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Review Article

Exoskeleton Interactions in Industrial Work Tasks: A Scoping Review of Applications, Evaluation Methods, and Challenges

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Abstract

Introduction: Musculoskeletal symptoms are a major occupational health concern worldwide, contributing to increased sickness absence, reduced work capacity, and substantial healthcare and economic costs. Wearable exoskeletons are increasingly used in industrial work to reduce musculoskeletal strain and support physically demanding tasks. The aim of this study was to review the user-exoskeleton interactions while performing industrial work tasks.

Methods: The relevant journal papers published between 2009 and 2024 from SciVerse Scopus and PubMed were extracted, following the PRISMA guidelines. The focus was on applications, evaluation methods, outcomes, and design challenges.

Results: One hundred and fifty-five papers included in the review. Fifty-two different industrial exoskeletons were identified (20 active and 32 passive exoskeletons), which were mainly evaluated in manual lifting/lowering (56%), overhead (29%), and assembly (6%) tasks. The exoskeletons were generally aimed to support the back (51%) and arms (21%). The exoskeletons decreased muscle activity levels (9–81%) and physiological strain (oxygen consumption and heart rate) as well as perceived exertion and discomfort experience, although they had negative consequences in terms of balance control and stability, working postures, and joint range of motion. The effects of exoskeletons on muscle fatigue, musculoskeletal/biomechanical loading and performance measures were contradictory. Most studies were short-duration lab trials, limiting generalizability to real workplaces. Key challenges include lack of standardized evaluation protocols, limited field validation, and potential for unintended biomechanical effects.

Conclusion: Findings support the need for harmonized testing methods, longer field trials, and user-centered designs to ensure safe and effective implementation in industrial settings.

Introduction

Musculoskeletal symptoms (MSS) are one of the major problems in almost all working environments and countries.[1] A significant proportion of sickness absenteeism, functional limitations and reduced work abilities, as well as considerable healthcare and economic costs can be attributed to the MSS.[2,3] The global burden of the MSS is considerable, and this is likely to increase in future.[4] Therefore, prevention of MSS in the working environments is a global priority.[5]

Physical risk factors for the development of MSS among workers in different working environments generally include repetitive movements, forceful exertions, manual material handling (MMH) activities and awkward body postures.[3] Despite increased automation and mechanization in industry, a large proportion of workers in occupational settings are still exposed to these physical risk factors.[6] In fact, full automation of working and production processes can be a solution to protect workers from the MSS. However, this may not be always possible. For instance, in a highly dynamic production setting or a in storehouse environment, a large diversity of products and relatively small sizes of packages necessitates a high level of flexibility, which in this case, full automation is either impossible or too expensive. When products or work tasks are changing rapidly, there is a need for humans to take decisions and appropriate actions immediately. This process can causes exposure to high levels of physical hazards such as MMH activities and repetitive tasks, and consequently may put workers at high risk for development of MSS. Currently, there is a developing trend in the modern industry toward the collaboration between human-robot for improving implementation of work tasks.[7] The use of exoskeletons is one example in this regard. As a wearable, external mechanical structure, exoskeletons can increase the

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physical capabilities of individuals to cope with physical stressors in their routine work. The main advantage of using exoskeletons compared to other robotic systems (e.g., classic robots, humanoids robots or full automation systems), particularly in dynamic settings, is possessing of human creativity and flexibility, without the need for robot training or programming.[8]

Over the last two decades, the exoskeletons have been used increasingly in various fields and domains such as industrial settings,[9,10] sport activities,[11] medicine and rehabilitation,[12] military operations,[13] teleoperation and virtual environments[14] for different purposes. The Exoskeletons can be divided into active and passive exoskeletons depending on using or not using an actuator. Exoskeletons can also be classified based on the supported body regions (e.g., upper body exoskeletons, lower body exoskeletons, or full-body exoskeletons). Another classification method is based on human anthropometry (e.g., anthropomorphic and non-anthropomorphic exoskeletons).[8]

Consistent with the aims of ergonomics/human factors, which focuses on performance and well-being outcomes,[15] exoskeletons should be evaluated based on these two related outcomes as well as user experience. In this regard, applications, evaluation methodologies and protocols as well as the exoskeleton effects should be assessed thoroughly in each working context. In other words, advantages, disadvantages, and challenges of using exoskeletons and a compromise has to be determined. For instance, alongside the improvements in physical performance of the users, the use of exoskeletons may lead to increased biomechanical or muscle loading in different body parts due to the exoskeleton's weight, size and structure as well as task condition.[16-18] Additionally, the exoskeleton-related standards/guidelines are still inadequate. To date, several review papers have been published on specific aspects of exoskeletons such as for example, applications of exoskeletons for manual material handling tasks in military[19] and construction works,[20] modelling for design and evaluation of industrial exoskeletons,[21] motor skills and performance indicators while using lower limb exoskeletons,[22] or on the methodology[23] or the effects of exoskeletons on physical work load[8,24] and metabolic cost during work tasks.[25] However, as it has been emphasized by several of these researchers,[21,23] the current literature on the industrial exoskeleton evaluation methodologies or modellings are generally neither comprehensive nor consistent. Therefore, considering the increasing interest in the utilization of exoskeletons in various industrial work environments, the present review builds upon the previous work to present a more comprehensive view on the applications, evaluation methodologies and challenges of using exoskeletons for industrial work tasks.

Methods

The present review was performed in two stages. In the first stage, research papers related to applications of exoskeletons for various industrial work tasks were identified and selected. In the second stage, the published information was analysed in terms of user–exoskeleton interactions in the context of industrial work tasks.

A review of the literature was conducted using SciVerse Scopus and PubMed to identify articles relevant to the exoskeletons. These databases were searched because they cover a wide variety of research topics with the most relevant peer-reviewed journals.[26] This was performed separately by two authors, who were blinded from each other's assessments. It should be noted that the primary aim of this study was to map the existing literature on user-exoskeleton interactions, identify key concepts (types, tasks, measures), and pinpoint gaps in research, rather than to assess the quality of evidence for a specific intervention as typical in systematic reviews. Therefore, while the authors followed a systematic search and screening process consistent with PRISMA guidelines, they did not perform a formal quality assessment (risk of bias) of the included studies, which aligns with the methodology of a scoping review. The search was performed using the following keywords: "exoskeleton" OR "exoskeletons" OR "exoskeletal" OR "wearable" OR "assist device" OR "assistive device" OR "assistance system" OR "worker assistance" OR "operator assistance", "task" OR "tasks" OR "work" OR "activities" OR "assembly" OR "lifting" OR "manual lifting". The Boolean operator "AND" was also used together with the search terms "ergonomics" OR "ergonomic" OR "human factor" OR "human factors" to avoid articles not relevant to this review. The two authors (AV and ID) screened titles and abstracts of the articles retrieved from the literature search. If the titles and abstracts did not contain enough data to assess the eligibility, the full texts of potentially relevant papers were also obtained and checked independently by the two authors. References of the retrieved articles were also manually scanned for additional relevant literature. Cohen's Kappa coefficient was used to indicate the agreement between two authors in the selection of the included articles. Substantial agreement between authors was considered as Cohen's kappa coefficient > 0.80.[27] Any disagreement between the authors was resolved through discussion and consensus. Data extracted included the author's name and publication year, work context, supported body part, exoskeleton type, exoskeleton name, study participants, study setting, and evaluated measures. The following inclusion criteria were applied:

- Papers published or in press in the English language;
- Papers published or in press in peer-reviewed journals;
- Papers published or in press until December 2024;
- Papers included working population (regardless of gender, age, or ethnicity) with industrial work tasks application (rather than studies related military, sports, elderly and patients, as well as teleoperation and virtual environments). More clearly, industrial work tasks were defined broadly to include occupational activities in manufacturing, construction, logistics, warehousing, and public

services, while excluding clinical rehabilitation and military combat applications;
- Papers with evaluation and analysis of human–exoskeleton interaction methodology (rather than studies that merely introduce a new design concept or prototype).

The papers had to meet the above-mentioned eligibility criteria to be included in the review. Papers with no application in the field of industrial work tasks were excluded. Exoskeleton studies related to military,[13] sports,[11] elderly and patients,[12,28] teleoperation and virtual environments [14] are examples of exclusions.

The extracted data were summarized in figures for further analysis and interpretation. SPSS v.17 software (SPSS Inc., Chicago, IL, USA) and Microsoft Excel (2013) were used for data analysis. Statistical analysis included Kappa Coefficient inter-rater reliability analysis for measurement of the agreement between two authors. Descriptive statistics were also used for description of the findings.

The literature search resulted in 627 records (Scopus = 353 and PubMed = 274) using different keyword combinations, of which 176 records were removed due to duplication (Figure 1). Screening the papers' titles, abstracts and keywords yielded 451 papers as being potentially relevant to this review. After reading the full texts, 149 studies were selected based on the inclusion criteria. In addition, 6 studies were identified from the manual searches of the reference lists of the retrieved papers, resulting in a total number of 155 papers for the final review. The degree of agreement between two authors was considered substantial (Cohen's kappa coefficient = 0.86).

Results

Figures 2 to 5 present the results from papers included in the review. In this section, different types, characteristics, and applications of exoskeletons for various industrial work tasks are discussed first (section 3.1). Then, methods of evaluating interaction between the users and exoskeletons are discussed in section 3.2.

Types, Characteristics and Applications of Exoskeletons

The results identified a total of 52 different industrial exoskeletons including 20 active and 32 passive exoskeletons. The Laevo passive exoskeletons were the most frequently used devises (18 studies). This was followed by the PLAD and PAEXO exoskeletons (9 studies), which were also passive exoskeletons. Figure 2 shows different brands of exoskeletons used in previus research. The results reveal a considerable use of passive exoskeletons (113 of the 155 reviewed papers), while 42 papers were related to active exoskeletons. This finding may highlights a growing popularity and acceptability of passive exoskeletons due to their lower prices, lighter weights and simpler designs. Although active exoskeletons may have more potential for reducing loads on body joints compared to the passive exoskeletons, it should be considered that the weight of device increases with increasing number of supported joints because each joint needs its own actuator. For instance, a lightweight upper body active exoskeleton weighs approximately 9 kg, and this may be considered as a disadvantage for this type of exoskeleton. In this regard, an anthropomorphic (e.g., might resemble a human) exoskeleton allows movements similar to the wearer's joints, and therefore provides greater range of motion for the joints. In contrast, non-anthropomorphic (e.g., not human like) exoskeletons have generally a simpler structure than anthropomorphic exoskeletons, and can be designed for specific tasks for energy efficiency purposes. In other words, task-specific exoskeletons which provide support for a particular body part might be more efficient than anthropomorphic ones due their lighter weight and fewer mobility limitations.

The exoskeletons can be used in a variety of domains and task types. According to the results of this review, exoskeletons were mainly evaluated in manual lifting/lowering (56%), overhead (29%), and assembly (6%) tasks (Figure 3). In terms of the body parts supported by the exoskeletons, in more than half of the reviewed papers (88 of the 155 papers), exoskeletons were designed to support the back (Figure 3). This is of particular interest in terms of prevention of the MSS. The MSS in different body

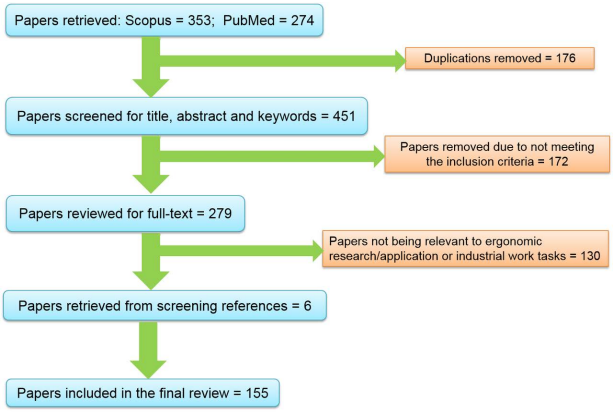


Figure 1. Flow diagram of the literature review strategy



Figure 2. Word cloud presentation of different brands of exoskeletons used in previous research

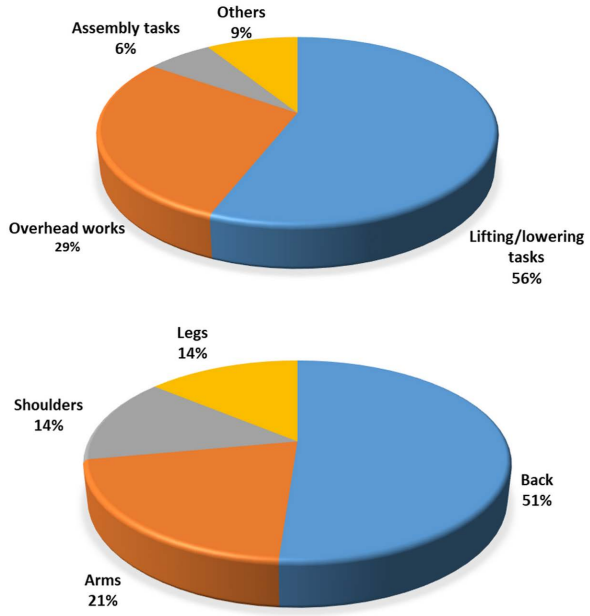


Figure 3. Distribution of exoskeletons in terms of task type (top) and body parts supported (down)

regions, particularly in the back, are very common and are one of the main reasons for sick leave and disability among workers.[2,3] Several risk factors including MMH tasks and awkward working postures can contribute to the development of such symptoms. This was followed by the exoskeletons that provided arm support for the users during the performance of overhead tasks (36 of the 155 papers). This highlights the importance of consideration of these tasks in the workplace. Shoulder musculoskeletal disorders are a major issue in terms of the workers' health since they require a relatively long recovery period. For instance, according to the Bureau of Labor Statistics,[29] shoulder disorders required a median of 23 days away from work, which is much higher than injuries or illnesses occurred in other parts of the body.

Measures and Methods for Evaluating Industrial Exoskeletons

Interaction between human and exoskeleton could be influenced by either various exoskeleton attributes such as design, weight, material and fit or the task requirements and specifications. Based on the included papers in this review,[1,9-10,16-18,30-182] human-exoskeleton interactions can be generally evaluated in terms of (1) muscle loading (e.g., muscle activity or fatigue indices), (2) biomechanical measures (e.g., postural control, working postures, (joint) range of motion, and interaction forces), (3) physiological measures (metabolic rates), (4) performance-related measures (e.g., number of errors, task completion time, endurance time, slip/trip risks), and (5) subjective measures of response to the work (e.g., usability, user acceptance/preference, perceived effort/excretion, workload, comfort/discomfort) (Figures 4 and 5). An appropriate exoskeleton evaluation protocol can, therefore, include

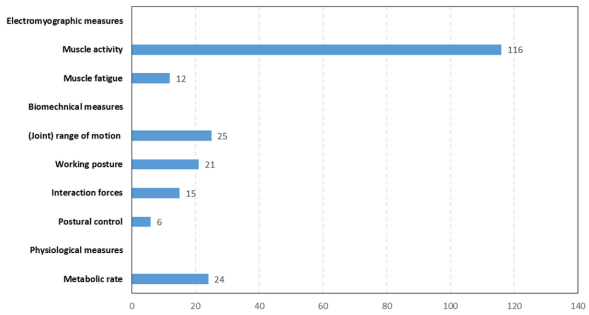


Figure 4. Electromyographic, biomechanical and physiological measures examined in exoskeleton evalauation studies

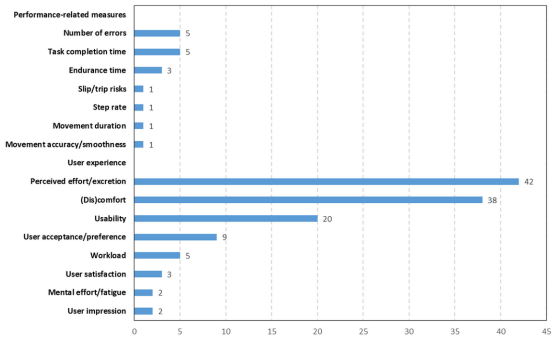


Figure 5. Performance-related and user experience measures examined in exoskeleton evalauation studies

a combination of the above-mentioned aspects that may be influenced when using exoskeletons within a specific work context. The following sections describe these outcomes in more detail.

Electromyographic Measures

Electromyographic (EMG) indices such as muscle activity and muscle fatigue have been frequently used in the exoskeleton evaluation studies. With regard to the muscle fatigue, Lotz et al.[30] evaluated the effects of a personal lift assist device (PLAD) on the general and local back muscle fatigue during a lifting task and found that the PLAD device reduced the severity of muscular fatigue in the studied muscles. Reductions in fatigue indices were also reported by Godwin et al. [31] and Schmalz et al.[32] who evaluated passive exoskeletons in lifting and overhead tasks, respectvely. However, other studies evaluating the effects of a passive shoulder exoskeleton in activities such as lifting and overhead tasks,[33] and the effects of a mechanical arm and an exoskeletal vest for overhead work[18] showed no significant effect of exoskeletons on the muscle fatigue indices. Compared to the muscle fatigue, more studies have used muscle activation for evaluation of exoskeletons (116 of the 155 reviewed papers). In almost all of these studies, the use of exoskeletons has reduced the level of muscular activity required to complete the task. The reduction in muscular activity levels of different muscles resulting from using exoskeletons ranged between 9% and 81%.[10,17,34-39] For instance, a study[35]

evaluating the effects of a prototype exoskeletal vest during simulated repetitive overhead drilling and light assembly tasks, reported a decrease up to 45% in shoulder muscle activity levels. Another study[10] evaluated the effect of a passive exoskeleton that provided gravity support while performing repeatedly or persistently squatting tasks and found an average reduction of 44.8 to 71.5% in thigh muscle activity levels.

Biomechanical Assessments

Human–exoskeleton interactions have also been evaluated by several biomechanical kinematic and kinetic indices in the literature. The possible interferences of the exoskeletons with natural joint kinematics (e.g., due to relative movements between the exoskeleton components and the human joints) is both important and challenging.[8] Of the reviewed papers, 62 reported the use of biomechanical measures such as postural control [40-46], working posture,[41,44,47-57] (joint) range of motion (ROM)[32,40,58-68] and interaction forces[9,10,16,33,40,50,59,69-72] in relation to the exoskeletons. These biomechanical measures are described in more detail as follows.

Postural Control

The results of this review reveal that using the exoskeletons may lead to some negative consequences in terms of postural control and stability (e.g., the ability of an individual to maintain his/her balance) depending on the exoskeleton design and working context.[41,45,46] This is an important issue because postural control impairment can lead to increased fall risk and fatigue due to persistent balance adjustment.[43] A study evaluating the influence of a prototype exoskeletal vest on postural control during overhead simulated tasks[40] showed an increase (by 12%) in the mean centre of pressure (COP) (e.g., the point at which the average location of the ground reaction forces act on a person's foot) velocity as a result of wearing the exoskeleton. Another research [41] evaluated the effect of a passive lower-limb exoskeleton during simulated assembly tasks on the postural control and reported up to 27% decrease in the relative static postural stability when sitting on the exoskeleton. When evaluating the effects of two passive exoskeletons on displacements in the COP while preforming overhead tasks,[42] authors reported changes in balance regulation, depending on the exoskeleton design and load condition. Nevertheless, a recent study[44] showed that the use of active exoskeletons do not adversely impact the stability of users during common construction tasks.

Working Postures

Several papers have highlighted changes in trunk/lumbar flexion angles,[41,47,48] hip and knee flexion[54] and shoulder joint kinematics[56] as a result of wearing exoskeletons in various working conditions. While performing a simulated assembly task with a passive exoskeleton,[47] authors found that the exoskeleton increased average trunk flexion angle (5.2°) compared to non-exoskeleton use condition. Another research [48] on working postures while performing different lifting tasks with two passive back-support exoskeletons showed minimal changes in working postures (e.g., lumbar flexion changes < 14°) due to exoskeletons. Other researchers[41] evaluating the effect of a passive lower-limb exoskeleton during simulated assembly tasks on upper body posture (flexion/lateral flexion angles of the lower back/upper back/head) have also reported an increase in non-neutral trunk flexion angle. Minimal[49,52,54] or reduced lumbar flexion[44,51,53] was reported in several research.

(Joint) Range of Motion

The results of this review reveals that wearing exoskeletons may have no[32,61,62,64] or moderate[40,58,60,65-67] effects in terms of the ROM of the human joints. A study evaluating the effects of a personal lift assistive device on the flexion/extension, lateral bending, and axial twisting of the trunk during lifting and static holding tasks,[58] reported 30% reduction in lateral bending, 24% reduction in rotational moments, and 19.5% reduction in flexion–extension moments. A 10% reduction in the shoulder abduction ROM was also reported when evaluating the effect of a prototype exoskeleton during overhead simulated tasks.[40] Another research[60] reported some differences in the range of movement of the back, neck, and arms (< 5%) when using an upper extremity exoskeleton in an automotive assembly line. Nevertheless, there was also some studies which showed no significant influence on the trunk or lumbar ROM when evaluating a passive back-support exoskeleton during repetitive lifting tasks.[63]

Interaction Forces

The interaction forces such as joint torques,[59] plantar pressure (e.g., force distribution over the foot sole)[10] and musculoskeletal or biomechanical loading[9,16,40,50,69-72] have been evaluated when using the exoskeletons. A study reported reduction in the mechanical energy (joint torques up to 38.9%) when using the exoskeleton in a simulated car assembly screwing task.[59] A reduction of 58.5–64.2% in the plantar pressure with the exoskeleton compared to without exoskeleton condition has also been reported when evaluating the effects of a passive exoskeleton on plantar pressure while performing a simulated assembly task with bended knee.[10] Nevertheless, there are contradictory findings about the effects of exoskeletons on the spinal loading, with some studies showing no effect[70,72] and others showing positive[9,33,40,69,71] or negative[16] effects. For instance, a study evaluating biomechanical loading to the low back when using an exoskeleton with a mechanical arm in a simulated drilling task with powered hand tools at the eye and waist levels, found that the exoskeletal device increased muscle forces in the torso extensor muscles and spinal loads in the lumbar spine.[16] The authors attributed this finding to the device weight and a larger moment about the low back due to the mechanical arm. Moreover, they concluded that mechanical loads might be shifted or transferred

with the use of exoskeletons, and therefore, an exoskeletal intervention should be capable of reducing loads to a joint of interest (e.g., shoulder) without a direct cost to another body region (e.g., low back). However, another study[40] showed that a prototype exoskeletal vest reduced spine loadings (up to 30%) during a simulated overhead drilling task. Reductions in the musculoskeletal loading on the lower back (5-15%) were also reported[9] when evaluating the exoskeletons in lifting and lowering manual handling tasks. Other authors[33] also found reductions in loading of the shoulder and elbow joint, without any increase in musculoskeletal load at the lower back, hip and knee during the high lift and the overhead wiring task. These contradictory findings may be explained by different design attributes of exoskeleton structures evaluated in these studies. These findings suggest that the design of an exoskeleton structure and its interaction with the musculoskeletal system of the human body should be closely examined when introducing an exoskeletal device in the work environment.

Physiological Measures

In addition to the mechanical loads, physiological load needs also to be considered when evaluating the exoskeletons. Metabolic rates as a measure of physiological strain have been evaluated in a number of previous exoskeleton studies.[32,43,44,73-77] Of the reviewed papers, 24 evaluated the metabolic rates. Heart rate and energy expenditure (e.g., oxygen consumption) are two common indices in this regard. Most of these studies have shown that the exoskeletons have a potential to reduce the metabolic cost (17% to 22%).

Performance-Related Measures

Number of errors,[35,78-80] task completion time[35,63,81,82] and endurance time[10,47,83] are common measures for evaluation of the task performance with exoskeletons. When evaluating the effects of a prototype exoskeletal vest on the simulated repetitive overhead drilling and light assembly task,[35] the authors reported that the time required to complete the drilling task was decreased (approximately 20%) and the number of errors was increased with the exoskeletal vest compared to without the vest condition. Anther study[78] also found that full-body and upper-body exoskeletons with attached mechanical arms tend to deteriorate task performance compared to other test conditions. The authors attributed this finding to the more complex articulations involved and the associated inertial properties of their prototype exoskeletons with mechanical arms. Other studies have reported minimal or no effect of exoskeletons on the task completion time and number of errors.[63,82,84] Endurance time was considered in another study as a measure of user performance when using exoskeletons.[47] The authors evaluated the effect of a passive exoskeleton on endurance time in a simulated assembly task (e.g., static holding in the forward bended trunk posture with the trunk in forward-bended position) and reported that the exoskeleton use was generally associated with an increase in the endurance time from 3.2 min to 9.7 min.

There are also other aspects of performance when wearing exoskeletons that needs to be noted here. In a study which assessed a prototype exoskeletal vest for its potential effects on slip and trip risks during level walking,[40] it was shown that the exoskeletal vest had minimal impact on trip/slip-related fall risks during level walking. A field study among workers in the wholesale and retail trade sector revealed that wearing passive back-assist and shoulder-assist exoskeletons reduced the mean step rate by 17.4%–20.5%[76] compared to without the exoskeleton condition. Workers also indicated concerns regarding movement quality and task performance when wearing the exoskeletons. Task performance in terms of movement duration while performing the overhead tasks with exoskeletons did not degrade in other studies.[43]

User Experience

A number of studies have assessed user experience using subjective measures such as usability,[9,33,40,85-89] user acceptance or preference,[49,76,85,90-92] perceived effort/excretion,[42,49,85,93-96] workload,[96-100] comfort/discomfort assessments,[10,18,34-36,47,49,101] and subjective fatigue. The following sections describe the user experience with exoskeletons in more detail.

Usability

Usability is one of the attributes that was evaluated in 20 exoskeleton-related studies. International Organization for Standardization (ISO) defines the usability as: "extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use".[102] Some studies[40] have evaluated the usability of an exoskeletal vest using calculation of the time required to don and doff the exoskeletal vest. The authors reported that the overall donning and doffing times were 67.1 and 17.4 sec., respectively. However, the System Usability Scale (SUS) was the commonly used measure in exoskeleton evaluation studies, which was administered in lifting/lowering manual handling tasks,[9,33,87-89] overhead work,[33,103] and cleaning job activities.[85] Two other studies have assessed usability using a continuous scale from 0 (not helpful at all) to 100 (absolutely helpful).[36,86] In majority of theses studies, the use of exoskeletons resulted in moderate-to-high ratings of perceived usability.

User Acceptance/Preference

One of the main challenges when introducing new technologies and practices is the level of acceptance from the users' perspective. As far as the use of exoskeletons is concerned, several authors have reported moderate to high ratings of user acceptance of the exoskeletons (e.g., intention-to-use of the exoskeletons in their work activities).[49,76,85,90,92,104] Nevertheless, some concerns have been raised regarding thermal comfort and weight of exoskeletons.[92] It has been reported that effort expectancy

(e.g., how easy it seems to use an exoskeleton) plays an important role in predicting the intention to use exoskeletons.[91] The authors also reported that social influence (e.g., whether others think workers should use exoskeletons) and performance expectancy (e.g., how useful exoskeletons seem to be for work) play a smaller role in predicting the intention to use the exoskeletons.

Perceived Effort/Excretion

Perceived effort or excretion is a commonly used measure (42 of the 155 papers) for evaluating exoskeletons. The results this review provide consistent evidence that the exoskeleton use in various contexts such as overhead work,[37,42,93,95,105] automotive assembly tasks [49], lifting and lowering manual handling tasks,[9,106] and cleaning activities[85] can reduce the perceived effort/exertion compared to the non-exoskeleton condition. However, a study evaluating the effect of a passive trunk exoskeleton on various work related tasks,[94] reported reduction in perceived task difficulty in static forward bending, but an increase in several other tasks, like walking, squatting and wide standing.

Workload

Of the reviewed papers, 5 were related to subjective workload when using the exoskeletons. Using the NASA-TLX method, some of these studies have noted decreases in physical workload when using the exoskeletons,[96,99] while others found no significant effect.[97,98,100]

(Dis)Comfort

Comfort and discomfort assessments are frequently being used in exoskeleton evaluation studies (38 of the 155 reviewed papers). Most of these studies have shown improved user experience as a result of using exoskeletons. There are also studies which have shown no positive effects of exoskeletons on subjective measures.[107] For instance, the results of a study[35] assessing the effects of a prototype exoskeletal vest during simulated repetitive overhead drilling and light assembly tasks showed no significant effect of exoskeletal vest on the perceived discomfort, although the authors reported a decrease up to 45% in shoulder muscle activity levels.

Other Aspects of User Experience

There are also other user experience aspects when using exoskeletons that needs to be considered. Several exoskeleton evaluation studies have considered subjective assessments of mental effort/fatigue,[97,104] user satisfaction[108,109] and user impression.[110,111]

Discussion

General Discussion of the Findings

The aim of this review was to explore the relevant literature on the interactions between users and exoskeletons in the contexts of industrial work tasks and the results revealed that exoskeletons have potential to decrease muscle activity, physiological strain (oxygen consumption and heart rate) as well as perceived exertion and discomfort experience. Decreased physiological strain, which is important in terms of prevention of fatigue and development of MSS,[73] and a relatively acceptable usability of the evaluated exoskeletons in previous studies can be considered as an advantage when incorporating this technology into various working practices. However, the exoskeletons may impose negative consequences in terms of balance control and stability, working postures, and range of motion of the human joints. Contradictory findings were also found about the effects of exoskeletons on muscle fatigue, musculoskeletal or biomechanical loading and performance measures, which may be attributed to the type and design of exoskeletons, inadequacies in the exoskeleton evaluation methods or to differences in evaluation measures and working contexts in different studies. The findings suggest the need for improving the design of exoskeletons in order to reduce the negative consequences of exoskeleton use in various industrial work tasks. There is also a need for an international consensus on standard and uniform evaluation protocols to improve the level of user acceptance and application of exoskeletons in various industrial settings.

Concerning the methodology of this review, although a quantitative meta-analysis could have yielded a higher level of evidence to resolve the contradictory results reported in the literature, a close examination of the extracted data revealed significant heterogeneity across the included studies. The existing variations in exoskeleton types, experimental tasks, study settings, and outcome measures made a valid statistical pooling of effect sizes (meta-analysis) unfeasible. This high level of heterogeneity was the primary reason for adopting a scoping review methodology — to map the breadth of the literature and identify these variations — rather than a systematic review with meta-analysis.

Regarding the muscle loading while using the exoskeletons, considerable reductions were found in muscle activity levels, whereas the findings of muscle fatigue assessments were contradictory. One point that can be made from these observations is that the reduction in the EMG activity of some muscles when performing occupational activities may necessitate the increase of others, irrespective of using or not using any external assistance such as exoskeletons.[17] This co-ordinated action of the lumbar and abdominal muscles is crucial for the stability of the lumbar spine. The practical implication of these findings is that the muscle activity reduction alone may not may be adequate to prescribe the exoskeletons for the prevention of MSS and particularly low back pain in the workplace. The individual's anthropometry and injury history as well as job characteristics and requirements may need to be considered in this regard. Another methodological point relates to the working context that has to be explored appropriately in ergonomic research. According to this review, most previous studies on industrial exoskeleton have been conducted in laboratory settings with limited operating time and task variations.

Duration of evaluation trials in most of these studies was relatively short and in only few studies it lasted up to 3 hours. Only 23 studies (of the 155 reviewed papers) evaluated their exoskeleton prototypes in the field. This may be responsible for contradictory findings on muscle fatigue. Contradicting results on the discomfort experience when wearing the exoskeletons may also be attributed to the relatively short duration of experimental trials which had minimal effect on subjective measures. As exoskeletons may be used for extended periods of time and in different working conditions (e.g., in different environmental conditions, limited working spaces, performing multitask activities, etc.), this evaluation method may not represent the actual working conditions in which exoskeletons are being used by workers. It is therefore worth investigating longer duration effects of exoskeletons on users' health and performance in future research. This is particularly important because long-time work with exoskeletons can be associated with unwanted side effects in terms of health and safety of their users. In addition, ergonomic recommendations and guidelines regarding task performance and health effects of exoskeletons are generally based on simple task simulations, and therefore it is required to consider more complex task conditions and interactions in future exoskeleton evaluation studies.

Gaps in Performance Evaluation Measures

Exoskeletons are designed in order to improve the user performance and to perform tasks in an ergonomic manner. A number of performance-related measures such as number of errors, task completion time, endurance time, slip/trip risks, step rate and movement duration have been considered in previous studies for evaluation of user performance when wearing the exoskeletons. Number of errors and task completion time are two commonly used performance measures in this regard. Nevertheless, other aspects of user performance have been considered either to a lesser extent or in a relatively non-realistic working context. For instance, exoskeletons have been assessed for their potential effects on slip/trip risks during level walking across a linear track,[40] while shoe-floor frictional demands when turning a corner or descending a ramp with exoskeletons may be more critical. Thus, it may be required to perform further studies to determine the exact effects of exoskeletons on slip and trip risks in these situations. Standard or task specific performance tests can be developed depending on the exoskeleton types and jobs/tasks that are being evaluated in each study. In this regard, some authors[81] proposed a battery of tests including 12 different simple functional tasks for evaluation of performance when using the trunk exoskeletons. In addition to these considerations, testing the exoskeleton prototypes with more actual users and different genders and age groups (rather than testing with young, healthy and non-professional users) using both objective and subjective assessment methods may give a better insight about the effects and effectiveness of this equipment. These considerations can help to better generalize the current findings to the actual working situations.

Exoskeleton Design Challenges

When designing exoskeletons, several factors such as exoskeleton weight, material, design, type and fit as well as task requirements/specifications, and work environment should be considered. These factors, together with technical and cost considerations, make the exoskeleton design process a complex challenge. Despite increasing interest and research on the development of exoskeletons, there is still a long way until extensive application of exoskeletons in various industrial settings. This may be attributed to a number of challenges that have not been fully resolved yet. For example, based on the results of this review, biomechanical limitations (e.g., negative consequences in terms of balance control/stability, work posture, and joint range of motion) is one area that needs special attention because if such equipment is inappropriately designed, workers frequently oppose wearing it or stop using it due to physical constraints. Human body joints, particularly shoulder joint, have also their own challenges and limitations. For instance, joint centre of rotation may changes during flexion or rotation movement in each joint requires movement between skin and skeletal structure. To overcome such difficulties, the exoskeleton should be lengthened or shortened as desired. Nevertheless, such issues have not been considered in the design of the reviewed exoskeletons. Anthropomorphic exoskeletons are also faced with serious design challenges such as fit between the exoskeleton and users with various body dimensions.

Exoskeleton-Related Standards and Guidelines

A major part of the above-mentioned challenges can be attributed to the lack of comprehensive guidelines and standards regarding the exoskeletons. So far, the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) have been two global leaders for developing standards with regard to the exoskeletons. In particular, ISO 13482 is a standard which explains the safety requirements for users of the exoskeletons and robotic systems.[112] This standard specifies design requirements and guidelines regarding personal care robots, but there is still no universally accepted standard or guideline for the safe use or designing industrial exoskeletons. This may be considered a major barrier to the adoption and use of this technology in industrial settings. More recently, a new ASTM International Technical Committee on Exoskeletons and Exosuits (ASTM F48) has been founded with the aim of enhancing the adoption and effective application of exoskeletons in the workplace. The ASTM F48 aims to develop exoskeleton standard requirements with regard to design and manufacturing, human factors and ergonomics, task performance and environmental considerations, maintenance and disposal,

security and information technology, and exoskeleton-related terminologies.[113] It is of utmost importance that, in addition to safety precautions and manufacturing requirements, exoskeleton standards consider the impact of exoskeletons on users' health and performance. Therefore, further studies considering various ergonomic requirements in designing exoskeletons can provide valuable information in developing exoskeleton-related standards.

Limitations of the Review

This review has limitations that should be noted. The first one is related to search process, which only considered two bibliographic databases (e.g., PubMed and SciVerse Scopus). While a wide range of publications are covered by these two databases, searching other databases might possibly have yielded additional relevant information. It is also necessary to acknowledge the linguistic limitation, as only English language studies were included. It should be also noted that this review considered human–exoskeleton interaction methodology in terms of evaluated measures, while the exoskeleton use in relation to demographic (e.g., age, gender, anthropometric characteristics, etc.) and workplace/job characteristics (e.g., working postures, jab/task duration, etc.) can make a significant contribution to the advancement of this field.

Practical Implications and Recommendations for Future Research

The findings from this review provide valuable insights that can inform future exoskeleton design and industrial applications, highlighting their real-world relevance in several ways:

- *Enhancing usability and reducing negative outcomes*: Unlike physical activities and exercises in sports science, which aim to strengthen and improve the muscle function, ergonomics seeks to maintain and improve the health and performance of employees. The rationale for using an exoskeleton in physically demanding occupational activities is to adhere to the recommended standard limits in terms of work physiology (e.g., observing 15% and 33% of an individual's physical capacity in static and dynamic activities, respectively), thereby preventing negative health consequences during the work shift. In other words, the use of an exoskeleton can help to conserve an individual's energy and increase endurance time while performing occupational tasks. While exoskeletons show potential to reduce muscle activity, physiological strain, and perceived discomfort, they also have drawbacks in terms of balance, stability, and range of motion. Future designs should focus on addressing these limitations by improving the ergonomics of exoskeletons. This could involve more adaptive mechanisms that enhance joint mobility without compromising balance, making the equipment more user-friendly in complex industrial tasks.
- *Improving long-term use and field applications*: The review suggests that most studies have been conducted in controlled laboratory settings with limited task variation and short evaluation protocols. To ensure exoskeletons are effective in real-world industrial environments, future research should include longer, diverse, and real-life working conditions. Understanding how exoskeletons work over extended duration of performing various work tasks, with particular attention to user comfort, muscle fatigue, and injury prevention over time, will be crucial for their industrial application.
- *Customizing for different user groups*: The need to consider individual anthropometry, injury history, and job-specific requirements is highlighted. This emphasizes that exoskeletons should be customizable to fit workers of different body sizes, genders, and physical conditions. Such adaptability will make exoskeletons more suitable for a diverse workforce, improving both safety and adoption in industrial environments.
- *Balancing muscle activity and reducing fatigue*: While the reduction in muscle activity is a positive finding, it may lead to increased strain on other muscle groups. This suggests that exoskeletons should be designed to support balanced muscle activity rather than merely reducing strain in isolated areas. By addressing this issue, future designs could more effectively prevent musculoskeletal injuries, particularly in the lower back, a common area of concern in industrial settings.
- *Establishing standardized evaluation protocols*: The review underscores the need for international standards and uniform evaluation protocols. The establishment of consistent guidelines for the testing and performance evaluation of exoskeletons, especially regarding safety, usability, and long-term health effects, will be key to their widespread industrial application. Collaboration with organizations like ISO and ASTM to develop such standards will ensure that future designs meet both safety and ergonomic criteria.
- *Real-world task simulation and performance testing*: The need for realistic task simulations is critical for ensuring that exoskeletons are truly effective in industrial settings. Future studies should incorporate complex tasks, such as navigating uneven terrain, working in confined spaces, or multitasking, to better understand how exoskeletons influence performance and safety in demanding work environments. Custom performance tests can be developed for specific industrial applications to optimize design and functionality.

By addressing the above-mentioned points, future exoskeleton designs can be more effectively integrated into industrial work tasks, improving worker safety, comfort, and productivity. Additionally, standardization efforts will support the broader adoption of exoskeleton technology, making it more practical and beneficial in

real-world industrial settings.

Conclusion

For more than a decade, a number of research studies have been undertaken to evaluate the human-exoskeleton interactions while performing various industrial tasks with both active and passive exoskeletons. Human-exoskeleton interactions can be assessed by various muscle loading, biomechanical, physiological, performance-related, and user experience (UX) measures. While many of these studies have shown that exoskeletons may have potential to reduce muscular activity levels, musculoskeletal loading, user discomfort and perceived exertion, they may have some limitations in terms of balance control and stability, working postures, and range of motion of the human joints. Such limitations may affect the level of user acceptance and intention-to-use of the exoskeletons in various working contexts. To overcome this issue, it is necessary to pay further attention to the design and evaluation of the exoskeletons in future research.

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Competing Interests

There is no potential conflict of interest to report.

Ethical approval

This study was approved by the Ethics Committee of Tabriz University of Medical Sciences (Approval ID: IR.TBZMED.REC.1400.125).

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