res. Public Health* 18 (10) (2021) 5199.
- [43] M.V. Pillai, L. Van Engelhoven, H. Kazerooni, Evaluation of a lower leg support exoskeleton on floor and below hip height panel work, *Hum. Factors* 62 (3) (2020) 489–500.
- [44] S. Chen, D.T. Stevenson, S. Yu, M. Mioskowska, J. Yi, H. Su, M. Trkov, Wearable knee assistive devices for kneeling tasks in construction, *IEEE/ASME Trans. Mechatronics* 26 (4) (2021) 1989–1996.
- [45] T. Poliero, M. Sposito, S. Toxiri, C. Di Natali, M. Iurato, V. Sanguineti, D.G. Caldwell, J. Ortiz, Versatile and non-versatile occupational back-support exoskeletons: A comparison in laboratory and field studies, *Wearable Technol.* 2 (2021) e12.
- [46] L. Farah, D. Roll, A. Sorais, A. Vallée, Assessment of exoskeletons on nurses' quality of work life: A pilot study at Foch hospital, *Nursing Rep.* 13 (2) (2023) 780–791.
- [47] T. Poliero, M. Lazzaroni, S. Toxiri, C. Di Natali, D.G. Caldwell, J. Ortiz, Applicability of an active back-support exoskeleton to carrying activities, *Front. Robot. AI* 7 (2020) 579963.
- [48] I. Pacifico, A. Scano, E. Guanziroli, M. Moise, L. Morelli, A. Chiavenna, D. Romo, S. Spada, G. Colombina, F. Molteni, et al., An experimental evaluation of the proto-mate: A novel ergonomic upper-limb exoskeleton to reduce workers' physical strain, *IEEE Robot. Autom. Mag.* 27 (1) (2020) 54–65.
- [49] J.C. Gillette, S. Saadat, T. Butler, Electromyography-based fatigue assessment of an upper body exoskeleton during automotive assembly, *Wearable Technol.* 3 (2022) e23.
- [50] M. Moulart, N. Olivier, Y. Giovannelli, F. Marin, Subjective assessment of a lumbar exoskeleton's impact on lower back pain in a real work situation, *Heliyon* (2022) e11420.
- [51] S.M. Siedl, M. Mara, Exoskeleton acceptance and its relationship to self-efficacy enhancement, perceived usefulness, and physical relief: A field study among logistics workers, *Wearable Technol.* 2 (2021) e10.
- [52] T. Schmalz, J. Schändlinger, M. Schuler, J. Bornmann, B. Schirmeister, A. Kannenberg, M. Ernst, Biomechanical and metabolic effectiveness of an industrial exoskeleton for overhead work, *Int. J. Environ. Res. Public Health* 16 (23) (2019) 4792.
- [53] T. Luger, M. Bär, R. Seibt, M.A. Rieger, B. Steinhilber, Using a back exoskeleton during industrial and functional tasks—Effects on muscle activity, posture, performance, usability, and wearer discomfort in a laboratory trial, *Hum. Factors* 65 (1) (2023) 5–21.
- [54] S. Amandels, H.O.h. Eyndt, L. Daenen, V. Hermans, Introduction and testing of a passive exoskeleton in an industrial working environment, in: *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018) Volume III: Musculoskeletal Disorders* 20, Springer, 2019, pp. 387–392.
- [55] I. Pacifico, A. Parri, S. Taglione, A.M. Sabatini, F.S. Violante, F. Molteni, F. Giovacchini, N. Vitiello, S. Crea, Exoskeletons for workers: A case series study in an enclosures production line, *Appl. Ergon.* 101 (2022) 103679.
- [56] D.J. Hyun, K. Bae, K. Kim, S. Nam, D.-h. Lee, A light-weight passive upper arm assistive exoskeleton based on multi-linkage spring-energy dissipation mechanism for overhead tasks, *Robot. Auton. Syst.* 122 (2019) 103309.
- [57] J.P. Pinho, C. Taira, P. Parik-Americano, L.O. Suplino, V.P. Bartholomeu, V.N. Hartmann, G.S. Umemura, A. Forner-Cordero, A comparison between three commercially available exoskeletons in the automotive industry: An electromyographic pilot study, in: *2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechanics, BioRob, IEEE, 2020*, pp. 246–251.
- [58] J.P. Pinho, P.P. Americano, C. Taira, W. Pereira, E. Caparroz, A. Forner-Cordero, Shoulder muscles electromyographic responses in automotive workers wearing a commercial exoskeleton, in: *2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society, EMBC, IEEE, 2020*, pp. 4917–4920.
- [59] R. Hensel, M. Keil, Subjective evaluation of a passive industrial exoskeleton for lower-back support: A field study in the automotive sector, *IIEE Trans. Occup. Ergon. Hum. Factors* 7 (3–4) (2019) 213–221.
- [60] R.B. Graham, M.J. Agnew, J.M. Stevenson, 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, *Appl. Ergon.* 40 (5) (2009) 936–942.
- [61] S. Iranzo, A. Piedrabuena, D. Iordanov, U. Martinez-Iranzo, J.-M. Belda-Lois, Ergonomics assessment of passive upper-limb exoskeletons in an automotive assembly plant, *Appl. Ergon.* 87 (2020) 103120.
- [62] M. Smets, A field evaluation of arm-support exoskeletons for overhead work applications in automotive assembly, *IIEE Trans. Occup. Ergon. Hum. Factors* 7 (3–4) (2019) 192–198.
- [63] J.C. Gillette, M.L. Stephenson, Electromyographic assessment of a shoulder support exoskeleton during on-site job tasks, *IIEE Trans. Occup. Ergon. Hum. Factors* 7 (3–4) (2019) 302–310.
- [64] J.C. Gillette, M.L. Stephenson, EMG analysis of an upper body exoskeleton during automotive assembly, in: *Proceedings of the American Society of Biomechanics Annual Meeting*, Rochester, MN, 2018.
- [65] M. Hefferle, M. Snell, K. Kluth, Influence of two industrial overhead exoskeletons on perceived strain—A field study in the automotive industry, in: *Advances in Human Factors in Robots, Drones and Unmanned Systems: Proceedings of the AHFE 2020 Virtual Conference on Human Factors in Robots, Drones and Unmanned Systems*, Springer, July 16–20, 2020, USA, 2021, pp. 94–100.
- [66] S. Kim, M.A. Nussbaum, M. Smets, S. Ranganathan, Effects of an arm-support exoskeleton on perceived work intensity and musculoskeletal discomfort: An 18-month field study in automotive assembly, *Am. J. Ind. Med.* 64 (11) (2021) 905–914.
- [67] M. Claramunt-Molet, B. Domingo-Mateu, J. Danús-Jaume, A. Ugartemendia-Exarri, I. De La Maza, V. Enriquez-Carrera, O. Muñoz-Fernandez, S. Domingo, F. Miralles, J.M. Font-Llagunes, et al., Biomechanical evaluation of upper limb exoskeletons in automotive assembly using EMG, *Reunión Del Capítulo Español de la Sociedad Europea de Biomecánica (2019)* 25–26.
- [68] S. Kim, M.A. Nussbaum, M. Smets, Usability, user acceptance, and health outcomes of arm-support exoskeleton use in automotive assembly: An 18-month field study, *J. Occup. Environ. Med.* 64 (3) (2022) 202–211.
- [69] A. Moyon, E. Poirson, J.-F. Petiot, Experimental study of the physical impact of a passive exoskeleton on manual sanding operations, *Procedia Cirp* 70 (2018) 284–289.
- [70] J. Hwang, V.N.K. Yerriboina, H. Ari, J.H. Kim, Effects of passive back-support exoskeletons on physical demands and usability during patient transfer tasks, *Appl. Ergon.* 93 (2021) 103373.
- [71] J.S. Cha, S. Monfared, D. Stefanidis, M.A. Nussbaum, D. Yu, Supporting surgical teams: Identifying needs and barriers for exoskeleton implementation in the operating room, *Hum. Factors* 62 (3) (2020) 377–390.
- [72] N. Settembre, P. Maurice, J. Paysant, J. Theurel, L. Claudon, A. Kimmoun, B. Levy, H. Hani, B. Chenuel, S. Ivaldi, The use of exoskeletons to help with prone positioning in the intensive care unit during COVID-19, *Ann. Phys. Rehabil. Med.* 63 (4) (2020) 379–382.
- [73] I. Pacifico, F. Aprigliano, A. Parri, G. Cannillo, I. Melandri, A.M. Sabatini, F.S. Violante, F. Molteni, F. Giovacchini, N. Vitiello, et al., Evaluation of a spring-loaded upper-limb exoskeleton in cleaning activities, *Appl. Ergon.* 106 (2023) 103877.
- [74] M. Ziaei, A. Choobineh, H. Ghaem, M. Abdoli-Eramaki, Evaluation of a passive low-back support exoskeleton (ergo-vest) for manual waste collection, *Ergonomics* 64 (10) (2021) 1255–1270.
- [75] M.F. Antwi-Afari, H. Li, S. Anwer, D. Li, Y. Yu, H.-Y. Mi, I.Y. Wuni, Assessment of a passive exoskeleton system on spinal biomechanics and subjective responses during manual repetitive handling tasks among construction workers, *Saf. Sci.* 142 (2021) 105382.
- [76] A.W. de Vries, F. Krause, M.P. de Looze, The effectivity of a passive arm support exoskeleton in reducing muscle activation and perceived exertion during plastering activities, *Ergonomics* 64 (6) (2021) 712–721.
- [77] A. de Vries, S. Baltrusch, M. de Looze, Field study on the use and acceptance of an arm support exoskeleton in plastering, *Ergonomics* (2022) 1–12, just-accepted.
- [78] S.T. Bennett, P.G. Adamczyk, F. Dai, D. Veeramani, M.W. Senior, Upper extremity exoskeletons in construction, a field-based study.
- [79] H.H. Harith, M.F. Mohd, S.N. Sowat, A preliminary investigation on upper limb exoskeleton assistance for simulated agricultural tasks, *Appl. Ergon.* 95 (2021) 103455.

- [80] M.K.F.M. Radzi, M.A.M. Bakri, M.R.M. Khalid, M.I.H. Azaman, M.R. Ahmad, Preliminary assessment of exoskeleton suit assistance for fresh fruit bunch (FFB) collecting task in oil palm plantation, *Adv. Agric. Food Res. J.* 3 (2) (2022).
- [81] A. Omoniye, C. Trask, S. Milosavljevic, O. Thamsuwan, Farmers' perceptions of exoskeleton use on farms: Finding the right tool for the work (er), *Int. J. Ind. Ergon.* 80 (2020) 103036.
- [82] O. Thamsuwan, S. Milosavljevic, D. Srinivasan, C. Trask, Potential exoskeleton uses for reducing low back muscular activity during farm tasks, *Am. J. Ind. Med.* 63 (11) (2020) 1017–1028.
- [83] H.-M. Wang, D.K.L. Le, W.-C. Lin, Evaluation of a passive upper-limb exoskeleton applied to assist farming activities in fruit orchards, *Appl. Sci.* 11 (2) (2021) 757.
- [84] Y. Liu, X. Li, J. Lai, A. Zhu, X. Zhang, Z. Zheng, H. Zhu, Y. Shi, L. Wang, Z. Chen, The effects of a passive exoskeleton on human thermal responses in temperate and cold environments, *Int. J. Environ. Res. Public Health* 18 (8) (2021) 3889.
- [85] R. Motmans, T. Debaets, S. Chrispeels, Effect of a passive exoskeleton on muscle activity and posture during order picking, in: *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018) Volume III: Musculoskeletal Disorders 20*, Springer, 2019, pp. 338–346.
- [86] M.B. Yandell, A.E. Wolfe, M.C. Marino, M.P. Harris, K.E. Zelik, Effect of a back-assist exosuit on logistics worker perceptions, acceptance, and muscle activity, in: *International Symposium on Wearable Robotics*, Springer, 2020, pp. 7–11.
- [87] S.M. Siedl, M. Wolf, M. Mara, Exoskeletons in the supermarket: Influences of comfort, strain relief and task-technology fit on retail workers' post-trial intention to use, in: *Companion of the 2021 ACM/IEEE International Conference on Human-Robot Interaction*, 2021, pp. 397–401.
- [88] R. Bostelman, Y.-S. Li-Baboud, A. Virts, S. Yoon, M. Shah, Towards standard exoskeleton test methods for load handling, in: *2019 Wearable Robotics Association Conference, WearRAcon, IEEE*, 2019, pp. 21–27.
- [89] M. Marino, Impacts of using passive back assist and shoulder assist exoskeletons in a wholesale and retail trade sector environment, *IIEE Trans. Occup. Ergon. Hum. Factors* 7 (3–4) (2019) 281–290.
- [90] D. Schwerha, N. McNamara, S. Kim, M.A. Nussbaum, Exploratory field testing of passive exoskeletons in several manufacturing environments: Perceived usability and user acceptance, *IIEE Trans. Occup. Ergon. Hum. Factors* 10 (2) (2022) 71–82.
- [91] Eurostat, Employed population by occupation and sector, 2019, Retrieved from <https://www.cedefop.europa.eu/en/tools/skills-intelligence/employed-population-occupation-and-sector?year=2019&country=EU#1>.
- [92] C. Di Natali, J. Mattila, A. Kolu, P. De Vito, S. Gauttier, M. Morata, M. Garcia, D. Caldwell, Smart tools for railway inspection and maintenance work, performance and safety improvement, *Transp. Res. Procedia* 72 (2023) 3070–3077.
- [93] H.H. Thakkar, S.K. E., Static and dynamic postural stability in subjects with and without chronic low back pain, *Int. J. Res. Med. Sci.* 3 (9) (2017) 2405–2409.
- [94] B. HOWORTH, Dynamic posture, *J. Am. Med. Assoc.* 131 (17) (1946) 1398–1404.
- [95] M. Lazzaroni, S. Toxiri, J. Ortiz, E. De Momi, D. Caldwell, Towards standards for the evaluation of active back-support exoskeletons to assist lifting task, 2018.
- [96] D. Stegeman, H. Hermens, Standards for surface electromyography: The European project surface EMG for non-invasive assessment of muscles (SENIAM), *Enschede: Roessingh Res. Dev.* 10 (2007) 8–12.
- [97] K.S. Türker, Electromyography: Some methodological problems and issues, *Phys. Therapy* 73 (10) (1993) 698–710.
- [98] L. Zheng, B. Lowe, A.L. Hawke, J.Z. Wu, Evaluation and test methods of industrial exoskeletons in vitro, in vivo, and in silico: A critical review, *Crit. Rev. Biomed. Eng.* 49 (4) (2021).
- [99] G. Borg, Borg's Perceived Exertion and Pain Scales, *Human kinetics*, 1998.
- [100] C. Johnson, Measuring pain. Visual analog scale versus numeric pain scale: What is the difference? *J. Chiropractic Med.* 4 (1) (2005) 43.
- [101] N. Hoffmann, G. Prokop, R. Weidner, Methodologies for evaluating exoskeletons with industrial applications, *Ergonomics* 65 (2) (2022) 276–295.
- [102] L. Wioland, J.-J. Atain Kouadio, H. Bréard, I. Clerc-Urmès, B. Paty, The adoption of occupational exoskeletons: From acceptability to situated acceptance, questionnaire surveys, *Int. J. Hum.-Comput. Interaction* (2024) 1–13.
- [103] N. Hoffmann, A. Argubi-Wollesen, C. Linnenberg, R. Weidner, J. Franke, Towards a framework for evaluating exoskeletons: Framework zur evaluation von exoskeletten, in: *Production At the Leading Edge of Technology: Proceedings of the 9th Congress of the German Academic Association for Production Technology, WGP*, September 30th–October 2nd, Hamburg 2019, Springer, 2019, pp. 441–450.
- [104] E. Digo, L. Gastaldi, M. Antonelli, S. Pastorelli, A. Cereatti, M. Caruso, Real-time estimation of upper limbs kinematics with IMUs during typical industrial gestures, *Procedia Comput. Sci.* 200 (2022) 1041–1047, 3rd International Conference on Industry 4.0 and Smart Manufacturing.
- [105] A.M. Valevicius, P.Y. Jun, J.S. Hebert, A.H. Vette, Use of optical motion capture for the analysis of normative upper body kinematics during functional upper limb tasks: A systematic review, *J. Electromyography Kinesiol.* 40 (2018) 1–15.
- [106] R. McCraty, M. Atkinson, W.A. Tiller, G. Rein, A.D. Watkins, The effects of emotions on short-term power spectrum analysis of heart rate variability, *Am. J. Cardiol.* 76 (14) (1995) 1089–1093.
- [107] M. Pesenti, A. Antonietti, M. Gandolla, A. Pedrocchi, Towards a functional performance validation standard for industrial low-back exoskeletons: State of the art review, *Sensors* 21 (3) (2021).
- [108] J.M. Kittelson, in: B. Rosner (Ed.), *A Review of Fundamentals of Biostatistics*, Brooks/Cole, Taylor & Francis, Boston, ISBN: 978-0-538-73349-6, 2011, xvii+859 pp. 190.95.
- [109] H.E. Malone, H. Nicholl, I. Coyne, Fundamentals of estimating sample size, *Nurse researcher* 23 (5) (2016).
- [110] K. Fitzner, E. Heckinger, Sample size calculation and power analysis: A quick review, *Diabetes Educator* 36 (5) (2010) 701–707.
- [111] S.S. Sawilowsky, New effect size rules of thumb, *J. Mod. Appl. Stat. Methods* 8 (2009) 597–599.
- [112] S. Gilotta, S. Spada, L. Ghibauda, M. Isoardi, C. Mosso, Acceptability beyond usability: a manufacturing case study, in: *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018) Volume VII: Ergonomics in Design, Design for All, Activity Theories for Work Analysis and Design, Affective Design 20*, Springer, 2019, pp. 922–934.



Jamil Ahmad received the B.S. degree in Computer Systems engineering from University of Engineering and Technology, Pakistan (2017) and received the master's degree in Biomedical engineering from National University of Sciences and Technology, Pakistan (2021). He is currently pursuing the Ph.D. degree in Bioengineering and Robotics from University of Genoa, Italy, affiliated with Istituto Italiano di Tecnologia. His research interests include EMG signal processing, pattern recognition, machine learning, and exoskeletons.



Vasco Fanti received the bachelor's degree in Biomedical Engineering from the University of Genoa (UniGe), Italy, in 2017, carrying out a thesis on endoprosthesis. In 2021 he received the master's degree in Bioengineering from UniGe, performing the thesis on an exoskeleton for lower limb assistance in affiliation with Istituto Italiano di Tecnologia (IIT). He worked for almost two years as a Fellow Jr. researcher on an exoskeleton for back support. He is currently pursuing the Ph.D. degree in Bioengineering and Robotics from UniGe, Italy, affiliated with IIT. His research interests include prosthetics, exoskeletons, assessment methodologies, and human-robot interaction.



Darwin G. Caldwell, FREng is Deputy Director of the Italian Institute of Technology (IIT), where he was also the founding Director of the Department of Advanced Robotics. He is or has been an Honorary Professor at the Universities of Manchester, Sheffield, Bangor, and Kings College London in the UK and Tianjin University and Shenzhen Academy of Aerospace Technology in China. His research interests include; medical, rehabilitation and assistive robotic technologies, humanoid (iCub, cCub, COMAN, WalkMan, Centauro and quadrupedal robotics (HyQ, HyQReal), innovative actuators, and haptics and force augmentation exoskeletons. He is the author or co-author of over 500 academic papers, 20+ patents, and has received over 40 awards and nominations from leading journals and conferences. Caldwell has been chair of the IEEE Robotics and Automation Chapter (UKRI), Secretary of the IEEE/ASME Trans. on Mechatronics, Editor for Frontiers in Robotics and AI, on the editorial board of the International Journal of Social Robotics and Industrial Robot and on the Advisory Board of Science Robotics. In 2015 he was elected a Fellow of the Royal Academy of Engineering.



Christian Di Natali received the Master degrees (Hons.) in Biomedical engineering from the University of Pisa, Italy (2010), and the Ph.D. in Mechanical engineering from Vanderbilt University, USA (2015). During his Ph.D., he was actively involved in the design of advanced magnetic coupling and magnetic localization for robotic surgery and endoscopy. After the Ph.D. he worked for the E.GO s.r.l. as Technical Manager designing industrial autonomous machines for the production of wound electric motors. In 2017 he joined the Istituto Italiano di Tecnologia, and he is currently Researcher at the exoskeletons group (XoLab) at the department of Advanced Robotics (ADVR) working on the development of industrial and soft exoskeletons.