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The Use of Exoskeletons in Industry: A Systematic Review Focused on Methodological Approaches

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Abstract

Exoskeletons are promising tools for preventing and reducing the effects of work tasks and optimizing worker performance. Given the increasing interest in exoskeletons in industrial settings, it is crucial to clarify the methodologies used to validate their effectiveness. A systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. Four electronic databases were searched for randomized and nonrandomized controlled trials. The investigation focused on healthy populations, studies that simulated typical industrial tasks, field studies, and the comparison of exoskeleton use with a control group, emphasizing assessment tools and outcome measures including kinematic and physiological parameters. Cohen's d and effect size were calculated to verify the impact of exoskeleton utilization. A total of 32 eligible studies were selected, including upper and lower passive and active exoskeletons. The results indicated significant benefits in reducing muscle activity, discomfort, and heart rate across various tasks. However, there were methodological limitations, such as the absence of standardized assessment tools and control group comparisons. This review will guide researchers in the adoption of robust frameworks for effective exoskeleton implementations in industrial environments. However, the focus on similar laboratory conditions, male participants, and passive upper exoskeletons limits the generalizability of the results, creating a significant knowledge gap for companies and workers, potentially impeding their willingness to adopt exoskeletons.

Keywords: Wearable assistive device, Kinematics, Ergonomics, Physiological measures, Industrial context

1. Introduction

Workplace environments often expose employees to various physical challenges that contribute to musculoskeletal problems. Some of the physical demands of work-related musculoskeletal disorders (WMSDs) include repetitive tasks, incorrect postures, heavy tasks, lifting loads, machine vibration, and low temperatures [1]. To address the increased incidence of these disorders, companies and researchers have collaborated to develop solutions that help workers prevent and mitigate damage caused by work-related musculoskeletal disorders [2]. According to some authors [2-4], improving the workplace, rotating tasks, changing between sitting and standing from time to time, taking regular breaks, and teaching workers ergonomic strategies are effective in preventing work-related musculoskeletal disorders.

In this context, the use of exoskeletons has emerged as a promising technological advancement for supporting or assisting workers and reducing work-related health risks. Exoskeletons are wearable devices designed to support and enhance a user's physical capabilities, thereby reducing strain on muscles and joints during physically demanding tasks [5]. The American Society for Testing and Materials (ASTM) [6] defines an exoskeleton as "a wearable device that augments, enables, assists, and/or enhances physical activity through mechanical interaction with the body". This mechanical assistive device supports the human body, contributing to (i) preventive measures, (ii) increases in physical strength, and (iii) increases in the performance of the wearer [7]. Additionally, exoskeletons can be categorized based on the body region they support, the source of energy supply, and the level of adaptation to the human body. Exoskeletons can be designed to support various body regions, including the upper body (such as the arms, hands, and lumbar region), lower limbs (including the knees, legs, and feet), and the entire body [8]. These wearable devices can also operate in different modes, which can be classified as active, semi-active, or passive. Active exoskeletons have an external power source such as an electric battery, which increases the power of the human body. However, this external source of energy increases both the weight and cost of the exoskeleton [9-10]. In contrast, passive exoskeletons lack actuators or electronic parts such as transducers or controllers, and the force required to support user actions is released by taking advantage of the elasticity of the materials (i.e., torsion springs or pistons). Compared with powered (semi-active and active) ones, this

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type is lightweight, economical, and easy to redesign [11]. Various exoskeletons have been used in the industrial sector to enhance worker performance and safety. For example, PAEXO and ShoulderX are specially designed for overhead tasks, whereas chairless chairs assist workers in tasks that require crouching for extended periods [12-13].

One of the first industries to test and use assistive technology to support labor-intensive tasks was the automotive sector [14]. Some companies have developed their exoskeletons depending on the requirements of the factory, while others have tested commercial exoskeletons. For instance, Honda developed Walking Assist, an active lower exoskeleton that influences the user to achieve efficient walking, while Hyundai developed a Wearable Vest Exoskeleton (VEX), a passive upper exoskeleton that assists industrial workers who spend several hours performing overhead tasks [15]. Furthermore, AUDI and BMW tested the Chairless Chair, a passive lower exoskeleton that allows workers to sit anywhere while working, reducing the mechanical load on the lumbar spine and legs. Other industrial brands, such as Ford, AUDI, and Volkswagen, tested a passive upper exoskeleton specifically for overhead tasks and above-shoulder levels [2], [12].

The implementation of exoskeletons in the industrial sector also has significant economic implications. Reducing injury values can help companies reduce medical costs and minimize absenteeism [1]. Additionally, improving productivity and reducing fatigue among workers can increase efficiency, making exoskeletons a valuable investment. These financial advantages should be considered combined with the health and safety provided by exoskeleton use.

Several studies have investigated the effects of exoskeletons on the human body using electromyography, near-infrared spectroscopy, heart rate monitors, motion capture systems, plantar pressure platforms, and questionnaires [7],[16]. The data obtained using this equipment can be translated into objective variables, such as muscle activity, oxygen saturation, and heart rate, or subjective variables, including answers obtained via questionnaires [12],[17]. Most available studies combine these two types of research methods and data because their complementary nature increases the likelihood of understanding the exoskeleton effects [9],[18]. Nevertheless, there is limited discussion on the variety and appropriateness of the assessment tools used to evaluate exoskeleton effectiveness [19]. Few studies have calculated and reported effect sizes, such as Cohen's d, to quantify the impact of exoskeletons, limiting their ability to perform meta-analyses and draw robust conclusions. Furthermore, many studies lack rigorous control-group comparisons, making it difficult to attribute the observed benefits solely to exoskeleton use. Moreover, there is a lack of detailed analysis of worker feedback, acceptance, comfort, and usability of exoskeletons in the literature [20].

This systematic review was conducted to address the following questions: (1) What methodologies have been used to evaluate the effectiveness of exoskeletons in industrial environments? (2) How does the variation in the evaluation methods influence the results and generalization of studies on the effectiveness of exoskeletons? (3) What are the impacts, benefits, and criticalities of exoskeletons in an industrial context? In particular, this review will guide researchers in adopting robust frameworks for effective exoskeleton implementation in industrial environments.

2. Methods

2.1. Protocol and Registration

This study was conducted and reported according to the general guidelines recommended by the Primary Reporting Items for Systematic Reviews and Meta-Analyses statement (Appendix A) [21] was registered in the PROSPERO database (registration number: CRD42024562309).

2.2. Eligibility Criteria

This systematic review included randomized and nonrandomized trials that met the following criteria: (i) articles in English published by 2023 and (ii) samples involving healthy participants; (iii) studies with a control group (no exoskeleton); (iv) studies that analyzed physiological outcomes (e.g., muscle activity, heart rate, and muscle oxygen variation) and comfort measures; and (v) studies available in full text. Articles in which experiments did not occur in a lab or field, or comprised the development of a new exoskeleton, were eliminated from the analysis. Conference proceedings, opinions, review articles, and book chapters were excluded from the analysis.

2.3. Search Strategy

A literature search was carried out using frequently used search engines (PubMed, Web of Science, Scopus, and ScienceDirect). The following keywords and Boolean operators were used to search on databases: (exoskeleton AND industr*) OR ("wearable device" AND industr*) OR (exoskeleton AND industr* AND effects) OR ("wearable device" AND industr* AND effects) OR ("wearable device" AND industr* AND (muscle activity OR EMG OR oximetry) OR (exoskeleton AND industr* AND (muscle activity OR EMG OR oximetry). Articles published between March 1 and June 30, 2023, were searched. The identified citations were stored in the EndNote® X21 bibliographic database (Thomson Reuters, New York, NY, USA). All the results of the abstract and full-text review were recorded in the EndNote database. PDF files of all full-text articles were stored on a server accessible to all review team members.

2.4. Selection Strategy and Data Collection

After removing duplicates, the titles and abstracts were screened by two independent reviewers (B.A. and F.P.) and classified as either excluded or potentially included. After a full reading of the selected articles, the reviewers applied the inclusion and exclusion criteria. Any disagreements between the two reviewers were resolved by discussion until a consensus was reached, and when necessary, a third reviewer was consulted.

2.5. Data Extraction

For each article included, the following information was obtained:

- Authors
- Participants
- Exoskeleton type (passive, active, or hybrid)
- Supported body part (lower, upper, or whole-body)
- Activity sector (automobile, manufacturing, agriculture, or other)
- Modelling task (squatting, kneeling, stoop, standing/sitting, pushing/pulling, twisting, or other)
- Methods
- Main outcomes
- Main findings

2.6. Risk of bias and quality assessment

To assess the quality of the studies and detect biases, two reviewers (A.T. and B.A.) independently applied the Johanna Briggs Institute (JBI) scale [22] for each type of study. These techniques provide a systematic framework for assessing the potential sources of bias-inducing factors and the methodological integrity of various study designs. Each tool consists of ten (Case Series) (Table 1) [23], eight (Cross-Sectional Studies) (Table 2) [22], nine (Quasi-Experimental Studies) (Table 3) [24], or 13 (Randomized Controlled Trials) (Table 4) [24], and different questions that assess the methodological quality of each study. After evaluating each criterion, the reviewers assigned a score of "Yes," "No," "Unclear" or "Not applicable" to each. According to the above, studies were considered as "low-quality evidence" (≤49% of the items were met), "medium-quality evidence" (50–74% of the items were met), and "high-quality evidence" (≥75% of the items were met). It should be noted that the responses "not applicable" and "unclear" were excluded from the evaluation, as they do not contribute to the quality of evidence [25]. Quality evaluation was expressed as a percentage frequency of items (yes rating) for each checklist and quality assessment plots were produced using risk-of-bias visualization 'robvis' [26]. The quality score was not used to exclude low-quality studies from the review but to inform the reader about the quality of the included studies.

Table 1. Risk of bias analysis for case series studies.

Study	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
Pacifico et al. [39]	+	+	+	X	X	+	-	-	-	+

D1: Were there clear criteria for inclusion in the case series? D2: Was the condition measured in a standard, reliable way for all participants included in the case series? D3: Were valid methods used for identification of the condition for all participants included in the case series? D4: Did the case series have consecutive inclusion of participants? D5: Did the case series have complete inclusion of participants? D6: Was there clear reporting of the demographics of the participants included in the study? D7: Was there clear reporting of clinical information of the participants? D8: Were the outcomes or follow-up results of cases clearly reported? D9: Was there clear reporting of the presenting sites'/clinics' demographic information? D10: Was statistical analysis appropriate?

Table 2. Risk of bias analysis for cross-sectional studies.

Study	D1	D2	D3	D4	D5	D6	D7	D8
Omoniyi et al. [33]	+	X	+	-	X	X	X	+

D1: Were the criteria for inclusion in the sample clearly defined? D2: Were the study subjects and the setting described in detail? D3: Was the exposure measured in a valid and reliable way? D4: Were objective, standard criteria used for measurement of the condition? D5: Were confounding factors identified? D6: Were strategies to deal with confounding factors stated? D7: Were the outcomes measured in a valid and reliable way? D8: Was appropriate statistical analysis used?

2.7. Statistical Analyses

Cohen's d and the effect sizes for both the experimental group (with exoskeleton) and the control group (without exoskeleton) [27] were categorized according to Cohen's d classification, [27], [28]: trivial (Cohen's d ≤.2), small (>.2), moderate (>.5), big (>.8), and very large (>1.3). Three studies did not report sufficient information to calculate the effect sizes.

3. Results

3.1. Study Selection

A total of 1305 potentially relevant articles were extracted from the database search, and 373 articles were discarded because of duplication. A total of 853 articles were removed after scanning titles (712 articles) and abstracts (140 articles). The remaining 79 full-text articles were examined in detail, and 51 articles that did not meet the inclusion criteria were excluded. Finally, 28 articles that fulfilled the inclusion criteria were included in this systematic review. Through a citation search, four additional articles met the inclusion criteria and were included in this systematic review (Figure 1). An overview of the 32 articles included in this systematic review is shown in Appendix B, organized according to the type of exoskeleton, activity sector, modeling tasks, methods and outcomes, and findings

Table 3. Risk of bias analysis for non-randomized studies.

Study	D1	D2	D3	D4	D5	D6	D7	D8	D9
Iranzo et al. [2]	+	+	X	+	+	-	+	+	+
Gonsalves et al. [8]	+	+	+	+	X	-	+	+	+
Bosch et al. [9]	+	+	+	+	X	-	+	+	+
Linnerberg et al. [14]	+	+	+	+	-	-	+	+	+
Bridger et al. [17]	+	+	+	+	X	-	+	+	+
Jorgensen et al. [29]	+	+	+	+	-	-	+	+	+
Sylla et al. [30]	+	+	+	+	X	-	+	+	-
Spada et al. [31]	+	+	+	+	+	+	+	+	-
Qu et al. [32]	+	+	+	+	X	-	+	+	+
Hensel & Keil. [34]	+	+	+	+	-	+	+	+	+
Marino [35]	+	+	X	+	X	-	+	+	-
Smets [38]	+	+	+	+	+	+	+	+	X
Luger et al. [41]	+	+	+	+	-	X	+	+	+
Kim et al. [47]	+	+	+	+	X	-	+	+	+

D1: Is it clear in the study what is the 'cause' and what is the 'effect' (i.e. there is High confusion about which variable comes first)? D2: Were the participants included in any comparisons similar? D3: Were the participants included in any comparisons receiving similar treatment/care, other than the exposure or intervention of interest? D4: Was there a control group? D5: Were there multiple measurements of the outcome both pre and post the intervention/exposure? D6: Was folLow up complete and if Hight, were differences between groups in terms of their folLow up adequately described and analyzed? D7: Were the outcomes of participants included in any comparisons measured in the same way? D8: Were outcomes measured in a reliable way? D9: Was appropriate statistical analysis used?

Table 4. Risk of bias analysis for randomized studies.

Study	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13
Van der Have et al. [4]	+	X	+	X	X	X	+	-	+	+	+	+	X
Pinho & Forner-Cordero [7]	+	-	+	X	X	-	+	+	+	+	+	+	+
Huysamen et al. [10]	+	-	-	X	X	-	+	+	+	+	+	X	-
Luger et al. 2019 [12]	+	-	-	X	X	-	+	+	+	+	+	+	-
Schmalz et al. [13]	+	X	-	X	X	-	+	-	+	+	+	+	X
Yin et al. [18]	-	-	-	X	X	-	+	-	+	+	+	+	-
Luger et al. [20]	+	-	-	X	X	-	+	-	+	+	+	+	-
Giustetto et al. [36]	-	-	+	X	X	-	+	-	+	+	+	+	-
Bock et al. [37]	+	-	+	X	X	-	-	-	+	+	+	+	+
Bock et al. [40]	+	+	+	X	X	-	+	-	+	+	+	+	+
Luger et al. [41]	+	-	+	X	X	-	+	+	+	+	+	+	+
Vries et al. [42]	X	-	-	X	X	-	-	-	+	+	+	+	-
Pillai et al. [44]	X	-	-	X	X	-	+	+	+	+	+	X	-
Bär et al. [45]	+	-	+	X	X	-	+	-	X	+	-	+	+
Bock et al. [46]	+	-	+	X	X	-	+	+	+	+	+	+	+
Weston et al. [48]	+	X	+	X	X	X	+	-	+	+	+	+	+
Kong et al. [49]	-	-	-	X	X	-	+	-	+	+	+	+	+

D1: Was true randomization used for assignment of participants to treatment groups? D2: Was allocation to treatment groups concealed? D3: Were treatment groups similar at the baseline? D4: Were participants blind to treatment assignment? D5: Were those delivering treatment blind to treatment assignment? D6: Were outcomes assessors blind to treatment assignment? D7: Were treatment groups treated identically other than the intervention of interest? D8: Was follow up complete and if not, were differences between groups in terms of their follow up adequately described and analyzed? D9: Were participants analyzed in the groups to which they were randomized? D10: Were outcomes measured in the same way for treatment groups? D11: Were outcomes measured in a reliable way? D12: Was appropriate statistical analysis used? D13: Was the trial design appropriate, and any deviations from the standard RCT design (individual randomization, parallel groups) accounted for in the conduct and analysis of the trial?

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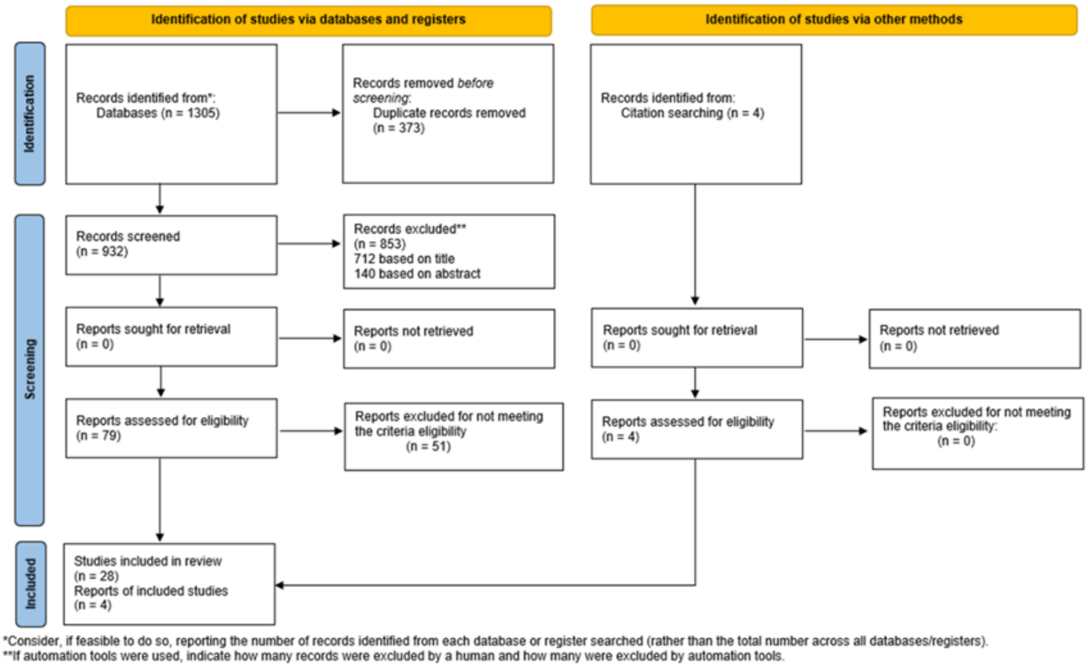


Fig. 1. Flow diagram of the literature according to PRISMA guidelines.

3.2. Participants

Participants in the studies included in this systematic review exhibited a wide range of characteristics. The number of participants varied between four and 46, with a predominance of men in many studies. The average age of the participants ranged from 21.9 years to 45.7 years. The average weight values varied from 63.00 kg to 87.25 kg, while the average height of the participants ranged between 1.68 m and 1.83 m. The average body mass index (BMI) of the participants ranged from 21.80 kg/m² to 29.49 kg/m², indicating a diverse sample in terms of body composition. Many studies did not report the sex distribution of participants or did not provide values for all variables, which limits a more detailed analysis of these characteristics.

3.3. Exoskeleton

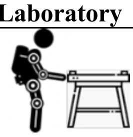
Information on the brand, type, and body parts supported by the exoskeleton was retrieved from the articles. SuitX and Laevo were the most evaluated brands, with 12 studies evaluating Laevo exoskeletons and 10 evaluating SuitX; the remaining articles assessed other brands. Some studies have compared the use of different exoskeletons [14], [29]. Passive exoskeletons were the most commonly used type of exoskeleton in the studies (n=30). Of the 32 articles included, four investigated the use of exoskeletons in the lower body. Most studies have used a passive exoskeleton, except for those by [30] and [10]. The lower cost of passive exoskeletons compared to active ones and their simplicity, which allows workers to remain autonomous, justify why the passive type is the most commercialized [31]. Upper passive exoskeletons (Figure 2a) were the most frequently used and appeared in 28 studies, while lower passive exoskeletons (Figure 2b) were present in four studies, and upper active exoskeletons (Figure 2c) were found in two studies.

Figure 2. a) Upper passive exoskeleton IPAE [32], **b)** Lower passive exoskeleton Chairless Chair [12], **c)** Upper active exoskeleton [10].

3.4. Testing environment

Predominantly, the studies were carried out under closed lab conditions; only eight were conducted in the field (Table 5). Studies carried out in the laboratory simulated the field environment and tasks that are common in that environment; most of these studies simulated an automotive industry environment. In the lab, the environment is controlled, and participants, who can or cannot be workers, simulate industry tasks; therefore, the effects obtained can be very different when compared to effects in the workplace.

Table 5. Testing environment

Field	Laboratory
	
Omoniyi et al. [33]; Sylla et al. [30]; Iranzo et al. [2]; Hensel & Keil [34]; Marino [35]; Giustetto et al. [36]; Bock et al. [37]; Smets [38]; Pacifico et al. [39]*	Linnenberg & Weidner [14]; Van der Have et al. [4]; Bock et al. [40]; Bosch et al. [9]; Jorgensen et al. [29]; Bridger et al. [17]; Huysamen et al. [10]; Luger et al. [41]; Vries et al. [42]; Luger et al. [20]; Luger et al. [12]; Luger et al. [43]; Pillai et al. [44]; Pinho & Forner-Cordero [7]; Bär et al. [45]; Bock et al. [46]; Kim et al. [47]; Gonsalves et al. [8]; Schmalz et al. [13]; Yin et al. [18]; Weston et al. [48]; Kong et al. [49]; Ziaei et al. [19]; Pacifico et al. [39]*

* Study conducted in the two environments.

3.5. Modelling tasks

The studies included in this review examined a wide range of tasks involving exoskeletons. These tasks ranged from static activities, such as maintaining elevated arm positions, assembly tasks, and holding a 45-degree trunk flexion, to dynamic tasks, such as repetitive load handling, stair climbing, and lift-and-carry tests. Agricultural tasks include egg collection, digging, bale lifting, grinding, machine maintenance, wood cutting, and fence repair. Automotive industry tasks such as bolt tightening, sealant application, assembly and logistics tasks, and rebar tasks. Overall, exoskeletons generally had a positive impact on reducing muscle fatigue, improving ergonomics, and reducing the risk of work-related musculoskeletal disorders across various tasks (Table 6). However, the effectiveness can vary depending on the specific task, the proper fit of the exoskeleton (type and body support), and the conditions of use, with some studies indicating non-significant or inconsistent benefits.

Table 6. Associations of type of tasks and exoskeleton use.

	⊕	⊖	±
Manual lifting and moving	Bock et al. [40]; Van der Have et al. [4]; Huysamen et al. [10]	Linnenberg & Weidner [14]	Bridger et al. [17]; Qu et al. [32]; Omoniyi et al. [33]; Bock et al. [37]
Dynamic work	Luger et al. [41]		Bock et al. [46]
Assembly and Handling of Components	Sylla et al. [30]; Luger et al. [20]; Kim et al. [47]; Schmalz et al. [13]; Pacifico et al. [39]	Bosch et al. [9]	

Static posture	Vries et al. [42]; Giustetto et al. [36]		Hensel & Keil [34]
General industrial work	Jorgensen et al. [29]; Yin et al. [18]; Kong et al. [49]		Bock et al. [46]; Weston et al. [48]
Material Handling			Luger et al. [20]
Tasks specific to the automotive industry	Pinho & Forner-Cordero [7]; Luger et al. [20]; Smets [38]; Pillai et al. [44]		Iranzo et al. [2]; Marino [35]; Gonsalves et al. [8]

⊕ - positive associations; ⊖ - no significant associations; ± - inconsistent associations

3.6. Methodologies applied

Studies assessing the impact of exoskeletons have measured a wide range of kinematic, physiological, and psychological outcomes (Table 7). For kinematic outcomes, four studies [2], [13], [30], [40] measured joint angles, such as those of the shoulder, elbow, and knee, to understand how exoskeletons influence the posture and range of motion during tasks. Additionally, other authors [40], [41], [44] evaluated changes in the overall body posture when using the exoskeleton, including trunk flexion/extension. Luger et al. [12] also measured accelerations to assess the impact of exoskeletons on dynamic movements and task performance and further explored how these devices affect balance and stability during tasks. In terms of physiological responses, electromyography (EMG) has been used extensively in 24 studies to quantify changes in muscle activation patterns and fatigue. Some studies (n=5) assessed heart rate to measure the physiological effort and fatigue associated with wearing the device. Other studies, such as those by Qu et al.[32], have measured oxygen consumption to assess the metabolic cost of performing tasks with exoskeletons. Jorgensen et al. [29] and Kong et al. [49] analyzed changes in maximum voluntary muscle contractions to assess the impact of the exoskeleton on strength. Regarding psychological outcomes, subjective evaluations of comfort, discomfort, and pressure at the human exoskeleton interface were performed (n=16). The perceived usability, ease of use, and user acceptance of exoskeletons have also been assessed in various studies, [10], [33], [40], [46]. Bock et al. [37] examined how exoskeletons influenced the perceived difficulty and demands of performing tasks. These outcomes show the importance of not only evaluating biomechanical, physiological and kinematic results, but also considering user experience, such as comfort, usability, and psychological acceptance. Understanding and analyzing these insights are vital for developing more ergonomic and accessible designs that correspond to user's needs and preferences.

Table 7. Outcomes evaluated.

Outcomes		
Kinematics	**Physiological**	**Psychological**
Accelerations (n=1) Angle joints (n=4) Body posture (n=3) Dynamic pressure (n=1) Ground reaction forces (n=1) Duration of movements (n=1) Mass distribution (n=1) Task duration (n=1)	Muscle activity (n=24) Heart rate (n=5) Oxygen rate (n=2) Tissue saturation index (n=1) Maximal contraction (n=2) Effort (n=3) Endurance (n=1)	Comfort (n=16) Local perceived pressure (n=2) Usability (n=1) Conflicting task demands (n=1)

3.7. Impact and Significance: Effect size and Cohen's d

The analysis of the 32 articles included in this systematic review revealed a wide range of outcomes distributed in different categories and reviewed according to the value of effect size and Cohen's d, as summarized in Appendix C. The calculations were performed for two groups: Group A (control group) and Group B (experimental group that used the exoskeleton). To measure the standardized effect size, Cohen's d was employed, which involved dividing the mean difference by the standard deviation. However, in certain cases, it was not feasible to calculate the effect size, owing to the unavailability of data. The use of an exoskeleton was proven to have a significant influence on the results. Many studies have reported a reduction in muscle activity and discomfort associated with the use of exoskeletons. A study by Luger et al. [41] showed that the use of the exoskeleton reduced muscle activity in the erector spinae and gastrocnemius medialis during the pallet box lifting task, resulting in a positive impact on the heart rate during this specific task (Cohen's d = 0.009, effect size r = 0.005). The positive impact of the use of exoskeleton on muscle activity also occurred in the work of Bär et al. [45] in erector spinae, biceps femoris, rectus abdominis, and vastus lateralis during a bent static trunk posture task (Cohen's d varies from 0.06 to 0.56, and effect size r varies from 0.03 to 0.27).

In addition, exoskeletons have a positive influence on perceived discomfort in specific tasks. Yin et al. [18] showed that the exoskeleton reduced neck, shoulder, upper arm, forearm, and leg discomfort. These results were also presented by Qu et al. [32], who used three exoskeletons and reported a positive impact on discomfort (Cohen's d varied from -2 to 5.14, and effect size r varied from -0.7 to 0.93). In summary, our findings indicate that the use of exoskeletons can significantly impact participants, corroborating their effectiveness as a support tool for intensive physical activities. These findings highlight the potential of these devices as effective tools for reducing muscle activity, heart rate, and discomfort in different tasks, which can lead to significant improvements in the health and well-being of workers.

4. Discussion

The purpose of this study was to conduct a systematic review of methodological approaches concerning the use of exoskeletons in the industry. This study aimed to analyze and synthesize the different methodologies employed in research related to evaluating the effects on the health and well-being of exoskeletons used in industrial settings. This includes an examination of data collection methods, experimental protocols, and analysis techniques. By exploring these methodological approaches, this study seeks to provide insights into best practices and offers recommendations for future research in this area.

4.1. Participants
The present review also revealed that most participants in exoskeleton research were men, which was justified by the prevalence of male workers in the industry. This could justify the lower representation of female participants in the experiments, even though musculoskeletal disorders are more prevalent in women than in men [1]. The underrepresentation of female participants will affect the generalizability of the results because there are differences in body composition, muscle strength, and biomechanical responses between men and women, which may influence the impact of exoskeletons. In addition to the gender imbalance, some studies pointed out sample size as a limitation, which restricts the statistical power and external validity of the findings [34]. Larger sample sizes are necessary to ensure that the results are not only significant but also applicable to a wider population.

4.2. Exoskeleton
In terms of exoskeleton type, passive upper exoskeletons are most commonly used in industry. Their weight and cost are much lower than those of active exoskeletons, owing to the absence of an external power source. The function of passive upper exoskeletons is much simpler, allowing the user to equip this device on their own; the human/robot interface is repetitive and intuitive. The passive exoskeleton is the most mature, developed, and replicated exoskeleton, making it the most commercialized exoskeleton. Hensel & Keil [34] analyzed a passive upper exoskeleton in the field (AUDI factory), and the results revealed that physical discomfort decreased in the lumbar region but increased in the chest owing to the presence of straps. Thus, usability was high in the beginning but reduced over time as a direct consequence of chest discomfort. Luger et al. [20] analyzed a passive lower exoskeleton (Chairless Chair) under laboratory conditions. The mechanical load on the legs decreased, but discomfort increased over time; however, this is not a conclusion that can be extrapolated because this type of exoskeleton is one of the least studied. In industry, the whole-body exoskeleton is not well studied, as it is more common in rehabilitation and military uses, and costs are higher than those for other exoskeleton types.

4.3. Testing environment
Another aspect to consider when choosing the type of exoskeleton is the type of task that is performed because the wrong choice of exoskeleton can lead to results that can be misinterpreted.

In the workplace, the tasks performed by participants are the same as they do every day; therefore, the exoskeleton can help them improve their performance and demonstrate a positive effect. For the use of exoskeletons in industry to increase and be successful, more experiments in the actual workplace need to be conducted [20]. The objective of field tests is to establish the practicality of interventions and understand the extended exposure to risk factors and longer follow-up intervals [1]. There are more studies in the lab than in the field, and those who use exoskeletons in the field are recommended to perform a lab session before the lab tests help validate the exoskeleton use, understand the biomechanical effects on users' physical effort, and understand the assistance provided by this device [39]. For any type of test, it is necessary to understand any undesired effects that the user may feel while performing the tasks [50]. For field studies carried out in the workplace, participants perform their routine tasks, allowing the exoskeleton's impact on performance to be accurately observed, whether the results are positive or highlight potential challenges in its use.

Giustetto et al. [36] carried out lab experiments that lasted around 90 minutes; the participants felt reduced discomfort in the lumbar region. In a study conducted by Hensel & Keil [34], the experiment lasted four weeks in an automotive factory, during which participants had time to adjust to the exoskeleton and spent an entire shift using the exoskeleton. With a longer period of using the exoskeleton, opinions diverged: participants' discomfort in the chest increased over time due to the device straps, and consequently, user acceptance decreased over time. Comparing the results obtained, we can conclude that the discomfort associated with wearing an exoskeleton depends on the duration of the experiment.

4.4. Duration
Analyzing exoskeleton use over longer periods is missing from the literature [7]. Factors such as acceptance, discomfort, and usability can differ when the exoskeleton is used in one session of a few hours or over a few days [34]. It seems that rehearsal duration directly influences the exoskeleton effect on the participants, especially on discomfort and acceptance of use.

4.5. Modelling tasks
According to the modeling tasks, exoskeletons generally demonstrated a positive impact. For static tasks, such as maintaining posture and in certain industrial settings, positive associations were more consistent. In automotive assembly lines, exoskeletons are used for workers who perform overhead tasks, such as installing components, where maintaining a static posture during periods of time is crucial. In a similar manner, in construction, exoskeleton is used for workers that must hold tools during extended periods. However, tasks requiring repetitive movements or higher mobility, such as dynamic work or component assembly, showed mixed results, although positive outcomes remained prevalent. These findings suggest that while exoskeletons have significant potential for enhancing workplace ergonomics, their efficacy is task dependent. For instance, Huysamen et al. [10] observed a positive impact of exoskeletons on manual lifting and moving, while Linnenberg & Weidner [14] reported a negative impact on similar tasks.

4.6. Methodologies applied
Kinematic evaluations, such as joint angles and body posture, were used to analyze the influence of exoskeletons on movement and stability during tasks. Some studies have also measured accelerations to assess dynamic performance. Physiological outcomes, including muscle activity through electromyography, heart rate, and oxygen consumption, provide insights into how exoskeletons affect muscle activation patterns, fatigue, and metabolic cost. Additionally, psychological assessments, such as comfort, usability, and task demands, have revealed the importance of user experience in determining the acceptability and effectiveness of exoskeletons. Studies combining these outcome measures, such as those by Bock et al. [40] and Bridger et al. [17], which evaluated kinematic, physiological, and psychological outcomes, provide a more comprehensive understanding of how exoskeletons perform. These evaluations not only assess their ability to reduce physical fatigue, but also ensure that they are comfortable and practical for users in diverse

work environments. Such integrative methodology highlights the importance of balance biomechanical gains with user design principles, allowing exoskeletons to be functional and ergonomic.

4.7. Impact and Significance: Effect size and Cohen's d

The study outcomes allowed us to combine all studies in a single analysis. This increased the statistical power of the analysis and enabled us to understand the combined effect of exoskeletons against a control group (without an exoskeleton). When comparing the control and experimental groups, there was a significant positive tendency in the diverse range of outcomes of the experimental group, illustrating the effectiveness of exoskeleton use. This can lead to decreased fatigue, a lower risk of injury, and greater efficiency in task performance. Negative trends in outcomes can be caused by movement restrictions provoked by the exoskeleton, interface with the user's natural biomechanics, or discomfort caused by the device.

The data presented in Appendix C from studies on exoskeletons and their relationships with different outcomes revealed varied tendencies. In the investigation by Luger et al. [20], the mass distribution of the high seat and mass distribution of the low seat were positive, which indicates that the use of an exoskeleton can improve efficiency and precision in certain tasks, reducing physical workload and the risk of injury. However, in another study [29], the maximum voluntary contraction (MVC) standing vertically highlighted negative results, pointing to a possible reduction in the efficiency and precision of tasks performed with the assistance device, as well as an increase in discomfort and muscle fatigue. While there is clear potential for benefits in terms of reducing physical load and preventing musculoskeletal disorders, there are some challenges related to adaptation, comfort, and efficiency. The variation in the results suggests a need for further research to optimize the design and application of exoskeletons in different work contexts.

To understand the effects of exoskeletons, it is necessary to analyze multiple outcomes including kinematics, physiology, and psychology. This demonstrates the importance of a comprehensive approach based on different aspects of human performance. The outcomes of exoskeleton use are influenced by several factors. These factors can be described by the task performed, the duration of exoskeleton use, individual user characteristics, and exoskeleton design. Additionally, psychological factors can influence positive outcomes such as comfort, usability, and perceived pressure. A lack of methodological standardization, heterogeneity of samples, duration of exoskeleton use, and user adaptation highlights the need for additional research and a critical perspective in interpreting the results.

5. Challenges and Opportunities

The main limitation of this systematic review was the lack of field experiments. Most studies focused on passive upper exoskeletons, taking place under laboratory conditions, with a small sample of healthy participants, predominantly male, and a short duration. Although laboratory studies provide significant advantages, such as greater control over variables and the ability to isolate the effects of exoskeletons use, we acknowledge that these controlled settings do not fully capture the complexities and challenges encountered in real-world industrial environments. These studies are essential not only for assessing efficacy but also for addressing practical considerations, such as worker acceptance, task compatibility, and long-term impacts. This approach is critical for filling the gap between laboratory findings and the dynamic demands of industrial applications. Our review reflects the literature currently available, which shows a predominance of studies carried out with male participants. This may well be related to the very composition of many industrial sectors in which these devices are tested. This gap represents an important bias in literature, which we highlight in our work as a limitation and an area of considerable need for future research. Recognizing that there is a high prevalence of musculoskeletal injuries in women [51], the inclusion of women in the influence of the exoskeleton in an industrial context becomes more justified. Since most studies involve short-duration evaluation, some effects related to long-term use are not estimated such as user adaptation, and device wearability. Such gaps show the need for long-term experiments to provide a more comprehensive understanding of the impacts over time. To prevent work-related musculoskeletal disorders, future studies should involve larger sample sizes and longer durations to better simulate real work conditions and to understand the long-term effects of exoskeleton use. Another limitation was that not all studies had sufficient exoskeleton familiarization time; therefore, the participants could still have adapted to the new device. Additionally, it seems important to address the challenges faced by workers in accepting and adapting exoskeletons, especially in ergonomics and the human-machine interface; however, not all studies have addressed these challenges. This aspect is essential for improving the design and usability of exoskeletons, warranting their acceptance and effectiveness [52]. Understanding ergonomic design issues is crucial to improving the practicality of these wearable devices and their adoption in various applications. One possible improvement is the incorporation of adjustable straps that allow better adaptation to the user's body shape and size [53]. Additionally, the use of filling materials, such as gel-based cushions, could help reduce user's discomfort.

Based on the findings of this systematic review, it seems that a consistent methodology needs to be widespread, so exoskeletons can be evaluated optimally and promptly. Protocols need to be established considering all the factors that can positively or negatively influence the use of exoskeletons covering tasks, participants, duration, environment, and evaluation. As exoskeleton use becomes more established, it can be integrated with other technologies such as artificial intelligence and robotics, leading to a more efficient and advanced system to prevent work-related musculoskeletal disorders [54]. However, it is important to consider the challenges, ethics, and safeguards of such advanced applications. Future studies should include female participants, non-healthy participants, active and passive lower exoskeletons, long-term rehearsals, and field experiments. Most studies included in this systematic review focused on passive exoskeletons, with limited exploration of active and hybrid models. Passive exoskeletons are more cost-effective, lightweight and simpler to implement, making them ideal for different applications. However, active exoskeletons have the potential to operate more complex and dynamic tasks providing additional assistance and adaptability to user's movements. Future research should accentuate the development and testing of active exoskeletons to understand their efficiency, viability, and safety. Integrating different types of exoskeletons with smart technologies, such as artificial intelligence and real-time systems, could ensure a more personalized and effective support for user [55]. These integrated systems offer robust and reliable solutions that improve dynamic adaptation to individual user needs and learn from input experiences [55]. Additionally, collaborative efforts between researchers and engineers are crucial to advance these technologies, enabling the development of exoskeletons that can be used in rehabilitation and workplaces, ultimately improving quality of life.

The real-world impact of exoskeletons on work-related musculoskeletal disorders remains unknown. Thus, it is important to prioritize this matter and anticipate the influence of this device on the health, productivity, and safety of workers. Finally, collaboration between relevant professionals is fundamental for understanding the challenges and opportunities of exoskeletons in the workplace. These devices present multiple complexities that require the contribution of professionals from different areas such as engineering, ergonomics, and occupational health and safety. Moreover, it is necessary to contemplate collaboration between companies, researchers, and professionals. This will facilitate the development of more effective solutions adapted to the specific needs of workers and industries.

6. Conclusion

Our study showed that the use of an exoskeleton provided positive outcomes, showing improvements in physiological measures, such as reduced muscle activity and heart rate, as well as enhanced comfort. This systematic review identified 32 articles to understand the different approaches used in studying exoskeletons in industrial applications. This allowed the identification of insufficient evidence on the impact exoskeletons bring to industry workers due to several factors: (i) a lack of field experiments to allow understanding of the benefits of exoskeletons, and also the main cause for only a few companies adopting exoskeleton use; and (ii) a small sample size of healthy male participants, of short duration and with a passive upper exoskeleton. These factors limit the interpretation of results, as it is relevant to analyze different conditions to understand the real-world impact of exoskeleton use. In addition, this study identified a wide variety of methodological approaches employed in industrial exoskeleton research. This indicates that researchers have adopted different strategies to investigate the topic, which adds to a more diverse but sometimes conflicting knowledge base. In the future, it is important to generalize the methodological approaches in the research of exoskeletons to increase the knowledge of these devices and adapt them more easily to industry. Involving companies in the process of validating exoskeleton is also an important step, making workers feel comfortable and safe with this equipment. The use of exoskeletons in the industry is a promising area that allows workers to increase their safety and well-being by preventing work-related musculoskeletal disorders.

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Appendix A – PRISMA 2009 Checklist.

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	1
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	1,2
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	1,2,3
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	4
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	4
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	4
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	4
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	4,5
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	5
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	5
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	5
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	5,6,7
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	N/A
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	N/A
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	N/A
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	N/A
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	N/A
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	N/A
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	5,6,7
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	7
RESULTS			

Section and Topic	Item #	Checklist item	Location where item is reported
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	7,8
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	N/A
Study characteristics	17	Cite each included study and present its characteristics.	26-35
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	6,7
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	7-12
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	N/A
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	N/A
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	N/A
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	N/A
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	N/A
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	N/A
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	12-16
	23b	Discuss any limitations of the evidence included in the review.	16,17
	23c	Discuss any limitations of the review processes used.	16,17
	23d	Discuss implications of the results for practice, policy, and future research.	16,17
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	4
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	4
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	4
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	19
Competing interests	26	Declare any competing interests of review authors.	N/A
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	N/A

For more information, visit: **http://prisma-statement.org/**

Appendix B - Summary of the information from the 32 articles analyzed.

Author	Participants	Exoskeleton	Activity sector	Modelling task	Methods and outcomes	Findings
Linnenberg & Weidner [14]	n= 20 (14 ♂; 6 ♀) age: 37.0±10.1 yr height: 1.76±0.08 m weight: 79.9±17.8 kg BMI: 25.3±4.1 kg/m^2	**Type:** Passive and Active **Supported body part:** Upper body **Model:** Mate EXO; Lucy EXO; Paexo Shoulder EXO; Skelex 360 EXO	Industrial	Overhead tasks	Instruments: Pneumatic pressure sensor Outcomes: Time to termination of the quantitative Roos test Pressure within the human-machine interface of the arm	· Overhead EXOs with circumferential arm interfaces impair neurovascular supply, causing earlier neuronal and vascular symptoms. Pressure within interfaces varied widely, exceeding safe thresholds and risking harm with long
Van der Have et al. [4]	n= 16 (8 ♂; 8 ♀) age: 21.9±0.99 yr BMI: 22.5±2.3 kg/m^2	**Type:** Passive **Supported body part:** Upper body **Model:** Exo4work	NR	Lifting and overhead tasks	Instruments: Motion capture Ground reaction forces EMG OpenSim software Outcomes: Musculoskeletal load Muscle activity and fatigue	**(↓)** Muscle activity in trapezius, deltoid, and biceps muscles **(↓)** Musculoskeletal loading in the shoulder and elbow during tasks above shoulder height **(↑)** Musculoskeletal loading in the shoulder and knee during lower-level lifting tasks.
Bock et al. [46]	n= 22 healthy ♂ age: 23.7±0.5 yr height: 181.6±1.4 cm weight: 75.9±1.8 kg	**Type:** Passive **Supported body part:** Upper body **Model:** Exo4work	NR	Wiring, drilling, repeated high lifting, repeated low lifting, walking	Instruments: EMG 3D accelerometers Cosmed K5 Outcomes: Muscle activity HR Respiratory data	**(↓)** Muscle activity in trapezius, deltoid, and biceps **(=)** Drilling and force precision **(↓)** Joint load in the shoulder, arm, and lower back
Omoniyi et al. [33]	n= 16 (15 ♂; 1 ♀) age: 25–70 yr	**Type:** Passive **Supported body part:** Upper body **Model:** Laevo V2.5	Agriculture	Farming tasks (collecting eggs, shoveling, lifting bales, grinding work, machine maintenance, and cutting of wood and repairing fences) (agriculture), static and dynamic tasks	Instruments: Interviews Outcomes: Performance on standardized lifting and bending tasks Performance on regular farm tasks involving lifting, stooping, or squatting	· Participants expressed that movements with an EXO are not always consistent with their normal movements making them perceive the work task as more difficult · Successful implementation of EXOs on farms will require aligning the EXO design, the users, and the tasks being performed.

Sylla et al. [30]	n= 8 ♂ age: 24±7 yr height: 1.70 m±5 cm weight: 63±11 kg	**Type:** Active **Supported body part:** Upper body **Model:** ABLE	Automotive industry	Screwing task	Instruments: Vicon motion capture Force plates Outcomes: Foot/floor contact forces Joint angles and torques Task duration	**(↓)** The sum of joint torques (38.9%) during tasks **(?)** Effect on ground reaction forces
Bosch et al. [9]	n= 18 (9 ♂; 9 ♀) age: 25±8 yr height: 1.76±0.1 m weight: 71±12.4 kg	**Type:** Passive **Supported body part:** Upper body **Model:** Laevo	NR	Simulated assembly and static holding tasks	Instruments: EMG Outcomes: Muscle activity Perceived local discomfort Endurance time	**(↓)** Muscle activity (by 35-38%) in the lower back, upper back, and leg muscles, and lower discomfort in the lower back in assembly tasks **(↓)** Hip extensor activity **(↑)** Discomfort in the chest region **(↑)** Endurance time from 3.2 to 9.7 minutes in the static holding task
Jorgensen et al. [29]	n= 16 (8 ♂; 8 ♀) Men ♂ age: 44.3±11 yr heigh: 181.2±5.1 cm weight:104.8±14.8 kg aircraft manufacturing experience: 18.0±7.2 yr Women ♀ age: 47.0±11.4 yr height: 162.4±5.7 cm weight: 69.7±13.6 kg aircraft manufacturing experience: 19.3±11.4 yr	**Type:** Passive **Supported body part:** Upper body **Model:** EVO; Skelex 360XFR; Paexo	Aircraft industry	Sealant smoothing tasks	Instruments: EMG Outcomes: Percent of maximum voluntary contraction (%MVC) Muscle activity	**(↓)** Muscle activity shoulder agonist muscles in the various sealing tasks standing and seated **(?)** Participants didn't show consensus about the benefits of using EXO for sealing task
Bridger et al. [17]	n= 12 UK Royal Marines age: 29±6 yr height: 179±4.3 cm weight: 83±7 kg	**Type:** Passive **Supported body part:** Lower body **Model:** Chairless Chair	NR	Squat and standing posture	Instruments: Sustained Attention to Response Test (SART) Task Load Index Self-control scale HR monitors (Polar S810™) Outcomes: Postural control Reaction time TLX scale Self-control demands Sustained attention Perceived workload	**(?)** The exoskeleton did not mitigate the negative impact of the squatted posture on SART performance · Mitigate the increase of heart rate observed with squatting **(↓)** task demands perceived by participants

					HR	
Iranzo et al. [2]	n= 12 automotive workers (11 ♂; 1 ♀) age: 35±5 yr height: 175.2±5.3 cm weight: 73.9±4.9 kg	**Type:** Passive **Supported body part:** Upper body **Model:** Levitate **AIRFRAME™**	Automotive industry	Tasks of an automotive assembly line	Instruments: EMG Motion capture using inertial sensors Outcomes: Muscular activity Joint angles	**(↓)** Dangerous levels to 30% of the work time with the suit **(↓)** Deltoid (34%) and trapezius (18%) muscular activity · Some differences (<5%) were found in the range of movement of the back, neck, and arms owing to the use of the EXO
Huysamen et al. [10]	n= 12 healthy ♂ age: 27±2 yr height: 1794±6.56 mm weight: 75.38±10.1 kg	**Type:** Active **Supported body part:** Upper body **Model:** Robomate	Industry	Lifting tasks	Instruments: EMG Pressure measurement mats Borg Category Ratio (CR-10) scale Local Perceived Pressure System Usability Scale Outcomes: Muscle activity Contact pressure Perceived musculoskeletal effort and pressure Usability of the exoskeleton	**(↓)** Erector spinae (12%-15%) and biceps femoris (5%) muscle activity during the lifting and lowering tasks **(↓)** Perceived trunk effort · Contact pressure was below the pain threshold; discomfort and usability scores were acceptable · Six users rated EXO acceptable; and effective in reducing lower back musculoskeletal loading
Luger et al. [41]	n= 36 ♂ age: 25.9±4.6 yr height: 178.8±6.4 cm weight: 73.5±8.9 kg BMI: 22.9±2.1 kg/m^2, rest blood pressure: 129/79±7.7 mmHg	**Type:** Passive **Supported body part:** Upper body **Model:** Laevo	NR	Stair climbing test (SCT), Timed-up-and-go test (TUG), Course (COU)	Instruments: EMG Anthropometric data Outcomes: Muscle activity Posture HR	**(↓)** median/peak muscle activity in erector spinae (≤6%), biceps femoris (≤28%), and rectus abdominis (≤6%) **(↑)** muscle activity in vastus lateralis (≤69%) and trapezius descendent (≤19%) **(↑)** median knee (≤6%) and **(↑)** hip flexion angles (≤11%), (↓) HR: 5 bpm (η^2p = 0.40) **(↑)** Minimal, median, and maximal knee flexion by 3.0° (>100%), 4.9° (22.9%), **(↑)** maximal knee flexion by 2.2° (4.6%), **(↑)** 11% maximal hip flexion angle (6.7°) in a stoop lifting style
Hensel & Keil [34]	n= 30 ♂ age: 29.2±10.6 yr height: 175.3±6.5 cm weight: 76±9 kg	**Type:** Passive **Supported body part:** Upper body **Model:** Laevo	Automotive industry	Static (assembly line, press shop) and dynamic (logistics) work	Instruments: Standardized questionnaires Outcomes: Physical discomfort Wearing	**(↓)** Lower back discomfort in static work tasks **(↑)** Discomfort in chest regions for dynamic work tasks

				tasks	discomfort Usability Intention-to-use	(↓) User acceptance and perceived usability
Vries [42]	n= 12 healthy ♂ age: 25±1.3yr height: 1.83±0.8 m weight: 77.8±8.7 kg	**Type:** Passive **Supported body part:** Upper body **Model:** Skelex	NR	Static arm positions	<u>Instruments:</u> EMG Force transducer Inertial measurement unit Two video cameras <u>Outcomes:</u> Muscle activity Supportive force applied by the exoskeleton Arm posture	(↓) Muscle activity in shoulder muscles (↓) Shoulder joint moment · EXO provided the most support, around 50% of the total required moment, at arm elevation angles between 60-120 degrees
Marino [35]	n= 14 (11 ♂; 3 ♀) age: 25-47 yr height: 165-185 cm weight: 62-121 kg	**Type:** Passive **Supported body part:** Upper body **Model:** SuitX; Levitate	Stocker and tire installer jobs	Stocker and tire installer daily tasks	<u>Instruments:</u> Wearable sensors Questionnaires Heart rate monitor <u>Outcomes:</u> HR Step rate Usability	(↓) Muscle activity in trunk muscles in quasi-static assembly tasks (↓) Peak activity of trunk muscles in repetitive lifting (↓) Discomfort
Giustetto et al. [36]	n= 13 ♂ age= 28±2.8 yr height: 178±8 cm weight: 74.5±7.5 kg BMI = 24±2.00 kg/m^2	**Type:** Passive **Supported body part:** Upper body **Model:** Laevo	Automotive industry	Static 45-degree trunk flexion task and dynamic repetitive lifting task	<u>Instruments:</u> EMG Linear encoder sensor Electrogoniometer <u>Outcomes:</u> Local perceived discomfort Perceived effort Muscle activity	(↓) Discomfort in the lower back region (↑) Discomfort in chest and feet (↓) Perceived effort during static tasks (↓) Muscle activity in low back muscle
Luger et al. [12]	n= 46 healthy ♂ age: 24.8±2.9 yr height: 182.6±5.5 cm weight: 78.1±8.7 kg	**Type:** Passive **Supported body part:** Lower body **Model:** Chairless Chair	NR	Screwing, clip fitting, and cable mounting while standing	<u>Instruments:</u> EMG Force platform Motion capture Subjective self-reported discomfort Boorg CR10 scale <u>Outcomes:</u> Muscle activity Mass distribution Center of pressure (COP) and postural stability Trunk and neck angles Subjective discomfort ratings	(↓) Physical load up to 64% of the subject's body mass · The COP remained with the lowest values of static postural stability for high sitting (27%) (↑) Vastus activity (≈95–135%) during sitting (↓) Gastrocnemius activity ≈25%)
Pillai et al.	n = 15 (11 ♂; 4 ♀)	**Type:** Passive	NR	Dynamic panel	<u>Instruments:</u>	(↓) Rectus femoris muscle activity

[44]	Men ♂ height: 1.73±0.07 m weight: 71±10 kg Women ♀ height: 1.63±0.07 m weight: 58±4 kg	**Supported body part:** Lower body **Model:** LegX		task and sustained ground task	EMG Video recording of the tasks Outcomes: Muscle activity	by a median of 22% to 56% and a peak of 12% to 48% during the panel task, and by a median of 57% and peak of 34% during the floor task, with exoskeleton.
Pinho & Forner-Cordero [7]	n= 14 industry workers (12 ♂; 2 ♀) age: 32±5 yr height: 1.74±0.12 m weight: 76±7 kg	**Type:** Passive **Supported body part:** Upper body **Model:** ShoulderX	Automotive industry	Screw a M12 hex head cap screw until the end of the course and then unscrew it with different shoulder positions	Instruments: EMG Synchronized video recording Questionnaires Outcomes: Muscle activity Maximum voluntary isometric contraction (MVIC) Co-contraction index (CCI) Task completion time Perceived comfort Perceived exertion impairment, safety, and overall acceptance of the EXO	**(↑)** Task completion time in the task where the elbow was flexed at ≈ 90º and shoulder at 0º flexion and with elbow and shoulder flexed in ≈ 45º flexion **(↓) M**uscle activity in anterior and medial deltoid **(=)** Participants did not perceive differences in effort between tasks with different shoulder positions **(↓)** Discomfort in arms and shoulders **(↑)** Acceptance of the EXO
Luger et al. [20]	n = 45 healthy ♂ age:24.8±2.9 yr height: 182.6±5.5 cm weight: 78.1±8.7 kg	**Type:** Passive **Supported body part:** Lower body **Model:** Chairless Chair	Automotive industry	Simulated assembly activities common in automotive factories	Instruments: Electrodes - 3D Gravimetric position sensors Simulated assembly tasks using a triangular prism Questionnaire Outcomes: Discomfort and wearer comfort Muscle activity Mass distribution Postural control	**(↓)** Weight carried by feet (≈ 64%) **(↓)** Load on gastrocnemius muscle (≈ 75%) · Relative static postural stability decreased (≈ 27%) when sitting high on exoskeleton, absolute static postural stability (SS ABS.MIN) remained stable, indicating that postural stability did not approach a critical state. · EXO led to non-neutral trunk flexion angles, which may increase the risk of back disorders, though it also reduced neck flexion angles.

Bär et al. [45]	n= 36 healthy ♂ age: 25.9±4.6 yr height: 178.7±7.3 cm weight: 73.5±8.9 kg BMI: 18.5-30 kg/m^2	**Type:** Passive **Supported body part:** Upper body **Model:** Laevo	NR	Static sorting task	Instruments: EMG Position sensors Electrocardiography (ECG) Outcomes: Muscle activity Body posture HR	**(↓)** muscle activity [biceps femoris ≈ 8.12%], (erector spinae by 1.29%), rectus abdominis by 0.28%), vastus lateralis by 0.49%) **(↑)** activity in trapezius descendent (1.13%) **(↑)** hip and knee flexion by 8.1° and 6.7°, respectively, with EXO **(↓)** HR by 2.1 bpm with EXO
Luger et al. [43]	n= 36 ♂ age: 25.9±4.6 yr height: 178.8±6.4 cm weight: 73.5±9.0 kg BMI: 22.9±2.1 kg/m^2	**Type:** Passive **Supported body part:** Upper body **Model:** Laevo	NR	Lifting task	Instruments: EMG Gravimetric position sensors Electrocardiography Outcomes: Muscle activity Joint angles HR	(↓) HR (-1.5 bpm) with EXO (↓) Median and peak muscle activity of the erector spinae (up to 6%) and biceps femoris (up to 28%) **(↑)** Activity in the vastus lateralis (up to 69%) and trapezius descendent (up to 19%) **(↑)** Median knee (up to 6%) and hip flexion angles (up to 11%) to accommodate the support during lifting
Bock et al.[37]	n= 4 industrial workers ♂ age: 33.4 ± 5.7 yr height: 1.79 ± 0.02 m weight: 80.9 ± 5.8 kg work experience: 9.3 ± 6.4 yr	**Type:** Passive **Supported body part:** Upper body **Model:** ShoulderX; Skelex	Industry	Horizontal lift, overhead lift, squat, stoop lift, horizontal hold and stoop hold	Instruments: EMG Electrocardiography (ECG) Accelerometers Subjective measures Outcomes: Muscle activity HR Ratings of perceived exertion Discomfort TLX scale	(↓) Upper trapezius activity (up to 46%) and HR in isolated tasks using both EXOs (↓) Up to 26% upper trapezius activity reduction using both EXOs when lifting heavier weights. · ShoulderX had high shoulder discomfort and moderate usability ratings · Skelex offered better support in real-world scenarios.
Kim et al. [47]	n= 18 (9 ♂; 9 ♀) age: 24.7±3.7 yr height: 170.7±6.5 cm weight: 69.4±8.2 kg	**Type:** Passive **Supported body part:** Upper body **Model:** BackX; Laevo	NR	Assembly task	Instruments: Inertial motion capture system EMG Dynamometer Outcomes: Whole-body kinematics Muscle activity Perceived balance Localized discomfort	· EXos caused small, inconsistent posture changes, with lumbar flexion altering up to ~14° · Secondary muscle activity (shoulders, thighs) varied minimally, with < 2% of maximum voluntary isometric contractions **(=)** perception of balance between

					Overall helpfulness Fit Comfort Body movement constraints	the conditions with and without the EXO · EXO usability ratings varied by gender, with differing responses from participants.
Gonsalves et al. [8]	n= 10 ♂ age: 23±2 yr height: 175.95±4.70 cm weight: 75.14±8.74 kg BMI: 24.36±3 kg/m^2	**Type:** Passive **Supported body part:** Upper body **Model:** BackX	Construction industry	Rebar task	<u>Instruments:</u> EMG Time-stamped camera Borg 10-point scale <u>Outcomes:</u> Completion time Muscle activity Perceived discomfort	**(↓)** Time to complete rebar tasks and **(↑)** task performance **(↓)** Lumbar muscle activity (3% to 11%) during both placing and tying subtasks **(?)** Erector spinae muscle activity **(↓)** Perceived discomfort in the lower back **(↑)** Perceived discomfort in the chest
Bock et al. [40]	n= 16 healthy ♂ age: 29.3±9.3 yr height: 1.81±5.7 m weight: 81.4±7.6 kg	**Type:** Passive **Supported body part:** Upper body **Model:** Exo4work	NR	Overhead task	<u>Instruments:</u> EMG Dynamometer Questionnaire (NASA-TLX) <u>Outcomes:</u> Overhead work precision performance Muscle activity Task duration (speed) Error score (accuracy) Muscle activity	**(=)** Overhead work precision performance but mitigated shoulder elevation angle **(↓)** and **(↑)** co-contraction of stabilizer muscles (↓) Anterior and medial deltoid muscle activity, leads to smoother movements **(=)** Participants' subjective experiences (NASA-TLX), with **(↑)** mental and physical demands reported post-fatigue
Schmalz et al. [13]	n= 12 (6 ♂; 6 ♀) age: 24±3 yr Height: 176±15 cm weight: 73±15 kg	**Type:** Passive **Supported body part:** Upper body **Model:** Paexo	NR	Static overhead task (screwing nuts) and a semi-static overhead task (drilling)	<u>Instruments:</u> MetaMax3b spiroergometric system and T31 sport tester Optoelectronic system (VICON) EMG <u>Outcomes:</u> Oxygen rate HR Shoulder anteversion/abduction angles Elbow flexion angle Muscle activity	**(↑)** Shoulder abduction angles of 6° and 8° were observed during semi-static overhead work (T1 and T2) with the EXO compared to without it, while elbow flexion angles significantly **(↑)** in T2 with EXO. (↓) EMG amplitude of all assessed muscles (48%- 22%), especially during the static task (↓) HR (6%-5%) when using the EXO
Yin et al. [18]	n= 15 ♂ age: 28.6±4.2 yr height: 1.73±0.15 m weight: 68.5±12.3 kg	**Type:** Passive **Supported body part:** Upper body **Model:** PULE	Industry	Overhead industrial tasks	<u>Instruments:</u> EMG Subjective ratings Participant feedback	(↓) Initial nEMG values for right anterior deltoideus (38.5%), right middle deltoid (33.1%), right triceps brachii (30.7%), and left

					Outcomes: Muscle activity Work height Perceived discomfort	anterior deltoid (32.2%). **(↓)** Median nEMG values for right anterior deltoideus (45.1%), right middle deltoid (33.1%), right triceps brachii (32.2%), left anterior deltoid (33.5%), and left middle deltoid (31.7%). **(↓)** RPDs for shoulders, upper arms, and forearms wearing the PULE. The reduction was most substantial (51.3%) when participants performed tasks at high work heights. · Participants gave positive feedback on the PULE, with 11 of 15 willing to use it for overhead tasks. Some noted discomfort and range of motion loss, suggesting design improvements
Smets [38]	*Trial Phase 1* n= 8 (7 ♂;1♀) age: 20-47 yr height: 164-180.5 cm weight: 68-92 kg work experience: 0.25-26 yr *Trial Phase 2* n= 10 (9 ♂;1♀) age: 20-56yr height: 165-185 cm weight: 73-100 kg work experience: 0.25-26 yr *Trial Phase3* n= 4 (3 ♂;1♀) age: 30–62 yr height: 155-183) cm weight: 73-91 kg work experience: 6-30 yr	**Type:** Passive **Supported body part:** Upper Body **Model:** Ekso Bionics	Automotive industry	Overhead automotive tasks	Instruments: Fit and Functionality Questionnaire Cornell Musculoskeletal Discomfort (MSD) Questionnaire Outcomes: Percentage of shift that participants chose to use the EXO Self-reported changes in musculoskeletal discomfort, especially in the shoulders, arms, and neck	**(↓)** Discomfort in the neck and shoulders · 86% of the participants used the EXOs for their work shifts.
Pacifico et al. [39]	n= 7 ♂ age: 26-54 yr height:1.75±0.07 m	**Type:** Passive **Supported body part:** Upper Body	Industrial manufacturing	Mounting and dismounting panels	Instruments: EMG Electrogoniometry	**(↓)** Muscle activity of middle and anterior deltoid, triceps brachii, and trapezius muscle

	weight: 72.29±10.07 kg	**Model:** MATE			Questionnaires <u>Outcomes:</u> Muscle activity Shoulder joint angle Local Perceived Exertion Usability Technology acceptance Model	**(↓)** Perceived effort during repetitive overhead work tasks **(↑)** Usability and acceptance
Weston et al. [48]	n= 12 (6 ♂; 6 ♀) Men ♂ age: 21.2±2.9 yr height: 179.5±4.2 cm weight: 79.8±10.1 kg Women ♀ age: 22.5±3.3 yr height: 165.5±7.1 cm weight: 57.6±6.8 kg	**Type:** Passive **Supported body part:** Upper body **Model:** Ekso Bionics Ekso Vest; Levitate AIRFRAME; suitX ShoulderX	NR	Head height and overhead tasks	<u>Instruments:</u> NIRS EMG Assisted biomechanical modeling Questionnaire Motion capture <u>Outcomes:</u> Tissue saturation index (ΔTSI) Peak resultant load Subjective discomfort	**(↓)** ΔTSI using the ShoulderX at overhead heigh **(=)** Spinal loading or discomfort suggests minimal benefit from the EXOs · The task was not highly fatiguing, as shown by low changes in ΔTSI values across conditions
Kong et al. [49]	n= 20 healthy ♂ age: 24.4±2.4 yr height: 176.0±3.1 cm weight: 78.0±9.0 kg	**Type:** Passive **Supported body part:** Upper body **Model:** VEX; Airframe	NR	Drilling task	<u>Instruments:</u> EMG Maximum voluntary contractions (MVCs) Borg CR-10 scale <u>Outcomes:</u> Muscle activity Subjective discomfort	**(↓)** Muscle activity (↓29.3%-58.1%) in eight muscles during overhead tasks **(=)** Subjective discomfort ratings (limited differences between with and without EXOs)
Qu et al. [32]	n= 8 healthy ♂ age: 27.4±4.1 yr height: 174±5.4 cm weight: 73.2±8.1 kg	**Type:** Passive **Supported body part:** Upper body **Model:** IPAE	NR	Lifting tasks	<u>Instruments:</u> EMG VO_2 sensor Measure subjective responses through LPP, Borg RPE, and SUS <u>Outcomes:</u> Muscle activity Oxygen consumption Perceived musculoskeletal pressure Perceived fatigue level System usability	**(↓)** Muscle activity in the low back and upper arm muscles during lifting tasks: lumbar erector spinae (↓26.5%), thoracic erector spinae (↓12%), middle deltoid (↓32.3%), and labrum-biceps (↓38.1%) **(=)** Oxygen consumption and fatigue **(↑)** Pressure on shoulders, thighs, wrists, and waist · Usability (acceptable by 50% of subjects)

(↓) Decrease; (↑) Increase; (=) No difference; (?) Unclear; EXO - exoskeleton; yr - years; EMG - Surface electromyography; HR - Heart Rate; BMI - body mass index; NIRS - Near-infrared spectroscopy.

Appendix C – Effect size and Cohen's d

Study	Outcomes	Cohen's d	Effect-size r	Trend analysis
Omoniyi et al. [33]	Cognitive assessment	*	*	*
	Interview analysis	*	*	*
Sylla et al.[30]	Ground reaction forces	*	*	*
	Joint angles	*	*	*
	Duration of movements	*	*	*
	Joint torques	*	*	*
Bosch et al. [9]	Muscle activity	*	*	*
	Discomfort	*	*	*
	Trunk kinematics	*	*	*
	Endurance time	*	*	*
Jorgensen et al.[29]	MVC Standing vertical DELT_A No-EVO Upper stringer	1.22	0.52	(+)
	MVC Standing vertical DELT_A No-Paexo Upper stringer	1.08	0.48	(+)
	MVC Standing vertical DELT_A No-Skelex Upper stringer	1.33	0.55	(+)
	MVC Standing vertical DELT_L No-EVO Upper stringer	1.77	0.66	(+)
	MVC Standing vertical DELT_L No-Paexo Upper stringer	1.66	0.64	(+)
	MVC Standing vertical DELT_L No-Skelex Upper stringer	1.83	0.67	(+)
	MVC Standing vertical TRA No-EVO Upper stringer	0.46	0.23	(+)
	MVC Standing vertical TRA No-Paexo Upper stringer	0.05	0.03	(+)
	MVC Standing vertical TRA No-Skelex Upper stringer	0.38	0.18	(+)
	MVC Standing vertical LATD No-EVO Upper stringer	0.04	0.02	(+)
	MVC Standing vertical LATD No-Paexo Upper stringer	-0.1	-0.05	(-)
	MVC Standing vertical LATD No-Skelex Upper stringer	0.3	0.15	(+)
	MVC Standing vertical ES No-EVO Upper stringer	-0.08	-0.04	(-)
	MVC Standing vertical ES No-Paexo Upper stringer	0.02	0.008	(+)
	MVC Standing vertical ES No-Skelex Upper stringer	0.016	0.008	(+)
	MVC Standing vertical BIC No-EVO Upper stringer	0.034	0.017	(+)
	MVC Standing vertical BIC No-Paexo Upper stringer	0.31	0.15	(+)
	MVC Standing vertical BIC No-Skelex Upper stringer	0.2	0.1	(+)
	MVC Standing vertical TRI No-EVO Upper stringer	0.06	0.03	(+)
	MVC Standing vertical TRI No-Paexo Upper stringer	-0.045	-0.023	(-)
	MVC Standing vertical TRI No-Skelex Upper stringer	0.51	0.25	(+)
	MVC Standing vertical DELT_A No-EVO Middle stringer	0.94	0.42	(+)
	MVC Standing vertical DELT_A No-Paexo Middle stringer	1.03	0.46	(+)
	MVC Standing vertical DELT_A No-Skelex Middle stringer	1.24	0.52	(+)
	MVC Standing vertical DELT_L No-EVO Middle stringer	1	0.45	(+)
	MVC Standing vertical DELT_L No-Paexo Middle stringer	1.25	0.53	(+)
	MVC Standing vertical DELT_L No-Skelex Middle stringer	1.43	0.58	(+)
	MVC Standing vertical TRA No-EVO Middle stringer	0.57	0.27	(+)
	MVC Standing vertical TRA No-Paexo Middle stringer	0.13	0.07	(+)
	MVC Standing vertical TRA No-Skelex Middle stringer	0.37	0.18	(+)
	MVC Standing vertical LATD No-EVO Middle stringer	0	0	(+)
	MVC Standing vertical LATD No-Paexo Middle stringer	0.16	0.08	(+)
	MVC Standing vertical LATD No-Skelex Middle stringer	-0.02	-0.009	(-)
	MVC Standing vertical ES No-EVO Middle stringer	0	0	*
	MVC Standing vertical ES No-Paexo Middle stringer	0.06	0.03	(+)
	MVC Standing vertical ES No-Skelex Middle stringer	0.08	0.04	(+)
	MVC Standing vertical BIC No-EVO Middle stringer	-0.36	-0.18	(-)
	MVC Standing vertical BIC No-Paexo Middle stringer	-0.08	-0.04	(-)
	MVC Standing vertical BIC No-Skelex Middle stringer	-0.27	-0.13	(-)
	MVC Standing vertical TRI No-EVO Middle stringer	0.12	0.06	(+)
	MVC Standing vertical TRI No-Paexo Middle stringer	0.11	0.05	(+)
	MVC Standing vertical TRI No-Skelex Middle stringer	0.39	0.19	(+)
	MVC Standing vertical DELT_A No-EVO Lower stringer	0.76	0.35	(+)
	MVC Standing vertical DELT_A No-Paexo Lower stringer	0.63	0.3	(+)
	MVC Standing vertical DELT_A No-Skelex Lower stringer	0.92	0.42	(+)
	MVC Standing vertical DELT_L No-EVO Lower stringer	0.64	0.3	(+)
	MVC Standing vertical DELT_L No-Paexo Lower stringer	0.42	0.2	(+)
	MVC Standing vertical DELT_L No-Skelex Lower stringer	0.79	0.37	(+)
	MVC Standing vertical TRA No-EVO Lower stringer	0.59	0.28	(+)
	MVC Standing vertical TRA No-Paexo Lower stringer	0.07	0.03	(+)
	MVC Standing vertical TRA No-Skelex Lower stringer	0.38	0.19	(+)

MVC Standing vertical LATD No-EVO Lower stringer	0.01	0.006	(+)
MVC Standing vertical LATD No-Paexo Lower stringer	-0.24	-0.12	(-)
MVC Standing vertical LATD No-Skelex Lower stringer	0.32	0.16	(+)
MVC Standing vertical ES No-EVO Lower stringer	0.27	0.13	(+)
MVC Standing vertical ES No-Paexo Lower stringer	0.35	0.17	(+)
MVC Standing vertical ES No-Skelex Lower stringer	0.76	0.36	(+)
MVC Standing vertical BIC No-EVO Lower stringer	-0.41	-0.2	(-)
MVC Standing vertical BIC No-Paexo Lower stringer	-0.23	-0.11	(-)
MVC Standing vertical BIC No-Skelex Lower stringer	-0.34	-0.17	(-)
MVC Standing vertical TRI No-EVO Lower stringer	0.04	0.02	(+)
MVC Standing vertical TRI No-Paexo Lower stringer	0.27	0.14	(+)
MVC Standing vertical TRI No-Skelex Lower stringer	0.21	0.11	(+)
MVC Standing horizontal DELT_A No-EVO Upper stringer	1.34	0.56	(+)
MVC Standing horizontal DELT_A No-Paexo Upper stringer	1.06	0.47	(+)
MVC Standing horizontal DELT_A No-Skelex Upper stringer	1.05	0.47	(+)
MVC Standing horizontal DELT_L No-EVO Upper stringer	1.35	0.56	(+)
MVC Standing horizontal DELT_L No-Paexo Upper stringer	1.02	0.47	(+)
MVC Standing horizontal DELT_L No-Skelex Upper stringer	1.02	0.46	(+)
MVC Standing horizontal TRA No-EVO Upper stringer	0.26	0.13	(+)
MVC Standing horizontal TRA No-Paexo Upper stringer	0.03	0.01	(+)
MVC Standing horizontal TRA No-Skelex Upper stringer	0.19	0.09	(+)
MVC Standing horizontal LATD No-EVO Upper stringer	0.13	0.07	(+)
MVC Standing horizontal LATD No-Paexo Upper stringer	0.07	0.04	(+)
MVC Standing horizontal LATD No-Skelex Upper stringer	0.38	0.19	(+)
MVC Standing horizontal ES No-EVO Upper stringer	-0.09	-0.04	(-)
MVC Standing horizontal ES No-Paexo Upper stringer	-0.2	-0.1	(-)
MVC Standing horizontal ES No-Skelex Upper stringer	-0.17	-0.09	(-)
MVC Standing horizontal BIC No-EVO Upper stringer	0.12	0.06	(+)
MVC Standing horizontal BIC No-Paexo Upper stringer	0.26	0.13	(+)
MVC Standing horizontal BIC No-Skelex Upper stringer	0.26	0.13	(+)
MVC Standing horizontal TRI No-EVO Upper stringer	-0.07	-0.04	(-)
MVC Standing horizontal TRI No-Paexo Upper stringer	0	0	*
MVC Standing horizontal TRI No-Skelex Upper stringer	0.08	0.04	(+)
MVC Standing horizontal DELT_A No-EVO Lower stringer	1.08	0.47	(+)
MVC Standing horizontal DELT_A No-Paexo Lower stringer	1.24	0.53	(+)
MVC Standing horizontal DELT_A No-Skelex Lower stringer	1.12	0.49	(+)
MVC Standing horizontal DELT_L No-EVO Lower stringer	0.92	0.42	(+)
MVC Standing horizontal DELT_L No-Paexo Lower stringer	1.03	0.46	(+)
MVC Standing horizontal DELT_L No-Skelex Lower stringer	0.91	0.41	(+)
MVC Standing horizontal TRA No-EVO Lower stringer	0.35	0.17	(+)
MVC Standing horizontal TRA No-Paexo Lower stringer	-0.05	-0.02	(-)
MVC Standing horizontal TRA No-Skelex Lower stringer	0.34	0.17	(+)
MVC Standing horizontal LATD No-EVO Lower stringer	0.13	0.07	(+)
MVC Standing horizontal LATD No-Paexo Lower stringer	-0.09	-0.04	(-)
MVC Standing horizontal LATD No-Skelex Lower stringer	0.22	0.11	(+)
MVC Standing horizontal ES No-EVO Lower stringer	-0.2	-0.1	(-)
MVC Standing horizontal ES No-Paexo Lower stringer	-0.27	-0.14	(-)
MVC Standing horizontal ES No-Skelex Lower stringer	-0.14	-0.07	(-)
MVC Standing horizontal BIC No-EVO Lower stringer	-0.23	-0.11	(-)
MVC Standing horizontal BIC No-Paexo Lower stringer	0.04	0.02	(+)
MVC Standing horizontal BIC No-Skelex Lower stringer	0.08	0.04	(+)
MVC Standing horizontal TRI No-EVO Lower stringer	-0.08	-0.04	(-)
MVC Standing horizontal TRI No-Paexo Lower stringer	0.17	0.09	(+)
MVC Standing horizontal TRI No-Skelex Lower stringer	0.09	0.04	(+)
MVC Seated horizontal DELT_A No-EVO Upper stringer	1.11	0.49	(+)
MVC Seated horizontal DELT_A No-Paexo Upper stringer	0.9	0.4	(+)
MVC Seated horizontal DELT_A No-Skelex Upper stringer	0.73	0.34	(+)
MVC Seated horizontal DELT_L No-EVO Upper stringer	1.61	0.63	(+)
MVC Seated horizontal DELT_L No-Paexo Upper stringer	1.07	0.47	(+)
MVC Seated horizontal DELT_L No-Skelex Upper stringer	1.11	0.48	(+)
MVC Seated horizontal TRA No-EVO Upper stringer	0.59	0.28	(+)
MVC Seated horizontal TRA No-Paexo Upper stringer	0.28	0.14	(+)
MVC Seated horizontal TRA No-Skelex Upper stringer	0.32	0.16	(+)
MVC Seated horizontal LATD No-EVO Upper stringer	0.51	0.25	(+)
MVC Seated horizontal LATD No-Paexo Upper stringer	0.37	0.18	(+)
MVC Seated horizontal LATD No-Skelex Upper stringer	0.45	0.22	(+)

	MVC Seated horizontal ES No-EVO Upper stringer	0.07	0.04	(+)
	MVC Seated horizontal ES No-Paexo Upper stringer	-0.11	-0.05	(-)
	MVC Seated horizontal ES No-Skelex Upper stringer	-0.05	-0.03	(-)
	MVC Seated horizontal BIC No-EVO Upper stringer	0.73	0.34	(+)
	MVC Seated horizontal BIC No-Paexo Upper stringer	0.39	0.19	(+)
	MVC Seated horizontal BIC No-Skelex Upper stringer	0.37	0.18	(+)
	MVC Seated horizontal TRI No-EVO Upper stringer	0.28	0.14	(+)
	MVC Seated horizontal TRI No-Paexo Upper stringer	0.24	0.12	(+)
	MVC Seated horizontal TRI No-Skelex Upper stringer	0.24	0.12	(+)
	MVC Seated horizontal DELT_A No-EVO Lower stringer	1.09	0.48	(+)
	MVC Seated horizontal DELT_A No-Paexo Lower stringer	1.01	0.45	(+)
	MVC Seated horizontal DELT_A No-Skelex Lower stringer	0.9	0.41	(+)
	MVC Seated horizontal DELT_L No-EVO Lower stringer	0.95	0.43	(+)
	MVC Seated horizontal DELT_L No-Paexo Lower stringer	1	0.45	(+)
	MVC Seated horizontal DELT_L No-Skelex Lower stringer	0.97	0.44	(+)
	MVC Seated horizontal TRA No-EVO Lower stringer	0.37	0.18	(+)
	MVC Seated horizontal TRA No-Paexo Lower stringer	0.15	0.07	(+)
	MVC Seated horizontal TRA No-Skelex Lower stringer	0.33	0.16	(+)
	MVC Seated horizontal LATD No-EVO Lower stringer	0.09	0.05	(+)
	MVC Seated horizontal LATD No-Paexo Lower stringer	0.05	0.03	(+)
	MVC Seated horizontal LATD No-Skelex Lower stringer	0.32	0.16	(+)
	MVC Seated horizontal ES No-EVO Lower stringer	-0.13	-0.07	(-)
	MVC Seated horizontal ES No-Paexo Lower stringer	-0.61	-0.29	(-)
	MVC Seated horizontal ES No-Skelex Lower stringer	-0.21	-0.11	(-)
	MVC Seated horizontal BIC No-EVO Lower stringer	-0.07	-0.04	(-)
	MVC Seated horizontal BIC No-Paexo Lower stringer	0.07	0.03	(+)
	MVC Seated horizontal BIC No-Skelex Lower stringer	0.12	0.06	(+)
	MVC Seated horizontal TRI No-EVO Lower stringer	-0.06	-0.03	(-)
	MVC Seated horizontal TRI No-Paexo Lower stringer	0.3	0.15	(+)
	MVC Seated horizontal TRI No-Skelex Lower stringer	0.13	0.06	(+)
	Postural control measures joint angle torso (º)	-0.016	-0.008	(-)
	Postural control measures joint angle knee (º)	0.6	0.3	(+)
	Postural control measures joint angle ankle (º)	0.33	0.16	(+)
	HR	*	*	*
	SART pre	0.06	0.03	(+)
	SART squatting	-0.25	-0.12	(-)
	SART post	0.02	0.01	(+)
	Mental demands	0.18	0.09	(+)
	Physical Demands	-0.55	-0.26	(-)
	Temporal Demands	-0.45	-0.22	(-)
	Performance	-0.23	-0.11	(-)
	Effort	-0.41	-0.2	(-)
	Frustration	-0.6	-0.3	(-)
	Conflicting Task Demands	-0.92	-0.42	(-)
	Self-Control Demands	-1.19	-0.51	(-)
Iranzo et al. [2]	HR	*	*	*
	Kinematic data	*	*	*
Huysamen et al. [10]	Muscle activity	*	*	*
	Perceived Exertion	*	*	*
	Contact pressure	*	*	*
	Local Perceived Pressure	*	*	*
	Usability	*	*	*
Luger et al. [41]	Muscle activity ES Pallet box lifting	0.21	0.11	(+)
	Muscle activity ES Fastening	0.21	0.1	(+)
	Muscle activity ES Lattice box lifting	-0.03	-0.015	(-)
	Muscle activity BF Pallet box lifting	0.44	0.22	(+)
	Muscle activity BF Fastening	0.28	0.14	(+)
	Muscle activity BF Lattice box lifting	0.09	0.04	(+)
	Muscle activity RA Pallet box lifting	0	0	*
	Muscle activity RA Fastning	-0.07	-0.033	(-)
	Muscle activity RA Lattice box lifting	0	0	*
	Muscle activity VL Pallet box lifting	-0.3	-0.15	(-)
	Muscle activity VL Fastening	-0.24	-0.12	(-)
	Muscle activity VL Lattice box lifting	0.03	0.016	(+)
	Muscle activity MG Pallet box lifting	0.17	0.08	(+)

	Muscle activity MG Fastening	-0.22	-0.11	(-)
	Muscle activity MG Lattice box lifting	-0.29	-0.144	(-)
	Muscle activity TRA_D Pallet box lifting	0.19	0.09	(+)
	Muscle activity TRA_D Fastening	-0.016	-0.08	(-)
	Muscle activity TRA_D Lattice box lifting	-0.14	-0.07	(-)
	Angle Trunk flexion Pallet box lifting	0.14	0.07	(+)
	Angle Trunk flexion Fastening	0.09	0.05	(+)
	Angle Trunk flexion Lattice box lifting	-0.04	-0.02	(-)
	Angle Knee flexion Pallet box lifting	-0.9	-0.4	(-)
	Angle Knee flexion Fastening	-0.6	-0.3	(-)
	Angle Knee flexion Lattice box lifting	-0.45	-0.22	(-)
	Angle Hip flexion Pallet box lifting	-0.85	-0.39	(-)
	Angle Hip flexion Fastening	-0.46	-0.23	(-)
	Angle Hip flexion Lattice box lifting	-0.59	0.28	(+)
	HR Pallet box lifting	0.009	0.005	(+)
	HR Fastening	0	0	*
	HR Lattice box lifting	0.11	0.06	(+)
	Usability	*	*	*
	Perceived task difficulty	*	*	*
	Time-to-task-accomplishment COU	-0.09	-0.05	(-)
	Time-to-task-accomplishment Pallet box lifting	-0.33	-0.17	(-)
	Time-to-task-accomplishment Fastening	-0.04	-0.02	(-)
	Time-to-task-accomplishment Lattice box lifting	-0.4	-0.2	(-)
	Time-to-task-accomplishment SCT	-0.23	-0.11	(-)
	Time-to-task-accomplishment TUG	-0.37	-0.18	(-)
	Task difficulty COU	0.01	0.005	(+)
	Task difficulty SCT	-0.55	-0.26	(-)
	Task difficulty TUG	-0.26	-0.13	(-)
	Wearer comfort	*	*	*
Pillai et al. [44]	Muscle activity	*	*	*
Pinho & Forner-Cordero [7]	MVIC c Task A	-0.33	-0.16	(-)
	MVIC DEL_A Task B	0.79	0.37	(+)
	MVIC DEL_A Task C	0.88	0.4	(+)
	MVIC DEL_A Task D	0.56	0.27	(+)
	MVIC DELT_L Task A	0	0	*
	MVIC DELT_L Task B	0.47	0.23	(+)
	MVIC DELT_L Task C	0.61	0.29	(+)
	MVIC DELT_L Task D	0.38	0.19	(+)
	MVIC TRI Task A	0.26	0.13	(+)
	MVIC TRI Task B	-0.33	-0.16	(-)
	MVIC TRI Task C	-0.18	-0.09	(-)
	MVIC TRI Task D	0	0	*
	MVIC BIC Task A	-0.3	-0.15	(-)
	MVIC BIC Task B	0.16	0.08	(+)
	MVIC BIC Task C	0.22	0.11	(+)
	MVIC BIC Task D	-0.12	-0.06	(-)
	Task duration Task A	-0.14	-0.07	(-)
	Task duration Task B	-0.57	-0.27	(-)
	Task duration Task C	0.22	0.11	(+)
	Task duration Task D	0	0	*
	Comfort	*	*	*
	Acceptance	*	*	*
	Safety	*	*	*
Luger et al. [12]	Muscle activity	*	*	*
	Mass distribution high seat	7.33	0.96	(+)
	Mass distribution low seat	6.92	0.96	(+)
	Kinematics	*	*	*
	Postural control	*	*	*
	Discomfort	*	*	*
Bär et al[45]	Joint inclination Left	-0.17	-0.09	(-)
	Joint inclination Frontal	-0.13	-0.06	(-)
	Joint inclination Right	-0.13	-0.07	(-)
	Muscle activity ES Total	0.2	0.1	(+)
	Muscle activity ES Ipsilateral	0.09	0.04	(+)
	Muscle activity ES Frontal	0.17	0.09	(+)

Muscle activity ES Contralateral	0.35	0.17	(+)
Muscle activity BF Total	0.3	0.15	(+)
Muscle activity BF Ipsilateral	0.56	0.27	(+)
Muscle activity BF Frontal	0.21	0.11	(+)
Muscle activity BF Contralateral	0.12	0.06	(+)