Abstract: The human-centered workplace design philosophy and the operator 5.0 concepts are gaining ground in modern industries moving through the personalization of the operators' workplace for improving workforce well being and capabilities. In such a context, new assistive technologies, such as passive exoskeletons, are good candidates to be wisely adopted in manufacturing and logistics systems. A growing interest in these devices has been detected over the last years, both from an academic and company perspective, with an increasing number of design solutions and tests according to their field of application. Aiming to investigate the current state of the art, we propose a literature review focused on passive exoskeletons for manufacturing and logistics (M&L) systems. We categorize the exoskeletons assessment in relation to the M&L tasks in which they are applied to give the reader an easy and direct insight into the exoskeleton performance in real settings. Further, the impact of the exoskeleton deployment from an efficiency perspective and its cost-effectiveness evaluation are provided. Finally, a maturity heat map is proposed to track the maturity level of different exoskeletons by focusing on a set of scientific and industrial domains. A discussion and a future research agenda are also provided by focusing on the managerial implications of investing in these devices.

Keywords: exoskeletons; human factor; manufacturing; logistics systems; social sustainability; industry 5.0

---

1. Introduction

The digital and technological transition in manufacturing and logistics (M&L) systems is now integrating the well-known Industry 4.0 paradigm with the Industry 5.0 one. Industry 5.0 vision reinforces the role and contribution of industry to society and the human-centric paradigm in manufacturing system design and management [1,2]. Moreover, a digital, resilient, and sustainable manufacturing system must be planned and designed to achieve a long-term competitive advantage [3,4]. Here, the "social sustainability" concept becomes central, aiming to support employees' well being [5,6]. This view becomes urgent, especially in labor-intensive M&L systems, where several activities are still performed manually nonetheless the opportunities given by automation. In such a context, considering human factors becomes strategic [1,7], since they are influenced by workers' diversity as individual capabilities, physical capacities, gender, age, and more [8]. Further, several technical factors influence the efficiency of workers in manual M&L systems linked mainly to the design of the workplace and the environmental working conditions. In such a context, workers are put in the center of the system, and different technologies can be used to improve their physical, mental, and cognitive efficiency in pursuing the creation of smart and resilient M&L systems [9]. By focusing on physical efficiency, worker-wear assistance suits, commonly known as exoskeletons, have started to gain the attention of managers and academics. The interest in exoskeletons has developed over the years as they showed the potential to improve workers' biomechanics, ergonomics and safety by reducing muscle effort while performing strenuous manual tasks [10]. In particular, the healthcare, construction, manufacturing, and logistics working environments seem to be the most suitable for applying passive exoskeletons since several tasks require high forces or highly demanding postures. Active and passive exoskeletons exist: the formers have motors and other actuators that provide the energy for the movement; the latter has a structure composed of elastic components (springs, elastics, etc.) that harvest energy from human movement and return it to the counter movement. Further, passive exoskeleton companies have highly increased in the last decade. This is also demonstrated by the number and types of exoskeletons which are present and available in the market (see Table A1 in the Appendix A section). Moreover, as reported by Laevo (2022), some commercial exoskeletons have been also accredited as Personal Protective Equipment (PPE) by the European Union.

According to de Looze et al. [11], exoskeletons can be classified according to the body part they support. Upper limb exoskeletons are devices supporting the arms, generally the shoulder joint. The back support exoskeletons support the back region reducing efforts on the back erector muscles, mainly working on the L5/S1 joint. Then, lower limb exoskeletons provide supporting torques at the knee and hip level. Finally, tool-support exoskeletons can considerably reduce the load in executing tasks that require the use of tools to handle for a prolonged time.

The interest in implementing exoskeletons to improve human well being is demonstrated by several literature reviews published in the last few years. De Looze et al. [11] provided an overview of 26 different assistive exoskeletons developed before 2016 for industrial purposes and integrated that with the addition of a stakeholder analysis of de Looze et al. [12] and updated it by adding other 33 studies [13]. Some reviews focused on the effects the exoskeletons in occupational industrial tasks [14–17]. Other reviews studied exoskeletons from a technological point of view [18–21]. Bostelman et al. [22], Pesenti et al. [23], Hoffmann et al. [24], de Bock et al. [25], and Kuber et al. [26] focused on test methods and standards for exoskeleton testing and deployment. Moreover, Kuber and Rashedi [27] studied the user acceptance of exoskeletons by identifying design features that could affect them and Massardi et al. [28] focused on human–exoskeleton interaction. From a physiological point of view, Bär et al. [29] in their review found that the utilization of an exoskeleton in M&L tasks seem to reduce the user's acute physical stress and strain in the exoskeleton-supported region. However, Theurel and Desbrosses [30] reviewed 30 articles trying to relate the claimed ability of the exoskeletons to reduce the muscular effort to the pathophysiological mechanisms underlying musculoskeletal disorders, concluding that there is not enough evidence to support an unreserved endorsement of these devices to prevent musculoskeletal disorders. Passive exoskeletons are indicated as more accessible for large industrial use due to their simplicity and lower cost compared to active ones [19]. For this reason, in this work, only passive exoskeletons deployment in M&L systems is studied. The existing literature reviews focused on methodological, biomechanical, and design studies giving their attention to both active and passive exoskeletons even if the active ones are not already preferable for large industrial use [19]. Our literature review is specifically focused on passive exoskeletons for M&L systems and their assessment is categorized in relation to the M&L task in which the exoskeleton is applied to give the reader an easy and direct insight into the exoskeleton performance in real settings. In addition, the impact of the exoskeleton deployment from an efficiency perspective and its cost-effectiveness evaluation are provided. Finally, a maturity heat map is proposed to track the maturity level of different exoskeletons by focusing on a set of scientific and industrial domains. Aiming to guide the in-depth analysis of the retrieved studies to practical, industrial, and economic implications, the following three research questions are formulated and answered in this work:

RQ1: *Which manual tasks can be supported by passive exoskeletons and which methods have been applied to assess their performance?*

RQ2: *How do the workers' height and waist size influence the exoskeleton selection process in industrial contexts?*

RQ3: *How do exoskeletons influence production efficiency in terms of time and working quality?*

The remainder of the paper is structured as follows. Section 2 explains the methodology used for the literature review. Section 3 reports the descriptive analysis, while Section 4 reports the content analysis. Section 5 discusses the main results derived from the literature review and the answers to the research questions. Finally, Section 6 provides a future research agenda and conclusions.

2. Methodology

The literature review presented in this paper has been conducted following a process based on the guidelines suggested by Tranfield et al. [31]. Figure 1 reports the research selection process. The literature search was conducted in the Scopus, Web of Science (WoS), and PubMed databases, and no limitation on publication year has been imposed (until 31 December 2022). Regarding the keyword identification process, we divided them into two groups as reported in Table 1. The first set of keywords is related to the way the literature refers to exoskeleton devices. In contrast, the second is associated with the application field of interest of the current work. In particular, the literature refers to exoskeletons also as 'exosuit', which is its synonym, or 'softsuit' when the device is made of soft elastic components and structures. The second set of keywords is intended to address the research of exoskeletons' application to the fields of manufacturing and logistics as well as a more general term, such as industry, to include all industrial work and more specific activity-related keywords, such as assembly, production, warehousing, and picking. The keywords belonging to the same group are connected with an OR logical operator aiming to enable their co-existence in the search, while the two groups of keywords are connected with a logical AND operator. In this way, the research selects the studies related to exoskeletal devices to which the literature refers to by the names of the first group and are applied to the fields that the second group of keywords addresses. Initially, the research for the two groups of keywords is carried out by analyzing their presence in the title, abstract, and keywords of the existing literature.

Table 1. Keyword groups used for the research.

Group 1 Appellative Keywords	Group 2 Field Keywords
'exoskeleton *' 'exosuit *' 'softsuit *'	'logistic *' 'manufacturing' 'industr *' 'assembly' 'production' 'warehous *' 'pick *'

Then, the identification queries are built to conduct the research in the three databases, Scopus, WoS, and PubMed, according to their query format.

The literature research process is reported in Figure 1 and produced 1501 hints until the end of December 2022. Then, the results have been limited to works written in English and belonging to the subject areas of engineering, material science, social sciences, multidisciplinary, business, decision sciences, and economics, and duplicates were removed bringing the numbers of papers to 897 to analyze. As defined in the introduction section, we focus on passive exoskeletons for several reasons. Firstly, they are characterized by a reliable mechanical actuation, easiness of maintenance, easiness of use, and lightness. Furthermore, they do not have built-in actuators and sensors, so the cost is more attractive than active exoskeletons. These features have allowed passive exoskeletons to be the most used for industrial purposes [19]. For this reason, we considered only papers that clearly investigate passive exoskeletons by reading the title and abstract. After this phase, the number of candidate papers has reduced to 106. The research was enriched by a snowball approach based on the studies already retrieved and analyzed. Finally, the number of papers considered for the in-depth analysis and full reading was 106 which reduces to 86 by excluding 20 reviews.

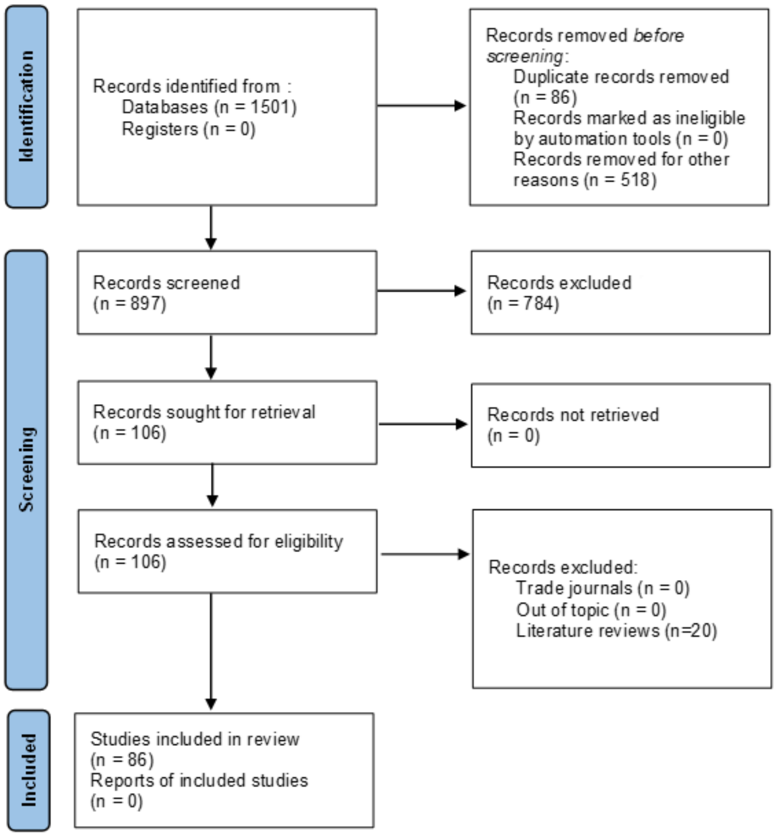

Figure 1. PRISMA flow diagram of the review process (derived from Page et al., 2021 [32]).

3. Descriptive Analysis

In this section, the 86 contributions emerging from the selection process described before are reported and classified. The distribution of publications over the years is shown in Figure 2.

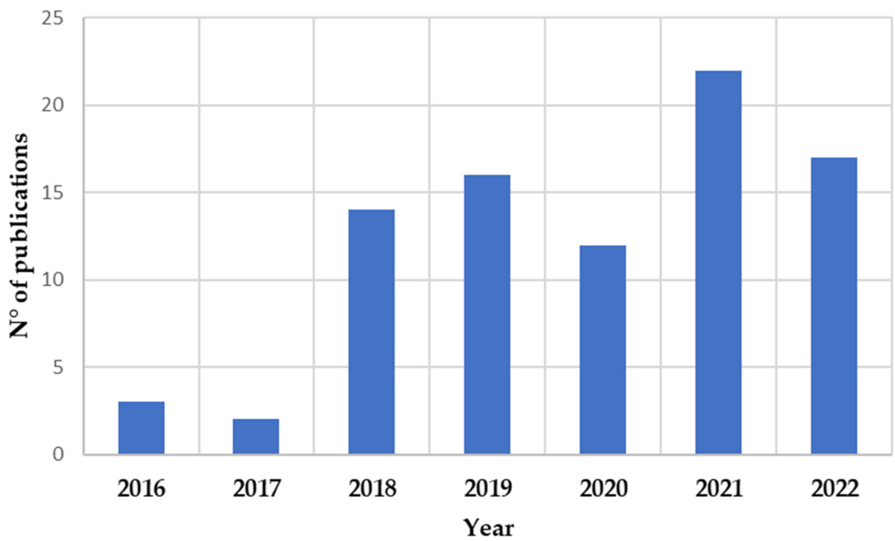

Figure 2. Distribution of publications over time.

As illustrated in Figure 2, an increasing interest has been detected in the research community since the review by de Looze et al. [11].

Among all the works considered and classified here, only 30 out of 86 reported the industrial sector on which they are focused. Furthermore, according to Figure 3, automotive is leading with 19 publications, more than half of the total industrial studies. This proves the growing interest in ergonomics in the automobile sector over the years to optimize physical and mental workload [33].

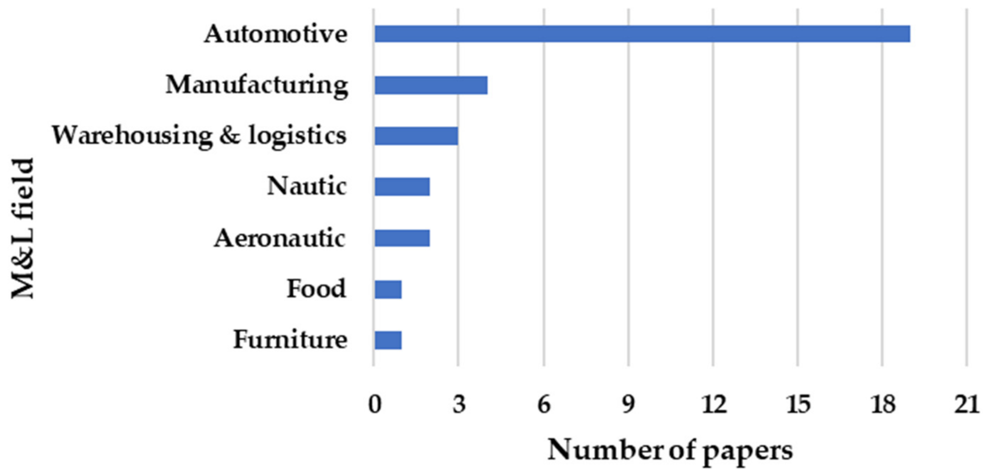

Figure 3. Field analysis for publications reporting industrial cases.

Additionally, a keyword analysis has been performed with VOSviewer based on bibliographic data of the research results. The occurrence map shown in Figure 4 groups the most frequent keywords. The size of the keywords circle varies according to their occurrence and the color changes based on the average publication year. Firstly, works focused on exoskeletons in M&L systems were published before 2018 and they were focused on simulation models to optimize workplaces by including ergonomics and fatigue aspects. Then, usability and possible discomfort in using assistive devices as exoskeletons started to be investigated in overhead works by measuring performances and conducting benchmarking analysis. Electromyography tests are conducted aiming to investigate the effects of wearing an exoskeleton while performing tasks as well as digital twin methods, such as simulations. However, motion tracking and posture tracking are not so much investigated until now. Finally, in 2022, human–machine interaction while using an exoskeleton has been investigated [28]. Considering the field in Figure 4, we can see that previous works focused on the automotive, aircraft, electric, and aircraft fields.

More than half of the contributions (54 out of 86) assessed the exoskeletons in different tasks, highlighting the interest and efforts put into physically testing their behavior. In addition, interest is posed in guidelines and methodological criteria in 21 publications which try to develop standard methods or instruments to test, measure, and implement them in industrial scenarios. Six works focus on simulating exoskeleton effects through digital modelling with software, such as Siemens Jack, Delmia, and AnyBody. Two frameworks and three surveys are also reported.

The following subsections classify all the 86 scientific contributions according to their focus. In particular, the 54 assessment studies are clustered in a paragraph and subclustered according to the task type where the exoskeleton is tested and the type of exoskeleton used in performing the task. Moreover, the remaining 32 studies out of the 86 selected are clustered as methodological, frameworks, simulation studies, and surveys.

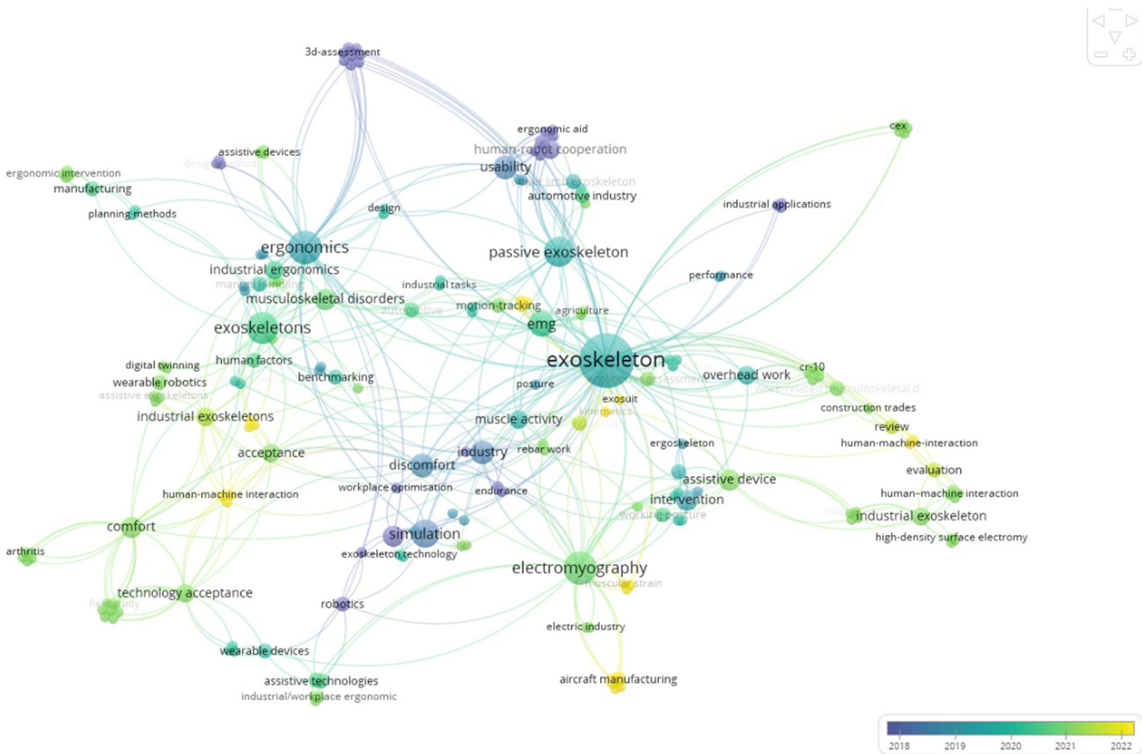

Figure 4. Keywords map made with VOSviewer. Colours change according to the average publication year.

Finally, Figure 5 reports the distribution of the different methodological approaches applied by the 86 selected publications.

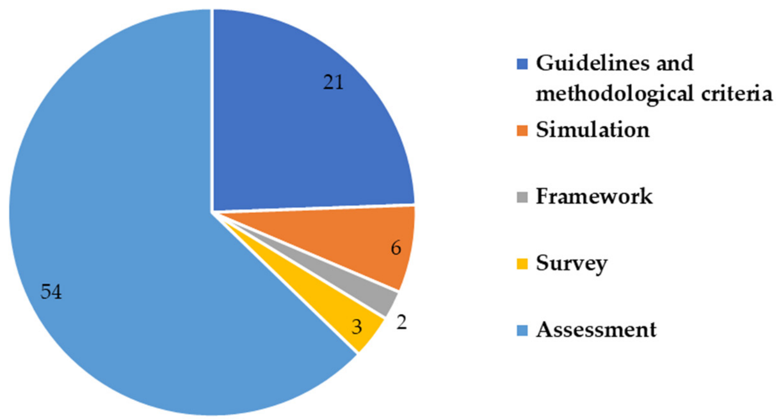

Figure 5. Methodological approaches distribution overview.

4. Content Analysis

4.1. Task-Based Categorization

In this section, the 54 assessment articles reported in Figure 5 are categorized according to the task executed by the worker while wearing the exoskeleton. Six main tasks have been identified: no-overhead assembly, overhead assembly, manufacturing, material handling, order picking, and motion-related tasks. The last category considers generic movements, such as raising the arms or walking which can be considered as a part of the assembly, manufacturing or picking activities as well as part of all-day activities. The task considered were also labeled as static when the joint supported by the exoskeleton was not moving during the task (i.e., when the shoulder joint is held in an overhead position during the task when an upper-limb exoskeleton was under investigation) and considered as dynamic when the supported joint is required to move during the execution of the task. Another recurrent labelling of the task is whether they are simulated or real. It is considered as "simulated" when a task that is performed in a laboratory to simulate a real task (i.e., when screwing is carried on a mock-up panel designed ad hoc for the experiment), while it is considered as "real" when every task executed in the shop floor and also a task performed in laboratory settings but on the real product on which the task is focused (i.e., the riveting on a part of an airframe is considered real also if performed in the laboratory even if it is not carried on the shop floor).

Figure 6 shows the balance between the different tasks on which the 54 assessment papers focus.

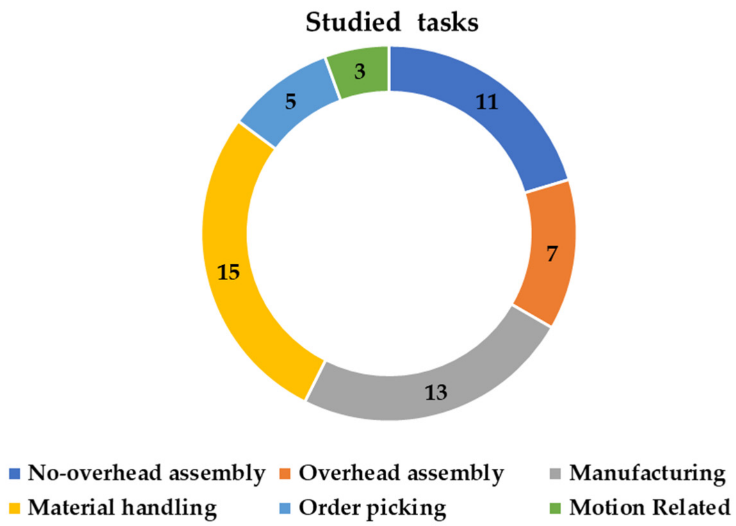

Figure 6. Distribution of the tasks studied by the 54 assessment papers.

Table 2 summarizes the number of studies according to the type of exoskeleton classified by the supported body region deployed and the grouping of tasks. From this table, it is possible to see the trends in the deployment of the different exoskeletons to perform other tasks. The total number of each column may not be the same as Figure 6, since in some studies, more than one exoskeleton has been tested in the same work (i.e., in the same manufacturing tasks upper-limb and tool-support exoskeletons have been tested and different back-support exoskeletons have been tested in a single study).

Table 2. Categorization of the exoskeletons tested by the selected papers in relation to the body region supported and task type. Cell colour intensity increasing according to reported number.

Body Region Supported by the Exoskeleton	1. No-Overhead Assembly	2. Overhead Assembly	3. Manufacturing	4. Material Handling	5. Order Picking	6. Motion-Related Tasks
Back	4	0	1	11	7	2
Upper limb	2	7	11	4	2	3
Tool Support	0	0	4	0	0	0
Lower limb	5	0	1	0	1	1

Furthermore, we identify the commercial or prototype exoskeleton, and we provide the clustering of tasks according to them. We can see from Table 3, the Laevo exoskeleton is widely investigated for material handling and order-picking tasks, since it leads to some benefits in the back. By moving on the upper limb, Levitate and ShoulderX are the leaders for overhead assembly tasks. However, it is necessary to say that they have been in the market for several years despite other new devices. Finally, the lower extremity and tool supports are not widely investigated as well as the back and upper extremity ones. The reason is that injury risks and musculoskeletal disorders involve the back, shoulders, and arms majorly as also reported by de Kok Jan et al. [34].

Based on this assessment, the methodology used to assess the benefit of the exoskeleton has also been investigated. We found seven different methods that have been used. Electromyography (EMG) is widely used for laboratory tests to quantify muscle engagement while performing tasks with and without exoskeleton support. However, it is a method that cannot be applied in an industrial environment due to the need for a team of experts to position the sensors on the tested person. Subjective evaluations consist of questionnaires generally developed in house and, in other cases, NASA-TLX questionnaires or Borg-Score are considered. In addition, some studies investigate the effects of exoskeleton wear by focusing on heart rate variation or oxygen consumption. Several works explore variations in ergonomic posture and range of motion through motion capture systems. Finally, some time performance measurements regarding task completion or endurance time while performing tasks have been conducted. Table 3 reports the studies that have assessed each exoskeleton for the identified tasks while Table 4 reports the methodological approach frequency applied in the selected studies to assess one of the categorized tasks.

Table 3. Paper categorization according to the task performed and the exoskeleton investigated in the paper.

	Type of Task					
Exoskeleton Name	**1. No-Overhead Assembly**	**2. Overhead Assembly**	**3. Manufacturing**	**4. Material Handling**	**5. Order Picking**	**6. Motion-Related Tasks**
Laevo	[35–37]			[38–43]	[44–47]	
Paexo back				[48]		
BackX	[37,49]		[50]			
Flx ergoskeleton				[51,52]		
V22				[51]		
Paexo soft back					[47]	
Rakunie					[47]	
Atlas					[47]	
Flexible prototype beams						[53,54]
IPAE				[55]		
Hero Wear Apex				[56]		
Levitate		[57–61]		[33,62]		
ShoulderX			[63–67]		[68]	
Mate	[69]	[58]	[67]			
Eksovest	[70]	[71]	[72–75]			
Skelex		[76]	[63,74,75,77]		[68]	
H-VEX			[78]			
IUVO				[79]		
Paexo shoulder			[67,74,75]			[80]
Crimson Dynamics		[76]				
Exhauss Stronger				[81]		
Fawcett + ZeroG			[65,73]			
Fortis + arm			[65,73]			
Chairless chair	[82–84]					[85]
LegX			[86]			
CEX	[87]					
Daedalus					[47]	
Leg prototype	[88]					

Table 4. Assessment methodology application according to the task performed. Cell colour intensity increasing according to reported number.

		Assessment Methodology						
		EMG	Subjective Evaluation	Heart Rate Evaluation	Oxygen Consumption	Postural Analysis	Range-of-Motion Analysis	Time Performance Measurement
Type of task	1. No-overhead assembly	8	11	0	0	3	1	4
	2. Overhead assembly	2	7	0	0	1	1	1
	3. Manufacturing	15	10	1	0	0	0	3
	4. Material Handling	8	9	2	2	6	4	5
	5. Order Picking	3	5	1	0	1	0	0
	6. Motion-related	1	1	0	0	3	1	0

4.1.1. No-Overhead Assembly

Candidates for exoskeleton deployment are no-overhead assembly tasks in which these devices are investigated in both real and simulated scenarios in 11 out of 54 assessment studies (see Figure 6). The back-support Laevo exoskeleton was tested in simulated and real tasks by Bosch et al. [35], Amandels et al. [36], Kim et al. [37], and Madinei et al. [49]. The Laevo deployment led to a more than triplicated endurance time and up to a 38% decrease in low back muscle activity in a static position, while it scored a 15% reduction time for the real car assembly task but a lower muscle activity reduction (12%). Furthermore, Kim et al. [37] and Madinei et al. [49] also tested the BackX back-support exoskeleton recording up to a 47% muscle activity reduction in the trunk. In real tasks, the muscle reductions are lower than in the simulated ones due to the natural movement variability of the shop floor context. In addition, the users report discomfort in areas of contact between the chest and thighs with the exoskeletons. The Chairless Chair, a lower-limb exoskeleton, is assessed by Luger et al. [82,83] and Groos et al. [84] in simulated assembly tasks, such as clip fitting and cable mounting. Relative stability decreased by 27%, while the exoskeleton carried 64% of users' weight. Despite a 25% decrease in gastrocnemius muscle activity, the quadriceps increased their engagement by 135%. The users reported general discomfort, safety concerns, and a bad rating in the treadmill walking test. Still, they also recognized the overall benefits of exoskeleton utilization. Hyundai designed and tested two lower-limb exoskeleton prototypes called CEX which received better user feedback on its new version [87]. Yan et al. [88] proposed a prototype scoring a five-times increase in endurance time, passing from 2.76 when unsupported to 13.58 min with exoskeleton support while performing static mid-sitted assembly tasks. Moreover, Pacifico et al. [69] compared the effects of the MATE, an upper limb exoskeleton, in enclosures assembly tasks in both simulated and real scenarios. Technology perception was improved in the real version of the task despite a decrease in muscle activity concerning the simulated version due to the unavoidable variability experienced in the field. Finally, Kim et al. [70] performed a long term 18-month study of an upper limb exoskeleton (Eksovest) in automotive assembly facilities finding that MDS scores did not differ significantly between the EXO and control groups.

4.1.2. Overhead Assembly Tasks

In overhead assembly, upper limb exoskeletons have been investigated, and 7 out of 54 studies have been reported in Figure 6. From this set of papers, 5 out of 7 studies have been conducted in the automotive industry. Spada et al. [57], Iranzo et al. [58], Carnazzo et al. [59], Groos et al. [60], and Masood et al. [61] tested a Levitate Airframe in both simulated and real tasks in FCA and PSA. The time and quality improved during simulated static holding tasks while reaching a 34% and 18% muscle activity reduction on deltoids and trapezius, respectively, for real tasks. Users raised concerns about interference between the exoskeleton and the car frame when performing real tasks, the potential range of motion limitations and thermal discomfort with the exoskeleton's prolonged use. Still, the overall support of the device is judged positively with a lower mental and physical load. Carnazzo et al. [59] also recorded the same user feedback for the MATE upper-limb exoskeleton which involved 135 workers from different cultures and plants worldwide.

An interesting study came from Ford, where an Eksovest upper limb exoskeleton was tested in an overhead assembly station. During a three-month test, the operators (4) were free to use the exoskeleton during their shift and asked to document their usage pattern and the reasons for not using it when they decided to. Users reported a high decrease in neck and shoulder discomfort and felt more productive. Overall, the exoskeleton was used 7.7 h per day, and thermal discomfort was the most common reason for not using the device. When asked if they would continue to use the ASE if given the opportunity, all participants answered yes with an estimated mean daily usage of 7.6 h. No additional discomfort was reported in the legs after prolonged use except for a participant 155 cm tall that withdrew due to fit issues and discomfort [71]. Skelex and Crimson Dynamics, two upper-limb exoskeletons were tested in the exhaust assembly process under the car body after the powertrain was merged into the chassis. In these situations, the car cannot be tilted due to the fluids already being filled, so the operators need to work overhead. The strain perceived by the users was reduced by 20% [76].

4.1.3. Manufacturing Tasks

Naval and aeronautical industry investigated tasks, such as welding, sealing, sanding, riveting, drilling and screwing, which can be categorized as manufacturing tasks in 13 papers out of the 54 analyzed (see Figure 6). Moyon et al. [77] recorded a 13.5% reduced cardiac cost in workers performing overhead sanding operations of boat body construction supported by the Skelex upper-limb exoskeleton. Skelex also performed well in naval welding operations as reported by Mouzo et al. [63] which tested the upper-limb ShoulderX exoskeleton too. They found improvements in muscular activity, metabolic cost, and driving torques, while the task completion times did not always improve. Pillai et al. [86] tested the LegX in simulated panel working and sustained groundwork, requiring the prolonged static holding of the squatted position. EMG measures for the leg muscles and erector spinae were performed. Quadricepses activity reduced to 57% in the most static task and 22–55% in the more dynamic task, while other muscle groups did not show any significant activity variation. Gonsalves et al. [50] studied the behavior of the BackX in rebar work tasks, finding a decrease of up to 50% in task completion times without finding any significant variation in muscle activity. Users reported lower discomfort in the back region but increased pain in the chest region, where the chest pad transfers the supportive force to the body. Finally, Eksovest, Skelex, and Paexo Shoulder were tested in airframe operations of riveting and sealing, reaching a reduction up to 15.7% and 9.3%, respectively, in anterior and medial deltoids activity showing also an increase of 7.6% in biceps activity. The exoskeletons were found beneficial by the users for the riveting task while did not perceive benefits for the sealing activities [74,75].

Other studies focused on drilling and screwing and performed the tests in simulated laboratory configurations with the operators supported by upper-limb or tool-carrying exoskeletons. Fortis and Fawcett with ZeroG arm, two tool-carrying exoskeletons, were tested by Alabdulkarim et al. [73] and Alabdulkarim and Nussbaum [65] in a laboratory simulated task recording an increase in errors with respect to the same task performed with the support of classical upper limb exoskeletons, such as ShoulderX. This is because the tool-carrying arm is latched to the trunk and follows its movement. ShoulderX and other upper-limb exoskeletons, such as MATE, Eksovest, and Paexo Shoulder, were also tested in drilling and screwing tasks by Kim et al. [72], Van Engelhoven et al. [64], and Pinho et al. [66,67] showing shoulder muscle activity decreasing from 32% up to 70%. An 18.9% reduction in task completion time was recorded in overhead drilling and wiring tasks supported by the Eksovest as well as increased error rates explained by the decrease in proprioception that could be restored with training [72]. Furthermore, increased muscle activity is detected in the triceps which are used to extend the arms in a downward movement pushing force against the support of the exoskeleton. In 2019, Hyundai designed the H-VEX, an upper limb passive exoskeleton, for its industrial plants. Despite achieving a 70% reduction in shoulder muscle activity, the erector spinae (back erector muscle) activity increased by 97% in overhead drilling tasks [78].

4.1.4. Material Handling Tasks

Focusing on material handling tasks, 15 papers out of 54 have been reported in Figure 6. From this set, five out of fifteen studies were conducted in the automotive industry while only one was in the logistics sector (warehousing). The tasks considered in this section include repetitive lifting and lowering, static holding of a load, and depalletizing. Gilotta et al. [33] and Spada et al. [62,79] tested Levitate and IUVO, two upper-limb exoskeletons, in laboratory-simulated material handling tasks. The time performance increased by 56% on the static holding of the arm at shoulder level and precision grew up to 33.6%, suggesting an increase in endurance capabilities in shoulder holding at height. However, no improvement in repetitive lifting was achieved (dynamic engagement of the supported joint), and the operators noticed the help in raising the arms but complained that they had to push against the exoskeleton to lower them. Another upper-limb exoskeleton, the Exhauss Stronger, was tested by Theurel et al. [81], finding reduced activity on deltoids but increases in anterior tibialis muscle, erector spinae as well as the well-known increment in triceps activity. The users accepted the exoskeleton well but underlined that it could not always fit real tasks and that its use should be non-mandatory. Picchiotti et al. [51] tested two StrongArm exoskeletons, the V22 and Flx, in material handling tasks using an EMG-driven biomechanical model of the spine implemented in Adams to predict stresses in the L5/S1 joint. The moment arm between the center of the mass of the torso and the L5/S1 joint remained the same, resulting in unvaried stress in the spinal joint with both exoskeletons. Flx limited the back's range of motion when the user tried to perform incorrect movements and had a 20% increment in task performance time [52]. Coming to back-support exoskeletons, the Laevo was tested in both simulated and real tasks. Flor et al. [38] concluded that the exoskeleton was best preferred in the workstations with tasks characterized by heavy lifting and a low mobility diversity tending to the static posture, with participants from all tested workstations reporting general help provided by the exoskeleton in performing their tasks. Similar conclusions about the better performance of the Laevo in static tasks were found by Giustetto et al. [41] and dos Anjos et al. [42], finding lower discomfort, doubled endurance times, and up to 10% decrease in back muscles activity against the 8.5% decrease as the only benefit in dynamic tasks. Dynamic tasks supported by Laevo were studied by Luger et al. [39,40] and Iranzo et al. [43] who found decreased heart rate (105–110 bpm), increased hip and knee flexion, and hip and trunk extensors. Trunk activity decreased up to 28% and an increase of 8% in task completion time was recorded as well as a slight reduction in range of motion due to the constriction given by the exoskeleton. Schmalz et al. [48] assessed the newly introduced back-support Paexo Back in material handling tasks, finding a 9% reduced oxygen consumption with muscle activity in the back and thighs, reduced by up to 18% and reduced peak and mean compression forces at L4/L5 (21%) and L5/S1 (20%). Moreover, Qu et al. [55] assessed an IPAE exoskeleton: similar to a classical back support device with the additional insertion of two ropes from the shoulder structure to the hands, which allows for carrying the load bypassing the arms. In isolated lifting, the primary outcome was reduced erector spinae activity by 26%. In contrast, the most EMG reductions for dynamic lifting occurred in the mid deltoid and labrum biceps with 32.3% and 38.1% showing effective relief of the arms. No differences were found in oxygen consumption, and users reported pressure on the shoulders, wrists, and thighs. Finally, a modular soft suit called Hero Wear Apex was investigated by Yandell et al. [56] in a distribution center for different real activities. Reductions in back muscle activity were detected at around 10%, and workers were satisfied with the soft suit that reported being assisted, comfortable, and free to move naturally.

4.1.5. Order Picking Tasks

Regarding order-picking tasks 5 out of 54 studies are available in our selection (see Figure 6) and 4 of them were carried out in real scenarios. Order-picking tasks consist of "retrieving products from storage (or buffer areas) in response to a specific customer request" [89]. The exoskeleton used in all the works described in this section is the Laevo. Motmans et al. [44] studied the exoskeleton's effects on order-picking activities in a dairy company. The activity of the erector spinae was reduced by 9–12%, and the workers reported a better perceived physical workload, but they also reported the necessity of higher energy for performing the downward movement by putting force against the exoskeleton. Furthermore, the exoskeleton rods collided with the pallet jack while performing tasks. The Laevo exoskeleton had good feedback for order-picking tasks also in the studies of Kinne et al. [45] and Cardoso et al. [46]. NASA TLX subdimensions decreased when using the exoskeleton except for the mental workload which had a slight increment. The task was also perceived as more effortless when performed with the exoskeleton. The users also reported interference, movement limitations, and discomfort in the neck, shoulder, thoracic region, hips, and thighs. Moreover, Siedl et al. [47] proposed a questionary-based survey on supermarket order-picking activities performed with different exoskeletons. They tested Laevo, Daedalus (lower-limb support), Atlas (upper-limb support), Rakunie (entire body elastic slings), and the Paexo soft back (back lumbar support band) from 0.5 to 7 h in different individuals. Soft exoskeletons were perceived better, having higher user scores in the questionnaire. Finally, de Bock et al. [68] tested two upper limb exoskeletons, the ShoulderX and the Skelex, in order-picking activities in a windshields warehouse. Conditions with and without exoskeleton were tested both in isolated and real-world scenarios. They showed that while for isolated tasks, the reductions in trapezius activity were up to 46% with ShoulderX and 30% with Sklelex, the reductions in real-world tasks were lower: from 8% to 26%. The study shows that laboratory results cannot be transferred to all field conditions, and caution is needed when interpreting laboratory-based data.

4.1.6. Motion-Related Tasks

As reported in Figure 6, only three studies performed exoskeleton evaluation in different tasks and other ways than the ones cited to this point. Näf et al. [53,54] designed a back-support exoskeleton with a supportive, flexible beam aligned with the spine. They compared it to the Laevo in different movements, such as lower lifting, forward bending, walking, sitting, trunk rotation, squatting, trunk bending, and wide stance. The newly designed exoskeleton was better perceived concerning Laevo in most movements and increased the range of motion by 25%. Finally, Latella et al. [80] analyzed whole-body joint torques thanks to a probabilistic estimator running with an inertial motion capture system in the overhead position. They tested the effects that the Paexo shoulder exoskeleton has on joint torques showing their reduction, from 66% to 86%, on the upper body, while an increase in effort is detected up to the hip level.

4.2. Guidelines and Methodological Criteria

According to Figure 5, 21 contributions out of 86 focused on providing methodological standards for selecting and assessing exoskeletons. In this section, the different works are discussed and grouped based on the topic they tackle. From an economic point of view, Todorovic et al. [90] proposed a review of monetary and non-monetary methods for technology evaluation that could also be suitable for exoskeletons. The technique suggested the 'as is', 'the should' be, and the benchmarking phase. Relevance is given to exoskeleton evaluation with the study by Hein and Lueth [91] that focuses on user acceptance aspects and describes the classification of evaluations for user acceptance using the criteria of the target, type, test environment, and measuring tool. Additionally, Ralfs et al. [92], more in general, propose a 7-step model for comprehensive evaluation of industrial exoskeletons: characterization, preparation, pre, core, and post-evaluation, analysis, and reflection, also proposing a test course made of different situations to assess the exoskeletons. Furthermore, de Looze et al. [93] offer a three-stage approach for measuring usefulness (potential fit), workload reduction effect, user acceptance, performance, and fatigue during the day. The three-stage method consists of field observation for assessing the fit to the task, a controlled experiment for determining effects on musculoskeletal systems, and a field study to understand the impacts of the exoskeleton on the shop floor. Toxiri et al. [94] underline the need for a standard. They suggested that a list of standard specifications for each exoskeleton should be critically evaluated to support deployment decisions in the industry. Additionally, an effort to reach a standard evaluation method was conducted by the NIST (National Institute of Standards and Technology) to develop a standard reconfigurable testbed for testing exoskeletons in different standardized industrial tasks [95]. Several important factors are given to the exoskeleton selection process which has to consider the workplace, the compatibility of the task and its impacts on the production system, and an ergonomic index approach [96–100]. Grazi et al. [101] and Hefferle et al. [102] gave an overview of the technologies involved in studying exoskeletons over the years, highlighting the importance of setting a standard of common evaluation methods for lumbar exoskeletons. The digital simulation could help to evaluate the impact of exoskeletons on production systems after collecting enough data on parts, tools, and cycle time to prepare and run it [103]. Then, if the simulation results show beneficial impacts, final recommendations, such as the layout or production schedule, could be provided [104]. From a mechanical point of view, Hartmann et al. [105] developed a cheap test bench for mechanically testing upper limb exoskeletons, proposing a new standard for benchmarking. They mapped the mechanical responses of the MATE upper-limb exoskeleton in both static and dynamic loading. Finally, attention is also paid to analytical methodologies to predict the effects of exoskeletons on the human body. Zelik et al. [106] modified the LIFFT equations (lifting fatigue failure tool) to estimate the impact of the back support exoskeletons in the low back. They decreased the peak moment in the input to the equations by the amount of torque provided by the exoskeleton, making these equations able to estimate the cumulative damage and the risk of low back disorders considering exoskeleton support. Moreover, another modification proposal on an existing ergonomic equation is proposed by Chini et al. [107]. After a static assessment of a back support exoskeleton, they suggest that reductions in back muscle activity could be taken into account by a multiplicative factor in the NIOSH equation. Moreover, Ralfs et al. [108] present a concept of a generic decision support matrix for exoskeleton and, in general, other technologies selection based on properties of tasks, work profiles, and system characteristics. Weckenborg et al. [109] propose an assembly line balancing method. They consider cobots and exoskeleton-supported workers, assuming no time impacts of the exoskeletons but an energy expenditure reduction of 20% and their cost. Finally, Schwerha et al. [110] tested the intention to use Eksovest, Levitate, BackX, and Laevo by testing them with fifteen operators from five companies employed in other manufacturing activities. As a result of the surveys, they proposed a decision tree be used as a predictor of the intention of the exoskeletons to use.

4.3. Simulation Studies

As shown in Figure 5, 6 studies out of 86 paid attention to digital simulation processes. Simulating the scenarios 'as is' and 'to be' with exoskeleton deployment could generate results that could support effective deployment decisions [111]. Constantinescu et al. [112] presented the concept of a modified Siemens Classical Jack paired with a RoboMate exoskeleton and then simulated three simple car assembly tasks. Spada et al. [85] simulated the interactions between the human body and a lower-limb exoskeleton: the Chairless Chair. The biomechanical model in AnyBody software predicted the weight balance between the feet and exoskeleton. Constantinescu et al. [113] focused on the challenges of making digital twins of exoskeleton-centered workplaces. The Classical Jack source code must be modified to pair the kinematics and dynamics of the digital mannequin to the digital exoskeleton model to enable the simulation to run itself instead of manually updating geometrical and force parameters as it is usually conducted. Rusu et al. [114]

highlighted the necessity to modify Classical Jack or Delmia to integrate the exoskeleton in the simulations to directly consider its impact on forces and torques and pair a motion capture instrument, such as Xsens, to move the simulations. At this date, exoskeletons are only graphically paired with the humanoid without any kinematic or dynamic constraints. The exoskeleton load reduction effect on the mannequin is obtained by manually reducing the carried load. This approach has a poor impact on the joints that are not interested in exoskeleton support, resulting in a nonrealistic simulation. Rivera et al. [115] proposed an automated virtual mannequin with simple instructions, a well-known behavior, and a realistic musculoskeletal system model necessary to calculate forces for simulating human–exoskeleton interaction. Using positions as input to the virtual exoskeleton should be possible to calculate the forces to apply to the mannequin and to calculate newly derived postures in the back loop.

4.4. Framework and Survey

In this section, the papers focused on surveys and frameworks are discussed. As reported in Figure 5, 3 surveys and 2 frameworks have been proposed over the 86 studies. With their survey, Reid et al. [116] offered different windows on different industries. In this work, different authors from the military, medicine, university, aerospace, naval, automotive, and ergonomic fields explained open questions and state-of-the-art industrial exoskeletons in their areas. Another survey interviewing 26 construction industry representatives about the potential deployment of exoskeletons suggests a lack of cost–benefit analysis, compatibility of exoskeletons with other personal protective equipment (PPE), specific benefits, and long-term effects [117]. Then, Schwerha et al. [118] surveyed small and medium enterprises in the US to study the adoption potential of exoskeletons. Levitate, Eksovest, BackX, Laevo, and ZeroG were presented in focus groups. The exoskeletons were judged positively, but concerns were raised about how to implement them, how much time to wear, and who and how they are distributed. From the framework perspective, Karvouniari et al. [119] proposed a theoretical framework for integrating exoskeletons in manufacturing lines composed of three services: exoskeleton virtual prototyping, simulation decision support, and operator training. Finally, Elprama et al. [120] proposed a framework for studying user acceptance derived from a literature review and addressing the main factors of acceptance.

5. Discussion and Future Research Agenda

This section discusses the main findings of the analyzed papers and their investigation methods by answering the research questions we proposed in the introduction section. Moreover, a future research agenda is proposed at the end of the section.

5.1. RQ1: Which Manual Tasks Can Be Supported by Passive Exoskeletons and Which Methods Have Been Applied to Assess Their Performance?

We note that most of the publications discussed before proposed simulated tasks instead of real case study analysis. This represents a strong limitation because laboratory-based research cannot record the natural variability of movements and complexity characteristics of the real scenario. This could lead to an overestimation of muscle activation reduction for simulated tasks that may be lower when applying the exoskeleton to a real environment [36]. Real scenario-based studies recorded a general reduction in lower muscle activations compared to studies conducted in laboratory settings with simulated tasks.

Most of the evaluation studies testing exoskeletons in users investigated the effects of male groups as a test sample [13,23]. Since men and women have different physical characteristics, and since the transition to human centricity with the concept of industry 5.0, more research needs to be carried out for the use of exoskeletons by women to evaluate their physical and psychological responses and drive design improvements if necessary.

Subjective evaluation of exoskeletons could vary between different ages and experiences of workers. Social aspects come into play related to others' judgment towards an individual who decides to use the exoskeleton or after the imposition of its utilization, making acceptability a critical aspect [33]. Since then, future evaluations must consider a test sample capable of covering different ages and levels of experience to generalize the results to a broader part of the working population.

Finally, after reliable data on the impact of exoskeletons on both industrial and physical aspects, methods and models could be developed to understand for which tasks and workers the exoskeletons are necessary.

The 30 exoskeletons used in the 54 studies reporting an assessment analysis are classified in a matrix (Figure 7) that could be useful for understanding their maturity level and the gaps that need to be studied for each. Each row represents an exoskeleton. In columns, we report the type of task performed as well as the assessment methodology they used. In several studies, more than one exoskeleton has been investigated as well as more than one assessment methodology has been adopted. By this matrix, the interest and maturity levels could be easily seen by the number of studies each device has. The classification is led by the Laevo back support exoskeleton which has been studied more than twice concerning the second exoskeleton in the list. The FLEX version of Laevo received the official European Union certification as Personal Protective Equipment (PPE) in April 2022 [121]. It can be also observed that the most used assessment methods are electromyography and subjective evaluation. Very few researchers used heart rate analysis and oxygen consumption which can be helpful for a general evaluation of the overall physical effort. Moreover, postural analysis has been conducted mainly for Laevo's exoskeleton.

Furthermore, digital simulation appears to be not studied as much despite having shown its potential to correctly predict load balancing between humans and exoskeletons [85], and its potential use to simulate the pre- and post-exoskeleton deployment effects in the manufacturing industry [111]. Finally, a crucial parameter for productivity evaluations, such as time performance measurement has been studied only for nine exoskeletons, of which eight are commercial models. These measurements, focused on time performance, were more used for the Laevo exoskeleton for five different studies on this aspect. Work on this aspect is still needed to have data to assess the tangible and mesasurable impact of exoskeletons on productivity and future decision making.

A final remark is necessary regarding the development of the EU normative panorama. No specific regulations were developed for exoskeletons, and uncertainties, such as long-term effects, create difficulties in creating a uniform certification protocol that requires more exhaustive studies [122]. However, the European Agency for Safety and Health at Work provided a report with existing international standards on the topics of physical dimensions and operator strength, space for movement, work rate, concentration, and human/machine interface which could help exoskeleton designers [123].

5.2. RQ2: How the Workers' Height and Waist Size Influence the Exoskeleton Selection Process in Industrial Contexts?

Exoskeletons are wearable devices that need to be adjusted to the body of the operators to fit them perfectly and make them comfortable. The fit to human anthropometric measures plays a crucial role in the success of exoskeletons during their deployment since problems with fit could cause discomfort and usability problems. For example, in [71] a worker whose height was close to the minimum height the manufacturer declared his product could accommodate withdrew from the three-month trial of the Eksovest, reporting fit problems and discomfort. Since no further information was found in the literature regarding workers' features, the answer to this question has been found by analyzing the manuals and the manufacturer's websites for each of the exoskeletons found during this review. In Table 5, relevant fit data about each exoskeleton considered in this review are reported. Some data are missing, and the conclusions about adjustability were carried out by analyzing the pictures of the exoskeletons. When the photographic analysis was not possible or no adjustment possibilities were found, the anthropometric field was flagged with NF (not found).

	N°	Type of task				Assessment Methodology						
		Real tasks	Simulated tasks	Dynamic tasks	Static tasks	EMG	Subjective evaluation	Heart rate evaluation	Oxygen consumption	Postural analysis	Range of motion analysis	Time performance measurement
Laevo	16	5	11	11	5	11	13	1	0	8	5	5
Levitate	7	3	4	3	4	2	7	0	0	1	1	2
ShoulderX	6	1	5	2	4	6	3	1	0	0	0	1
Eksovest	8	3	5	4	4	5	8	0	0	2	1	2
Mate	4	2	2	1	3	2	1	0	0	0	0	0
Skelex	6	3	3	2	4	4	5	2	0	0	0	1
Chairless Chair	4	0	4	1	3	1	3	0	0	0	0	0
BackX	3	0	3	0	3	2	3	0	0	0	0	1
Fawcwett + ZeroG	3	0	3	0	3	2	3	0	0	0	0	0
Fortis+arm	2	0	2	0	2	2	2	0	0	0	0	0
Prototype Flexible beams	2	0	2	1	1	0	1	0	0	2	2	0
Paexo shoulder	3	0	3	2	1	1	0	0	0	1	0	0
Flx ergoskeleton	2	0	2	2	0	2	2	0	0	2	2	1
V22	2	1	1	2	0	1	1	0	0	1	1	0
H-VEX	1	0	1	0	1	1	0	0	0	0	0	0
IUVO	1	0	1	1	0	0	1	0	0	0	0	1
Crimson Dynamics	1	1	0	0	1	0	1	0	0	0	0	0
Deadalus X	1	1	0	1	0	0	1	0	0	0	0	0
Paexo back	2	1	1	2	0	2	1	1	1	1	0	0
Paexo soft back	1	1	0	1	0	0	1	0	0	0	0	0
Rakunie	1	1	0	1	0	0	1	0	0	0	0	0
Exhauss Stronger	1	0	1	1	0	1	1	1	0	1	1	0
LegX	1	0	1	1	0	1	0	0	0	0	0	0
IPAE	1	0	1	1	0	1	1	0	1	0	0	0
Leg prototype	1	0	1	0	1	1	1	0	0	0	0	1
CEX	1	0	1	0	1	0	1	0	0	0	0	0
Hero Wear Apex	1	1	0	1	0	1	1	0	0	0	0	0
Atlas	1	1	0	1	0	0	1	0	0	0	0	0

Figure 7. Maturity level matrix related to the 54 papers focused on assessment study depicted in Figure 5.

The tendency found in Table 5 is that manufacturers try to accommodate most human anthropometrical characteristics by including many sizes in a few models or following the one-size-fits-all philosophy by designing devices with high adjustability. This design philosophy reduces internal variety and management complexity from the manufacturer's point of view but may lead to situations where some individuals cannot be accommodated [71]. HeroWear adopted an exciting design approach, offering more than 50 possible combinations and specific fits for men and women.

5.3. RQ3: How Do Exoskeletons Influence Production Efficiency Regarding Time and Working Quality?

There are only thirteen assessment studies considering this aspect, and only three evaluated time performance in real tasks. The literature found two main ways to intend the time performance. One of these two methods measures the time to complete an assigned task, and the more it decreases with the support of the exoskeletons, the higher is considered the performance. Another way to interpret this concept when the assigned tasks require a static holding of the joint supported by the exoskeleton is to measure the endurance time the user affords to hold the position until he feels comfortable. In this case, the performance is improved with the increase of the endurance time. Exoskeletons seem to perform very well in supporting static positions. In fact, endurance time was triplicated with a back-support exoskeleton (Laevo) in static forward bending [35]. Similar results to Bosch et al. [35] were found by Giustetto et al. [41] who found a two times increased endurance time in static forward-bending work. Another increase in endurance time for the static holding of a position has been found by Yan et al. [88] with the aid of a leg support exoskeleton prototype for assembly tasks in a squatted position with the endurance time passing from 2.76 to 13.58 min. Furthermore, Spada et al. [57,62,79] also found improvements in shoulder static holding endurance time between 31.6% and 56% while using the upper limb exoskeletons Levitate and IUVO with also a 17.5% improvement in quality. In contrast, errors increased when wearing tool support exoskeletons for drilling tasks, and quality performance seemed to depend on overall body stability [65,73]. Kim et al. [72] recorded a decrease of 18.9% in completion time for simulated drilling tasks in overhead position with Eksovest support, but the number of errors increased. Most task completion time performance enhancements are found in manufacturing with 7–50% reductions in the completion time of rebar work aided by the BackX exoskeleton [50]. Finally, in the work proposed by Mouzo et al. [63], task completion time in overhead exoskeleton-assisted welding is not always reduced.

Table 5. Anthropometric fits of exoskeletons. (Measures in centimeters).

Exoskeleton	Min. Height Size	Max. Heigh Size	Min. Waist Size	Max. Waist Size
Laevo (ref. to FLEX version)	150	200	34 (hip width)	43 (hip width)
Paexo back	S	XL	Adjustable	Adjustable
BackX	5–95% of human dimensions			
Flx ergoskeleton	167	213	68	130
V22	167	213	68	130
Paexo soft back	NA	NA	80	140
Rakunie	148	195	71	128
Atlas	170	185	Adjustable	Adjustable
Flexible prototype beams	Adjustable	Adjustable	Adjustable	Adjustable
IPAE	Adjustable	Adjustable	Adjustable	Adjustable
Hero Wear Apex	50+ module combination			
Levitate	157	183	Adjustable	Adjustable
ShoulderX	5–95% of human dimensions			
Mate	160	190	Adjustable	Adjustable
Eksovest	37 (torso length)	59 (torso length)	66	118
Skelex (ref. to 1.4.2 version)	44 (torso length)	54 (torso length)	84	124
H-VEX	Adjustable	Adjustable	Adjustable	Adjustable
IUVO	160	190	Adjustable	Adjustable
Paexo shoulder	160	190	Adjustable	Adjustable
Crimson Dynamics	165	195	Adjustable	Adjustable
Exhauss stronger	Adjustable	Adjustable	S	L
RoboMate passive	NF	NF	NF	NF
Fawcett + ZeroG	Adjustable	Adjustable	Adjustable	Adjustable
Fortis + arm	162	193	Adjustable	Adjustable
Chairless chair	150	200	Adjustable	Adjustable
LegX	Adjustable	Adjustable	Adjustable	Adjustable
CEX	160	195	Adjustable	Adjustable
Daedalus	NF	NF	NF	NF
Leg prototype	33 (thigh and leg)	43 (thigh and leg)	Adjustable	Adjustable

For dynamic tasks, there is not a clear trend showing the pros (or cons) on task completion time while wearing an exoskeleton. In such a context, some studies demonstrated a time reduction. Amandels et al. [36] measured a 15% reduction in a car assembly task completion time using a Laevo. Other studies identified an increase in time. Madinei et al. [49] tested the BackX exoskeleton in simulated assembly tasks and they found an increase of 7.6% in completion time for females while no changes are measured for men over an average task time of 30 s. Ogunseiju et al. [52] recorded a 20% increase in completion time for material handling while using Flx Ergoskeleton. Moreover, Luger et al. [39] found that the time to complete lifting and fastening tasks with a Laevo exoskeleton increased between 2% and 8%.

Nevertheless, few works focused on time efficiency evaluation, andthree focused on real tasks. More research is necessary to support decision-making regarding the deployment of exoskeletons. Table 6 summarized the main findings of exoskeletons' influence on time efficiency.

Table 6. Time efficiency main findings.

Publication	Exoskeleton	Task Type	Findings
[35]	Laevo	Static	Endurance time increased >3×(from 3.2 to 9.7 min)
[41]	Laevo	Static	Endurance time increased ≈2×
[88]	Leg prototype	Static	Endurance time increased from 2.76 to 13.58 min
[62]	Levitate	Static	Endurance time increased 31.6%
[57]	Levitate	Static	Endurance time increased 52.5%
[79]	IUVO	Static	Endurance time increased 56%
[72]	Eksovest	Static	Completion time decreased 18.9%
[50]	BackX	Static	Completion time decreased up to 50%
[63]	ShoulderX, skelex	Static	Completion time not always decreasing
[36]	Laevo	Dynamic	Completion time decreased 15%
[49]	BackX	Dynamic	Completion time increased 7.6% for females
[52]	Flx Ergoskeleton	Dynamic	Completion time increased 20%
[39]	Laevo	Dynamic	Completion time increased 8%

5.4. Future Research Agenda

In order to better combine economic and social sustainability paradigms in the near future and to enhance the exoskeletons adoption in the manufacturing setting, a future research agenda divided in eight research challenges is provided below based on the gaps detected in the discussion presented in the previous paragraphs.

1. *More focus on in-field studies*: The assessment studies classified in this review focused more on simulated tasks than real ones with 35 studies versus 19, respectively. More research is needed to clearly understand the impact of passive exoskeletons in the real industrial scenario. From the literature emerges a different impact of passive exoskeletons between real and laboratory-simulated tasks. In fact, Bosch et al. [35] found a 38% decrease in low back muscle activity in simulated tasks while Amandels et al. [36] recorded a 12% decrease for real tasks. This remarks that a real setting can create working conditions able to generate the natural variability of movements that cannot be captured in highly controlled laboratory settings [69].
2. *Production efficiency impact of exoskeletons*: Only 13 studies assessed the impact of passive exoskeleton deployment on production efficiency. As emerged in Section 5.3

and Table 6, the results are contrasting (i.e., [36,37]) and not sufficient to answer this question. A challenging future research question will be the study of the effects of passive exoskeletons on production efficiency in terms of both time performances and quality variations. These parameters will be concurrent in productivity, economic evaluations, and decision making.

3. *Injury reduction rate estimation*: Occupational injuries and WRMSDs generate absenteeism at work and all related costs for workforce management and re-scheduling and loss of productivity if shifts remain unreachable due to the lack of personnel. Managers could use these two parameters to better assess the exoskeleton deployment in factories and logistic facilities in the near future even if this approach is time-consuming and requires longer testing times and several efforts by companies. However, the literature analysis highlights the potential of passive exoskeletons to limit local muscular activations, but it is not sufficient to unreservedly promote passive exoskeletons as a WRMSD prevention technology and more research is needed in this direction [30].
4. *Decision support system for accelerating decision-making:* From a managerial point of view, there is an urgent need to develop a decision support system to guide practitioners in selecting the appropriate exoskeleton according to the tasks the workers are asked to perform and on a robust cost/benefits analysis. Several efforts were made to provide guidelines and methodological criteria as discussed in Section 4.2, but complete industrial and cost-oriented approaches are not yet available in the literature also due to a lack of different data mentioned also in the other open point of this future research agenda.
5. *Predictive biomechanical models:* Muscle activation variations are one of the direct effects of exoskeleton support on the human musculoskeletal system. Further research should carefully address this aspect and provide new predictive biomechanical models to enable musculoskeletal simulation for forecasting muscular effort given external load and movement as inputs instead of limiting to the EMG measurement as previously conducted by Tröster et al. [124].
6. *Long-term physical effects of exoskeletons:* Lack of long-term testing and research is also reported by the other reviews [15,16]. Since long-term effects on the human body after prolonged use of exoskeletons are still unknown, new data on this aspect will be essential for driving future developments and implementations in industrial settings. Here, the cooperation between industry and academia will be crucial and strategic. The available testing campaigns present in the published literature consider a maximum length of exoskeleton usage of 7.7 h per day over three months of industry testing [71].
7. *Effect of exoskeletons on workers' diversity, comfort and technology acceptance*: There is also a need for future testing activities on balanced test samples in order to understand if there are gender-based differences and guide future design developments of exoskeletons for gender equality. In the same way, also studies over test samples that cover a broader range of experience levels and workers' age will enable the generalization of the results to a more significant part of the working population [24]. Moreover, the integration of several key concepts from the human factors engineering discipline will be strategic to assess exoskeleton use and benefits in the context of Industry 4.0. The available literature is still not effective to demonstrate if the workforce can easily accept exoskeletons. To this purpose, the comfort level measurement needs to be better and carefully assessed by future researchThe so-called "side effects of the technology" need to be investigated also for exoskeletons since there might be side effects associated with the comfort of straps and mass of the device when worn for an entire working shift of 8 h.
8. *Evaluation of the return on investment in exoskeletons:* On the monetary side, none of the retrieved works directly studied the return on investment (ROI). Todorovic et al. [90] showed methods for the economic evaluation of technologies in the industry that

could be suitable for assessments on the introduction of exoskeletons in industrial contexts. Some relevant parameters that may affect the monetary aspect have been found by analyzing existing works classified here. Time efficiency is a key and direct parameter for evaluating the impact of exoskeletons on production efficiency. By influencing task completion times or operator endurance in demanding static positions as discussed in Section 5.3, exoskeletons could produce a tangible and measurable effect on the overall throughput of a line. Moreover, the quality (the error rate in production) could be affected by the utilization of exoskeletons and the impact on overall product quality as shown by Kim et al. [72]. The loss of quality of the production process could result in increased costs if the error rate increases and more products do not pass quality control tests, making a rework activity necessary or a complete waste of the products. Finally, the injury rate reduction will reduce absenteeism and all the related costs sustained by both the company and the collectivity, and, on the other hand, the loss of production and revenue.

6. Conclusions

In this review, 86 articles concerning passive exoskeletons application in logistics and manufacturing settings have been selected, categorized, and analyzed. The retrieved studies have been categorized by the authors according to their focus in groups divided into guidelines and methodological criteria, simulation, framework, survey, and assessment studies (see Figure 5). Furthermore, the 54 assessment studies that physically tested the exoskeleton were further categorized according to the tasks they performed during the experimental process: no-overhead assembly, overhead assembly, manufacturing, material handling, order picking, and motion-related tasks (in Figure 6). The passive exoskeletons, in this review, were classified according to the body regions they support and the tasks they studied in the literature (in Tables 2–4). Furthermore, for each exoskeleton, its anthropometric fit parameters have been provided (Table 5).

Additionally, a maturity level matrix to map the number of testing methodologies applied for each exoskeleton has been reported in Figure 7. Different aspects have been investigated for each exoskeleton, giving them different maturity levels. Even for a highly studied exoskeleton, such as Laevo, gaps are detected, for example, the lack of data related to time performance assessment and the total absence of studies focused on oxygen consumption which can be related to metabolic cost and very helpful for decision making support. Finally, a future research agenda has been proposed to address the main gaps to fill for enabling effective decision support and deployment of passive exoskeletons in the M&L systems.

Appendix A

Table A1. Exoskeletons analyzed in the review. URLs accessed on 20 June 2022.

Exoskeleton Name	Link to Manufacturer	Supported Body Part
Laevo	www.laevo-exoskeletons.com	Back
Paexo back	https://paexo.com	Back
BackX	www.suitx.com	Back
Flx ergoskeleton	https://www.strongarmtech.com	Back
V22	https://www.strongarmtech.com	Back
Paexo soft back	https://paexo.com	Back
Rakunie	www.morita119.com	Back
Atlas	https://www.exomys.com	Back
Flexible prototype beams	NA	Back
IPAE	NA	Back
Hero Wear Apex	herowearexo.com	Back
Levitate	www.levitatetech.com	Upper limb
ShoulderX	www.suitx.com	Upper limb
Mate	https://mate.comau.com	Upper limb
Eksovest	https://eksobionics.com	Upper limb
Skelex	https://www.skelex.com	Upper limb
H-VEX	https://tech.hyundaimotorgroup.com	Upper limb
IUVO	https://www.iuvo.company	Upper limb
Paexo shoulder	https://paexo.com	Upper limb
Crimson Dynamics	https://www.c-dyn.com	Upper limb
Exhauss Stronger	https://exhauss.com	Upper limb
RoboMate passive	www.robo-mate.eu	Upper limb
Fawcett + ZeroG	https://tiffen.com https://www.equipoisllc.com	Tool support
Fortis + arm	www.lockheedmartin.com	Tool support
Chairless chair	https://www.noonee.com	Lower limb
LegX	www.suitx.com	Lower limb
CEX	https://tech.hyundaimotorgroup.com	Lower limb
Daedalus	https://www.exomys.com	Lower limb
Leg prototype	NA	Lower limb

References

1. Battini, D.; Berti, N.; Finco, S.; Zennaro, I.; Das, A. Towards Industry 5.0: A Multi-Objective Job Rotation Model for an Inclusive Workforce. *Int. J. Prod. Econ.* **2022**, *250*, 108619. [CrossRef]
2. Berti, N.; Finco, S. Digital Twin and Human Factors in Manufacturing and Logistics Systems: State of the Art and Future Research Directions. *IFAC-PapersOnLine* **2022**, *55*, 1893–1898. [CrossRef]
3. Breque, M.; De Nul, L.; Petridis, A. *Industry 5.0: Towards a Sustainable, Human-Centric and Resilient European Industry*; European Commission, Directorate-General for Research and Innovation: Bruxelles, Belgium, 2021.
4. Daria, B.; Martina, C.; Alessandro, P.; Fabio, S.; Valentina, V.; Zennaro, I. Integrating Mocap System and Immersive Reality for Efficient Human-Centred Workstation Design. *IFAC-PapersOnLine* **2018**, *51*, 188–193. [CrossRef]
5. Nasirzadeh, F.; Mir, M.; Hussain, S.; Tayarani Darbandy, M.; Khosravi, A.; Nahavandi, S.; Aisbett, B. Physical Fatigue Detection Using Entropy Analysis of Heart Rate Signals. *Sustainability* **2020**, *12*, 2714. [CrossRef]
6. Battini, D.; Calzavara, M.; Otto, A.; Sgarbossa, F. The Integrated Assembly Line Balancing and Parts Feeding Problem with Ergonomics Considerations. *IFAC-PapersOnLine* **2016**, *49*, 191–196. [CrossRef]
7. Lee, J.; Kim, D.; Ryoo, H.-Y.; Shin, B.-S. Sustainable Wearables: Wearable Technology for Enhancing the Quality of Human Life. *Sustainability* **2016**, *8*, 466. [CrossRef]
8. Katiraee, N.; Calzavara, M.; Finco, S.; Battini, D.; Battaïa, O. Consideration of Workers' Differences in Production Systems Modelling and Design: State of the Art and Directions for Future Research. *Int. J. Prod. Res.* **2021**, *59*, 3237–3268. [CrossRef]
9. Romero, D.; Stahre, J. Towards the Resilient Operator 5.0: The Future of Work in Smart Resilient Manufacturing Systems. *Procedia CIRP* **2021**, *104*, 1089–1094. [CrossRef]
10. Ashta, G.; Finco, S.; Persona, A.; Battini, D. *Investigating Exoskeletons Applicability in Manufacturing and Logistics Systems: State of the Art and Future Research Directions*; Summer School Francesco Turco: Riviera dei Fiori, Italy, 2022.
11. De Looze, M.P.; Bosch, T.; Krause, F.; Stadler, K.S.; O'Sullivan, L.W. Exoskeletons for Industrial Application and Their Potential Effects on Physical Work Load. *Ergonomics* **2016**, *59*, 671–681. [CrossRef]

12. De Looze, M.P.; Krause, F.; O'Sullivan, L.W. The Potential and Acceptance of Exoskeletons in Industry. In Proceedings of the 2nd International Symposium on Wearable Robotics, WeRob2016, Segovia, Spain, 18–21 October 2016; Volume 16.
13. Kermavnar, T.; de Vries, A.W.; de Looze, M.P.; O'Sullivan, L.W. Effects of Industrial Back-Support Exoskeletons on Body Loading and User Experience: An Updated Systematic Review. *Ergonomics* **2021**, *64*, 685–711. [CrossRef]
14. Fox, S.; Aranko, O.; Heilala, J.; Vahala, P. Exoskeletons: Comprehensive, Comparative and Critical Analyses of Their Potential to Improve Manufacturing Performance. *J. Manuf. Technol. Manag.* **2020**, *31*, 1261–1280. [CrossRef]
15. Zhu, Z.; Dutta, A.; Dai, F. Exoskeletons for Manual Material Handling—A Review and Implication for Construction Applications. *Autom. Constr.* **2021**, *122*, 103493. [CrossRef]
16. Kaupe, V.; Feldmann, C.; Wagner, H. Exoskeletons: Productivity and Ergonomics in Logistics—A Systematic Review. In Proceedings of the Hamburg International Conference of Logistics, Hamburg, Germany, 1 September 2021; Volume 31, pp. 527–561.
17. Golabchi, A.; Chao, A.; Tavakoli, M. A Systematic Review of Industrial Exoskeletons for Injury Prevention: Efficacy Evaluation Metrics, Target Tasks, and Supported Body Postures. *Sensors* **2022**, *22*, 2714. [CrossRef] [PubMed]
18. Bogue, R. Exoskeletons—A Review of Industrial Applications. *Ind. Robot* **2018**, *45*, 585–590. [CrossRef]
19. Voilqué, A.; Masood, J.; Fauroux, J.C.; Sabourin, L.; Guezet, O. Industrial Exoskeleton Technology: Classification, Structural Analysis, and Structural Complexity Indicator. In Proceedings of the 2019 Wearable Robotics Association Conference, WearRAcon, Scottsdale, AZ, USA, 25–27 March 2019; pp. 13–20.
20. Toxiri, S.; Näf, M.B.; Lazzaroni, M.; Fernández, J.; Sposito, M.; Poliero, T.; Monica, L.; Anastasi, S.; Caldwell, D.G.; Ortiz, J. Back-Support Exoskeletons for Occupational Use: An Overview of Technological Advances and Trends. *IISE Trans. Occup. Ergon. Hum. Factors* **2019**, *7*, 237–249. [CrossRef]
21. Ali, A.; Fontanari, V.; Schmoelz, W.; Agrawal, S.K. Systematic Review of Back-Support Exoskeletons and Soft Robotic Suits. *Front. Bioeng. Biotechnol.* **2021**, *9*, 765257. [CrossRef]
22. Bostelman, R.; Messina, E.; Foufou, S. Cross-Industry Standard Test Method Developments: From Manufacturing to wearable Robots. *Front. Inf. Technol. Electron. Eng.* **2017**, *18*, 1447–1457. [CrossRef]
23. Pesenti, M.; Antonietti, A.; Gandolla, M.; Pedrocchi, A. Towards a Functional Performance Validation Standard for Industrial Low-Back Exoskeletons: State of the Art Review. *Sensors* **2021**, *21*, 808. [CrossRef]
24. Hoffmann, N.; Prokop, G.; Weidner, R. Methodologies for Evaluating Exoskeletons with Industrial Applications. *Ergonomics* **2022**, *65*, 276–295. [CrossRef]
25. De Bock, S.; Ghillebert, J.; Govaerts, R.; Tassignon, B.; Rodriguez-Guerrero, C.; Crea, S.; Veneman, J.; Geeroms, J.; Meeusen, R.; De Pauw, K. Benchmarking Occupational Exoskeletons: An Evidence Mapping Systematic Review. *Appl. Ergon.* **2022**, *98*, 103582. [CrossRef]
26. Kuber, P.M.; Abdollahi, M.; Alemi, M.M.; Rashedi, E. A Systematic Review on Evaluation Strategies for Field Assessment of Upper-Body Industrial Exoskeletons: Current Practices and Future Trends. *Ann. Biomed. Eng.* **2022**, *50*, 1203–1231. [CrossRef]
27. Kuber, P.M.; Rashedi, E. Product Ergonomics in Industrial Exoskeletons: Potential Enhancements for Workforce Efficiency and Safety. *Theor. Issues Ergon. Sci.* **2020**, *22*, 729–752. [CrossRef]
28. Massardi, S.; Rodriguez-Cianca, D.; Pinto-Fernandez, D.; Moreno, J.C.; Lancini, M.; Torricelli, D. Characterization and Evaluation of Human–Exoskeleton Interaction Dynamics: A Review. *Sensors* **2022**, *22*, 3993. [CrossRef] [PubMed]
29. Bär, M.; Steinhilber, B.; Rieger, M.A.; Luger, T. The Influence of Using Exoskeletons during Occupational Tasks on Acute Physical Stress and Strain Compared to No Exoskeleton—A Systematic Review and Meta-Analysis. *Appl. Ergon.* **2021**, *94*, 103385. [CrossRef] [PubMed]
30. Theurel, J.; Desbrosses, K. Occupational Exoskeletons: Overview of Their Benefits and Limitations in Preventing Work-Related Musculoskeletal Disorders. *IISE Trans. Occup. Ergon. Hum. Factors* **2019**, *7*, 264–280. [CrossRef]
31. Tranfield, D.; Denyer, D.; Smart, P. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. *Br. J. Manag.* **2003**, *14*, 207–222. [CrossRef]
32. Page, M.J.; Moher, D.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. PRISMA 2020 Explanation and Elaboration: Updated Guidance and Exemplars for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n160. [CrossRef] [PubMed]
33. Gilotta, S.; Spada, S.; Ghibaudo, L.; Isoardi, M.; Mosso, C.O. Acceptability beyond Usability: A Manufacturing Case Study. In Proceedings of the 20th Congress of the International Ergonomics Association, Florence, Italy, 26–30 August 2018; Volume 824, ISBN 9783319960708.
34. Jan, D.K.; Paul, V.; Jacqueline, S.; Georgios, R.; Martin, C.; Kees, P.; Pim, V.D.; Iñigo, I. *Work-Related Musculoskeletal Disorders: Prevalence, Costs and Demographics in the EU*; European Agency for Safety and Health at Work: Luxembourg, 2019.
35. Bosch, T.; van Eck, J.; Knitel, K.; de Looze, M. The Effects of a Passive Exoskeleton on Muscle Activity, Discomfort and Endurance Time in Forward Bending Work. *Appl. Ergon.* **2016**, *54*, 212–217. [CrossRef]
36. Amandels, S.; Eyndt, H.O.H.; Daenen, L.; Hermans, V. Introduction and Testing of a Passive Exoskeleton in an Industrial Working Environment. In Proceedings of the 20th Congress of the International Ergonomics Association, Florence, Italy, 26–30 August 2018; Volume 820, ISBN 9783319960821.

37. Kim, S.; Madinei, S.; Alemi, M.M.; Srinivasan, D.; Nussbaum, M.A. Assessing the Potential for "Undesired" Effects of Passive Back-Support Exoskeleton Use during a Simulated Manual Assembly Task: Muscle Activity, Posture, Balance, Discomfort, and Usability. *Appl. Ergon.* **2020**, *89*, 103194. [CrossRef]
38. Flor, R.; Gaspar, J.; Fujão, C.; Nunes, I.L. How Workers Perceive LAEVO Exoskeleton Use in Non-Cyclic Tasks. In Proceedings of the AHFE 2021 Virtual Conference on Human Factors and Systems Interaction, Virtual, 25–29 July 2021; Volume 265, ISBN 9783030798154.
39. Luger, T.; Bär, M.; Seibt, R.; Rieger, M.A.; Steinhilber, B. 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* **2021**, *65*, 5–21. [CrossRef]
40. Luger, T.; Bär, M.; Seibt, R.; Rimmele, P.; Rieger, M.A.; Steinhilber, B. A Passive Back Exoskeleton Supporting Symmetric and Asymmetric Lifting in Stoop and Squat Posture Reduces Trunk and Hip Extensor Muscle Activity and Adjusts Body Posture—A Laboratory Study. *Appl. Ergon.* **2021**, *97*, 103530. [CrossRef] [PubMed]
41. Giustetto, A.; Anjos, F.V.D.; Gallo, F.; Monferino, R.; Cerone, G.L.; Di Pardo, M.; Gazzoni, M.; Cremasco, M.M. Investigating the Effect of a Passive Trunk Exoskeleton on Local Discomfort, Perceived Effort and Spatial Distribution of Back Muscles Activity. *Ergonomics* **2021**, *64*, 1379–1392. [CrossRef] [PubMed]
42. Dos Anjos, F.V.; Vieira, T.M.; Cerone, G.L.; Pinto, T.P.; Gazzoni, M. Assessment of Exoskeleton Related Changes in Kinematics and Muscle Activity. In Proceedings of the 5th International Symposium on Wearable Robotics, WeRob2020, and of WearRAcon Europe 2020, Online, 13–16 October 2020; Volume 27.
43. Iranzo, S.; Piedrabuena, A.; García-Torres, F.; Martinez-De-Juan, J.L.; Prats-Boluda, G.; Sanchis, M.; Belda-Lois, J.-M. Assessment of a Passive Lumbar Exoskeleton in Material Manual Handling Tasks under Laboratory Conditions. *Sensors* **2022**, *22*, 4060. [CrossRef]
44. Motmans, R.; Debaets, T.; Chrispeels, S. Effect of a Passive Exoskeleton on Muscle Activity and Posture during Order Picking. In Proceedings of the 20th Congress of the International Ergonomics Association, Florence, Italy, 26–30 August 2018; Volume 820, ISBN 9783319960821.
45. Kinne, S.; Kretschmer, V.; Bednorz, N. Palletising Support in Intralogistics: The Effect of a Passive Exoskeleton on Workload and Task Difficulty Considering Handling and Comfort. In Proceedings of the 2nd International Conference on Human Systems Engineering and Design (IHSED2019): Future Trends and Applications, Universität der Bundeswehr München, Munich, Germany, 16–18 September 2019; Volume 1026, ISBN 9783030279271.
46. Cardoso, A.; Colim, A.; Sousa, N. The Effects of a Passive Exoskeleton on Muscle Activity and Discomfort in Industrial Tasks. In *Occupational and Environmental Safety and Health II*; Springer: Berlin/Heidelberg, Germany, 2020; Volume 277.
47. Siedl, S.M.; Wolf, M.; Mara, M. Exoskeletons in the Supermarket: Influences of Comfort, Strain Relief and Task-Technology Fit on Retail Workers' Post-Trial Intention to Use. In Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction, Boulder, CO, USA, 8–11 March 2021; pp. 397–401.
48. Schmalz, T.; Colienne, A.; Bywater, E.; Fritzsche, L.; Gärtner, C.; Bellmann, M.; Reimer, S.; Ernst, M. A Passive Back-Support Exoskeleton for Manual Materials Handling: Reduction of Low Back Loading and Metabolic Effort during Repetitive Lifting. *IISE Trans. Occup. Ergon. Hum. Factors* **2021**, *10*, 7–20. [CrossRef]
49. Madinei, S.; Alemi, M.M.; Kim, S.; Srinivasan, D.; Nussbaum, M.A. Biomechanical Evaluation of Passive Back-Support Exoskeletons in a Precision Manual Assembly Task: "Expected" Effects on Trunk Muscle Activity, Perceived Exertion, and Task Performance. *Hum. Factors* **2020**, *62*, 441–457. [CrossRef] [PubMed]
50. Gonsalves, N.J.; Ogunseiju, O.R.; Akanmu, A.A.; Nnaji, C.A. Assessment of a Passive Wearable Robot for Reducing Low Back DIsorders during Rebar Work. *J. Inf. Technol. Constr.* **2021**, *26*, 936–952. [CrossRef]
51. Picchiotti, M.T.; Weston, E.B.; Knapik, G.G.; Dufour, J.S.; Marras, W.S. Impact of Two Postural Assist Exoskeletons on Biomechanical Loading of the Lumbar Spine. *Appl. Ergon.* **2019**, *75*, 1–7. [CrossRef]
52. Ogunseiju, O.; Olayiwola, J.; Akanmu, A.; Olatunji, O.A. Evaluation of Postural-Assist Exoskeleton for Manual Material Handling. *Eng. Constr. Archit. Manag.* **2022**, *29*, 1358–1375. [CrossRef]
53. Näf, M.B.; Koopman, A.S.; Rodriguez-Guerrero, C.; Vanderborght, B.; Lefeber, D. Trunk Range of Motion in the Sagittal Plane with and without a Flexible Back Support Exoskeleton. In Proceedings of the 4th International Symposium on Wearable Robotics, WeRob2018, Pisa, Italy, 16–20 October 2018; Volume 22.
54. Näf, M.B.; Koopman, A.S.; Baltrusch, S.; Rodriguez-Guerrero, C.; Vanderborght, B.; Lefeber, D. Passive Back Support Exoskeleton Improves Range of Motion Using Flexible Beams. *Front. Robot. AI* **2018**, *5*, 72. [CrossRef]
55. Qu, X.; Qu, C.; Ma, T.; Yin, P.; Zhao, N.; Xia, Y.; Qu, S. Effects of an Industrial Passive Assistive Exoskeleton on Muscle Activity, Oxygen Consumption and Subjective Responses during Lifting Tasks. *PLoS ONE* **2021**, *16*, e0245629. [CrossRef]
56. Yandell, M.B.; Wolfe, A.E.; Marino, M.C.; Harris, M.P.; Zelik, K.E. Effect of a Back-Assist Exosuit on Logistics Worker Perceptions, Acceptance, and Muscle Activity. In Proceedings of the 5th International Symposium on Wearable Robotics, WeRob2020, and of WearRAcon Europe 2020, Online, 13–16 October 2020; Volume 27.
57. Spada, S.; Ghibaudo, L.; Gilotta, S.; Gastaldi, L.; Cavatorta, M.P. Analysis of Exoskeleton Introduction in Industrial Reality: Main Issues and EAWS Risk Assessment. In Proceedings of the AHFE 2017 International Conference on Physical Ergonomics and Human Factors, The Westin Bonaventure Hotel, Los Angeles, CA, USA, 17–21 July 2017; Volume 602, ISBN 9783319608242.

58. Iranzo, S.; Piedrabuena, A.; Iordanov, D.; Martinez-Iranzo, U.; Belda-Lois, J.-M. Ergonomics Assessment of Passive Upper-Limb Exoskeletons in an Automotive Assembly Plant. *Appl. Ergon.* **2020**, *87*, 103120. [CrossRef]
59. Carnazzo, C.; Spada, S.; Ghibaudo, L.; Eaton, L.; Fajardo, I.; Zhu, S.; Cavatorta, M.P. Exoskeletons in Automotive Industry: Investigation into the Applicability Across Regions. In Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021), Online, 13–18 June 2021; Volume 221, ISBN 9783030746070.
60. Groos, S.; Abele, N.D.; Fischer, P.; Hefferle, M.; Kluth, K. Evaluation of Physiological Costs Using Standardized Analysis Methods During Simulated Overhead Work with and Without Exoskeleton. In Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021), Online, 13–18 June 2021; Volume 223, ISBN 9783030746131.
61. Masood, J.; Triviño-Tonato, E.; Rivas-Gonzalez, M.D.P.; Arias-Matilla, M.D.M.; Planas-Lara, A.E. Subjective Perception of Shoulder Support Exoskeleton at Groupe PSA. In Proceedings of the 5th International Symposium on Wearable Robotics, WeRob2020, and of WearRAcon Europe 2020, Online, 13–16 October 2020; Volume 27.
62. Spada, S.; Ghibaudo, L.; Gilotta, S.; Gastaldi, L.; Cavatorta, M.P. Investigation into the Applicability of a Passive Upper-Limb Exoskeleton in Automotive Industry. *Procedia Manuf.* **2017**, *11*, 1255–1262. [CrossRef]
63. Mouzo, F.; Michaud, F.; Lugris, U.; Masood, J.; Cuadrado, J. Evaluation of Two Upper-Limb Exoskeletons for Ceiling Welding in the Naval Industry. In Proceedings of the 5th International Symposium on Wearable Robotics, WeRob2020, and of WearRAcon Europe 2020, Online, 13–16 October 2020; Volume 27.
64. Van Engelhoven, L.; Poon, N.; Kazerooni, H.; Ban, A.; Rempel, D.; Harris-Adamson, C. Evaluation of an Adjustable Support Shoulder Exoskeleton on Static and Dynamic Overhead Tasks. In Proceedings of the Human Factors and Ergonomics Society, Philadelphia, PA, USA, 1–5 October 2018; Volume 2, pp. 804–808.
65. Alabdulkarim, S.; Nussbaum, M.A. Influences of Different Exoskeleton Designs and Tool Mass on Physical Demands and Performance in a Simulated Overhead Drilling Task. *Appl. Ergon.* **2019**, *74*, 55–66. [CrossRef]
66. Pinho, J.P.; Americano, P.P.; Taira, C.; Pereira, W.; Caparroz, E.; Forner-Cordero, A. Shoulder Muscles Electromyographic Responses in Automotive Workers Wearing a Commercial Exoskeleton. In Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS, New Orleans, LA, USA, 4–7 November 1988; Volume 2020, pp. 4917–4920.
67. Pinho, J.P.; Taira, C.; Parik-Americano, P.; Suplino, L.O.; Bartholomeu, V.P.; Hartmann, V.N.; Umemura, G.S.; Forner-Cordero, A. A Comparison between Three Commercially Available Exoskeletons in the Automotive Industry: An Electromyographic Pilot Study. In Proceedings of the IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics, Pisa, Italy, 20–22 February 2006; Volume 2020, pp. 246–251.
68. De Bock, S.; Ghillebert, J.; Govaerts, R.; Elprama, S.A.; Marusic, U.; Serrien, B.; Jacobs, A.; Geeroms, J.; Meeusen, R.; De Pauw, K. Passive Shoulder Exoskeletons: More Effective in the Lab Than in the Field? *IEEE Trans. Neural Syst. Rehabil. Eng.* **2021**, *29*, 173–183. [CrossRef]
69. Pacifico, I.; Parri, A.; Taglione, S.; Sabatini, A.M.; Violante, F.S.; Molteni, F.; Giovacchini, F.; Vitiello, N.; Crea, S. Exoskeletons for Workers: A Case Series Study in an Enclosures Production Line. *Appl. Ergon.* **2022**, *101*, 103679. [CrossRef]
70. Kim, S.; Nussbaum, M.A.; Smets, M.; Ranganathan, S. 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.* **2021**, *64*, 905–914. [CrossRef] [PubMed]
71. Smets, M. A Field Evaluation of Arm-Support Exoskeletons for Overhead Work in Automotive Assembly. *IISE Trans. Occup. Ergon. Hum. Factors* **2019**, *7*, 192–198. [CrossRef]
72. Kim, S.; Nussbaum, M.A.; Esfahani, M.I.M.; Alemi, M.M.; Alabdulkarim, S.; Rashedi, E. 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.* **2018**, *70*, 315–322. [CrossRef]
73. Alabdulkarim, S.; Kim, S.; Nussbaum, M.A. Effects of Exoskeleton Design and Precision Requirements on Physical Demands and Quality in a Simulated Overhead Drilling Task. *Appl. Ergon.* **2019**, *80*, 136–145. [CrossRef] [PubMed]
74. Jorgensen, M.J.; Hakansson, N.A.; Desai, J. The Impact of Passive Shoulder Exoskeletons during Simulated Aircraft Manufacturing Sealing Tasks. *Int. J. Ind. Ergon.* **2022**, *91*, 103337. [CrossRef]
75. Jorgensen, M.J.; Hakansson, N.A.; Desai, J. Influence of Different Passive Shoulder Exoskeletons on Shoulder and Torso Muscle Activation during Simulated Horizontal and Vertical Aircraft Squeeze Riveting Tasks. *Appl. Ergon.* **2022**, *104*, 103822. [CrossRef]
76. Hefferle, M.; Snell, M.; Kluth, K. Influence of Two Industrial Overhead Exoskeletons on Perceived Strain—A Field Study in the Automotive Industry. In Proceedings of the AHFE 2020 Virtual Conference on Human Factors in Robots, Drones and Unmanned Systems, Virtual, 16–20 July 2020; Volume 1210, ISBN 9783030517571.
77. Moyon, A.; Poirson, E.; Petiot, J.-F. Experimental Study of the Physical Impact of a Passive Exoskeleton on Manual Sanding Operations. *Procedia CIRP* **2018**, *70*, 284–289. [CrossRef]
78. Hyun, D.J.; Bae, K.H.; Kim, K.J.; Nam, S.; Lee, D.H. A Light-Weight Passive Upper Arm Assistive Exoskeleton Based on Multi-Linkage Spring-Energy Dissipation Mechanism for Overhead Tasks. *Rob. Auton. Syst.* **2019**, *122*, 103309. [CrossRef]
79. Spada, S.; Ghibaudo, L.; Carnazzo, C.; Gastaldi, L.; Cavatorta, M.P. Passive Upper Limb Exoskeletons: An Experimental Campaign with Workers. In Proceedings of the 20th Congress of the International Ergonomics Association, Florence, Italy, 26–30 August 2018; Volume 825, ISBN 9783319960678.

80. Latella, C.; Tirupachuri, Y.; Tagliapietra, L.; Rapetti, L.; Schirrmeister, B.; Bornmann, J.; Gorjan, D.; Camernik, J.; Maurice, P.; Fritzsche, L.; et al. Analysis of Human Whole-Body Joint Torques During Overhead Work with a Passive Exoskeleton. *IEEE Trans. Hum. Mach. Syst.* **2021**, *52*, 1060–1068. [CrossRef]
81. Theurel, J.; Desbrosses, K.; Roux, T.; Savescu, A. Physiological Consequences of Using an Upper Limb Exoskeleton during Manual Handling Tasks. *Appl. Ergon.* **2018**, *67*, 211–217. [CrossRef] [PubMed]
82. Luger, T.; Seibt, R.; Cobb, T.J.; Rieger, M.A.; Steinhilber, B. Influence of a Passive Lower-Limb Exoskeleton during Simulated Industrial Work Tasks on Physical Load, Upper Body Posture, Postural Control and Discomfort. *Appl. Ergon.* **2019**, *80*, 152–160. [CrossRef]
83. Luger, T.; Cobb, T.J.; Seibt, R.; Rieger, M.A.; Steinhilber, B. Subjective Evaluation of a Passive Lower-Limb Industrial Exoskeleton During Simulated Assembly. *IISE Trans. Occup. Ergon. Hum. Factors* **2019**, *7*, 175–184. [CrossRef]
84. Groos, S.; Fuchs, M.; Kluth, K. Determination of the Subjective Strain Experiences During Assembly Using the Exoskeleton "Chairless Chair". In Proceedings of the Advances in Human Factors in Robots and Unmanned Systems, Washington, DC, USA, 24–28 July 2019; Chen, J., Ed.; Springer: Berlin/Heidelberg, Germany, 2020; Volume 962, pp. 72–82.
85. Spada, S.; Ghibaudo, L.; Carnazzo, C.; Di Pardo, M.; Chander, D.S.; Gastaldi, L.; Cavatorta, M.P. Physical and Virtual Assessment of a Passive Exoskeleton. In Proceedings of the 20th Congress of the International Ergonomics Association, Florence, Italy, 26–30 August 2018; Volume 825, ISBN 9783319960678.
86. Pillai, M.V.; Van Engelhoven, L.; Kazerooni, H. Evaluation of a Lower Leg Support Exoskeleton on Floor and Below Hip Height Panel Work. *Hum. Factors* **2020**, *62*, 489–500. [CrossRef] [PubMed]
87. Chae, U.R.; Kim, K.; Choi, J.; Hyun, D.J.; Yun, J.; Lee, G.H.; Hyun, Y.G.; Lee, J.; Chung, M. Systematic Usability Evaluation on Two Harnesses for a Wearable Chairless Exoskeleton. *Int. J. Ind. Ergon.* **2021**, *84*, 103162. [CrossRef]
88. Yan, Z.; Han, B.; Du, Z.; Huang, T.; Bai, O.; Peng, A. Development and Testing of a Wearable Passive Lower-Limb Support Exoskeleton to Support Industrial Workers. *Biocybern. Biomed. Eng.* **2021**, *41*, 221–238. [CrossRef]
89. Tompkins, J. *Facilities Planning*; John Wiley & Sons: Chichester, UK, 2003; 750p.
90. Todorovic, O.; Constantinescu, C.; Popescu, D. Foundations for economic evaluation of exoskeletons in manufacturing. *Acta Tech. Napoc. Ser.-Appl. Math. Mech. Eng.* **2018**, *61*, 221–230.
91. Hein, C.M.; Lueth, T.C. User Acceptance Evaluation of Wearable Aids. In *Developing Support Technologies*; Springer: Berlin/Heidelberg, Germany, 2018; Volume 23.
92. Ralfs, L.; Hoffmann, N.; Weidner, R. Approach of a Decision Support Matrix for the Implementation of Exoskeletons in Industrial Workplaces. In *Annals of Scientific Society for Assembly, Handling and Industrial Robotics 2021*; Schüppstuhl, T., Tracht, K., Raatz, A., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 165–176.
93. De Looze, M.; de Vries, A.; Krause, F.; Baltrusch, S. Three-Stage Evaluation for Defining the Potential of an Industrial Exoskeleton in a Specific Job. In Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021), Online, 13–18 June 2021; Volume 223, ISBN 9783030746131.
94. Toxiri, S.; Sposito, M.; Lazzaroni, M.; Mancini, L.; Di Pardo, M.; Caldwell, D.G.; Ortiz, J. Towards Standard Specifications for Back-Support Exoskeletons. In Proceedings of the 4th International Symposium on Wearable Robotics, WeRob2018, Pisa, Italy, 16–20 October 2018; Volume 22.
95. Bostelman, R.; Li-Baboud, Y.-S.; Virts, A.; Yoon, S.; Shah, M. Towards Standard Exoskeleton Test Methods for Load Handling. In Proceedings of the 2019 Wearable Robotics Association Conference, WearRAcon 2019, Scottsdale, AZ, USA, 25–27 March 2019; pp. 21–27.
96. Dahmen, C.; Hölzel, C.; Wöllecke, F.; Constantinescu, C. Approach of Optimized Planning Process for Exoskeleton Centered Workplace Design. *Procedia CIRP* **2018**, *67*, 268–273. [CrossRef]
97. Dahmen, C.; Wöllecke, F.; Constantinescu, C. Challenges and Possible Solutions for Enhancing the Workplaces of the Future by Integrating Smart and Adaptive Exoskeletons. *Procedia CIRP* **2018**, *67*, 268–273. [CrossRef]
98. Dahmen, C.; Constantinescu, C. Methodology of Employing Exoskeleton Technology in Manufacturing by Considering Time-Related and Ergonomics Influences. *Appl. Sci.* **2020**, *10*, 1591. [CrossRef]
99. Di Pardo, M.; Monferino, R.; Gallo, F.; Tauro, F. Exoskeletons Introduction in Industry. Methodologies and Experience of Centro Ricerche Fiat (CRF). In Proceedings of the 5th International Symposium on Wearable Robotics, WeRob2020, and of WearRAcon Europe 2020, Online, 13–16 October 2020; Volume 27.
100. Masood, J.; Dacal-Nieto, A.; Alonso-Ramos, V.; Fontano, M.I.; Voilqué, A.; Bou, J. Industrial Wearable Exoskeletons and Exosuits Assessment Process. In Proceedings of the 4th International Symposium on Wearable Robotics, WeRob2018, Pisa, Italy, 16–20 October 2018; Volume 22.
101. Grazi, L.; Chen, B.; Lanotte, F.; Vitiello, N.; Crea, S. Towards Methodology and Metrics for Assessing Lumbar Exoskeletons in Industrial Applications. In Proceedings of the 2019 IEEE International Workshop on Metrology for Industry 4.0 and IoT, MetroInd 4.0 and IoT, Naples, Italy, 4–6 June 2019; pp. 400–404.
102. Hefferle, M.; Lechner, M.; Kluth, K.; Christian, M. Development of a Standardized Ergonomic Assessment Methodology for Exoskeletons Using Both Subjective and Objective Measurement Techniques. In Proceedings of the AHFE 2019 International Conference on Human Factors in Robots and Unmanned Systems, Washington, DC, USA, 24–28 July 2019; Volume 962, ISBN 9783030204662.

103. Constantinescu, C.; Todorovic, O.; Ippolito, D. Comprehensive Modelling and Simulation towards the Identification of Critical Parameters for Evaluation of Exoskeleton-Centred Workplaces. *Procedia CIRP* **2019**, *79*, 176–179. [CrossRef]
104. Ippolito, D.; Constantinescu, C.; Riedel, O. Holistic Planning and Optimization of Human-Centred Workplaces with Integrated Exoskeleton Technology. *Procedia CIRP* **2020**, *88*, 214–217. [CrossRef]
105. Hartmann, V.N.; Rinaldi, D.M.; Taira, C.; Forner-Cordero, A. Industrial Upper-Limb Exoskeleton Characterization: Paving the Way to New Standards for Benchmarking. *Machines* **2021**, *9*, 362. [CrossRef]
106. Zelik, K.E.; Nurse, C.A.; Schall, M.C.; Sesek, R.F.; Marino, M.C.; Gallagher, S. An Ergonomic Assessment Tool for Evaluating the Effect of Back Exoskeletons on Injury Risk. *Appl. Ergon.* **2022**, *99*, 103619. [CrossRef]
107. Chini, G.; Di Natali, C.; Toxiri, S.; Draicchio, F.; Monica, L.; Caldwell, D.G.; Ortiz, J. Preliminary Study of an Exoskeleton Index for Ergonomic Assessment in the Workplace. In Proceedings of the 5th International Symposium on Wearable Robotics, WeRob2020, and of WearRAcon Europe 2020, Online, 13–16 October 2020; Volume 27.
108. Ralfs, L.; Hoffmann, N.; Weidner, R. Method and Test Course for the Evaluation of Industrial Exoskeletons. *Appl. Sci.* **2021**, *11*, 9614. [CrossRef]
109. Weckenborg, C.; Thies, C.; Spengler, T.S. Harmonizing Ergonomics and Economics of Assembly Lines Using Robots and Exoskeletons. *J. Manuf. Syst.* **2022**, *62*, 681–702. [CrossRef]
110. Schwerha, D.; McNamara, N.; Kim, S.; Nussbaum, M.A. Exploratory Field Testing of Passive Exoskeletons in Several Environments: Perceived Usability and User Acceptance. *IISE Trans. Occup. Ergon. Hum. Factors* **2022**, *10*, 71–82. [CrossRef]
111. Constantinescu, C.; Popescu, D.; Muresan, P.-C.; Stana, S.-I. Exoskeleton-Centered Process Optimization in Advanced Factory Environments. *Procedia CIRP* **2016**, *41*, 740–745. [CrossRef]
112. Constantinescu, C.; Muresan, P.-C.; Simon, G.-M. JackEx: The New Digital Manufacturing Resource for Optimization of Exoskeleton-Based Factory Environments. *Procedia CIRP* **2016**, *50*, 508–511. [CrossRef]
113. Constantinescu, C.; Rus, R.; Rusu, C.-A.; Popescu, D. Digital Twins of Exoskeleton-Centered Workplaces: Challenges and Development Methodology. *Proc. Procedia Manuf.* **2019**, *39*, 58–65. [CrossRef]
114. Rusu, C.-A.; Constantinescu, C.; Marinescu, S.-C. A Generic Hybrid Human/Exoskeleton Digital Model towards Digital Transformation of Exoskeletons-Integrated Workplaces. *Procedia CIRP* **2021**, *104*, 1787–1790. [CrossRef]
115. Rivera, F.G.; Brolin, A.; Luque, E.P.; Högberg, D. A Framework to Model the Use of Exoskeletons in DHM Tools. In Proceedings of the AHFE 2021 Virtual Conferences on Human Factors and Simulation, and Digital Human Modeling and Applied Optimization, Virtual, 25–29 July 2021; Volume 264, ISBN 9783030797621.
116. Reid, C.R.; Nussbaum, M.A.; Gregorczyk, K.; Harris-Adamson, C.; Kyte, K.; Lowe, B.; Smets, M.; Zmijewski, R. Industrial Exoskeletons: Are We Ready for Prime Time Yet? In Proceedings of the Human Factors and Ergonomics Society, Rome, Italy, 9–13 October 2017; Volume 2017, pp. 1000–1004.
117. Kim, S.; Moore, A.; Srinivasan, D.; Akanmu, A.; Barr, A.; Harris-Adamson, C.; Rempel, D.M.; Nussbaum, M.A. Potential of Exoskeleton Technologies to Enhance Safety, Health, and Performance in Construction: Industry Perspectives and Future Research. *IISE Trans. Occup. Ergon. Hum. Factors* **2019**, *7*, 185–191. [CrossRef]
118. Schwerha, D.J.; McNamara, N.; Nussbaum, M.A.; Kim, S. Adoption Potential of Occupational Exoskeletons in Diverse Enterprises Engaged in Manufacturing Tasks. *Int. J. Ind. Ergon.* **2021**, *82*, 103103. [CrossRef]
119. Karvouniari, A.; Michalos, G.; Dimitropoulos, N.; Makris, S. An Approach for Exoskeleton Integration in Manufacturing Lines Using Reality Techniques. In Proceedings of the 6th Cirp Global Web Conference—Envisaging the Future Manufacturing, Design, Technologies and Systems in Innovation Era (CIRPE 2018), Online, 23–25 October 2018; Simeone, A., Priarone, P.C., Eds.; Elsevier: Amsterdam, The Netherlands, 2018; Volume 78, pp. 103–108. Available online: https://www.sciencedirect.com/science/article/pii/S2212827118312289 (accessed on 15 March 2023).
120. Elprama, S.A.; Vanderborght, B.; Jacobs, A. An Industrial Exoskeleton User Acceptance Framework Based on a Literature Review of Empirical Studies. *Appl. Ergon.* **2022**, *100*, 103615. [CrossRef]
121. Laevo First PPE Certified Exoskeleton in the World! Meet the Laevo FLEX. 11 April 2022, Laevo News. Available online: https://www.laevo-exoskeletons.com/news/first-ppe-certified-exoskeleton-in-the-world-meet-the-laevo-flex (accessed on 15 March 2023).
122. Peters, M.; Wischniewski, S. *The Impact of Using Exoskeletons on Occupational Safety and Health*; EU-OSHA: Bilbao, Spain, 2019.
123. Monica, L.; Anastasi, S.; Draicchio, F. Occupational Exoskeletons: Wearable Robotic Devices to Prevent Work-Related Musculoskeletal Disorders in the Workplace of the Future; European Agency for Safety and Health in the Work. Available online: https://osha.europa.eu/en/publications/occupational-exoskeletons-wearable-robotic-devices-and-preventing-work-related (accessed on 9 September 2020).
124. Tröster, M.; Budde, S.; Maufroy, C.; Andersen, M.S.; Rasmussen, J.; Schneider, U.; Bauernhansl, T. Biomechanical Analysis of Stoop and Free-Style Squat Lifting and Lowering with a Generic Back-Support Exoskeleton Model. *Int. J. Environ. Res. Public Health* **2022**, *19*, 9040. [CrossRef] [PubMed]