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Article

Occupational Exoskeletons: Understanding the Impact on Workers and Suggesting Guidelines for Practitioners and Future Research Needs

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Featured Application: This research aims to provide support to industrial practitioners who are searching for suggestions and directions addressing the adoption of occupational exoskeletons supporting manual material handling at work.

Abstract: This paper examines occupational exoskeletons and their effects on workers. The study includes a thorough evaluation of the current literature on occupational exoskeletons, with an emphasis on the impact of these devices on workers' health and the safety, performance and users' subjective perceptions. The aim of the study was to gain knowledge of how exoskeletons affect the workers and to identify practical suggestions for practitioners. The findings of the study suggest that exoskeletons can have both positive and negative effects on workers. Some users claimed enhanced comfort and decreased fatigue, whilst others reported discomfort and suffering. The study highlights the importance of considering the individual needs and preferences of workers when selecting and implementing exoskeletons in the workplace, with a focus on health, safety, performance and user acceptance. Based on the findings, the paper presents suggestions for employers and practitioners to ensure the effective and safe use of exoskeletons in occupational settings. These recommendations cover areas such as the assessment of workplace requirements, the selection and fit of exoskeletons, the optimization of design and ergonomics and the evaluation of performance. The paper concludes by highlighting the need for further research in this area, particularly in the areas of long-term use.

Keywords: exoskeletons; ergonomics; occupational health and safety

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1. Introduction

Occupational exoskeletons are wearable devices that give external support to the body's joints and muscles in order to reduce physical strain and fatigue while doing manual tasks at work. These devices are often built of materials such as carbon fiber, aluminum, or plastic and comprise a lightweight frame or structure that is worn on the torso, arms, or legs. The growing interest of academia and industry in occupational exoskeletons is driven by several factors. There is a growing awareness of the risks of MusculoSkeletal Disorders (MSDs) in the workplace, which can result from repetitive or intensive manual tasks [1–5]. Exoskeletons offer a potential solution to this problem by providing external support to reduce the load on the body's joints and muscles. Advances in technology have made exoskeletons more affordable and practical for use in the workplace. This has led to an increase in the number of companies exploring the use of exoskeletons to improve worker safety and productivity. In addition, the potential benefits of exoskeletons for workers in industries such as manufacturing, construction, and healthcare are becoming more widely documented [6–14]. Recent research investigated how occupational exoskeletons may assist workers accomplish physically demanding activities with reduced tiredness and discomfort, assuming that these devices may decrease the risk of developing MSDs due to manual lifting and material handling. The rising interest in occupational exoskeletons demonstrates a desire to improve worker well-being and safety while simultaneously increasing job efficiency and performance. As a consequence, there is an extensive amount of studies, reviews and development currently being conducted in the area of occupational exoskeletons, as organizations and academics try to further develop and enhance these devices for utilization in many different kinds of contexts. This study differs from other reviews in the scientific literature on occupational exoskeletons in that the ultimate aim was to provide practical guidelines for the adoption of occupational exoskeletons in workplaces and to identify areas where further research is needed.

Exoskeletons are conventionally classified into two types: passive and active. Passive exoskeletons are lightweight devices that feature no powered components and rely on the body's natural motions to provide support. They are most commonly found in industries where workers are required to perform demanding manual jobs, such as manufacturing, construction, and agriculture. In contrast, active exoskeletons employ powered components to actively support the body during physical tasks. These devices, which may give more support and control than passive exoskeletons, are commonly utilized in sectors where workers do physically demanding activities, such as aerospace, defense, and healthcare. Active exoskeletons are commonly used to help people with impairments or injuries enhance their movement. However, numerous active exoskeletons have been developed for deployment in manufacturing, construction, and agriculture contexts. A third category of exoskeletons combines both active and passive components to augment human capabilities. These wearable robotic devices are known as hybrid exoskeletons. The combination of active and passive elements allows for a more versatile and efficient support system. An hybrid exoskeleton, for example, could combine powered actuators with a lightweight structure to support the user's legs during walking.

Exoskeleton technology research is distinguished by a quick rate of progress and innovation. One of the toughest challenges related to exoskeleton technology is creating devices that are functional, safe, and pleasant for workers to use. Exoskeleton design must consider employees' individual needs, and they must be extensively tested to ensure that they do not create additional physical strain or safety concerns. Another issue is the high cost of exoskeletons. However, as technology progresses and becomes more commonly utilized, the cost of exoskeletons is likely to decrease, making them more affordable to a broader range of businesses and industries. As practitioners and academics strive to design devices that may improve worker safety, health, and performance, the current state of occupational exoskeleton research is characterized by increased attention and investment. Still, there are many challenges that must be addressed. Nevertheless, the potential benefits of exoskeletons are enormous and are expected to drive industrial innovation in the coming years.

This study discusses the findings from the recent scientific literature on active, passive, and hybrid exoskeletons, as well as the advantages and disadvantages of employing occupational exoskeletons for different body regions in terms of safety, health, performance and user acceptance. The aim was to support practitioners who are considering the implementation of exoskeletons in their workplaces, as well as to provide support in the identification of the most successful occupational exoskeletons for different industries and work activities. The analysis of collected data provide insights into which exoskeleton variants are best suited to meet specific needs and requirements. Following the description of the materials and the methods adopted in this study (Section 2), Sections 3 and 4 describe the recent findings from the scientific literature on the impact of occupational exoskeletons on safety, health, performance and user acceptance, and the key parameters for their effective and safe implementation. A step-wise approach supports the integration of these devices in the workplace, while describing the technical aspects that must be addressed when designing work activities that include exoskeletons. Employers and safety professionals may then use this information to make educated decisions regarding whether and how to adopt exoskeletons in their workplaces. Finally, Section 5 provides the conclusions of this study, addressing the future needs and trends in occupational exoskeleton research.

2. Materials and Methods

A review was conducted on papers with focus on occupational exoskeletons, published from 2011 to the first quarter of 2023 in the scientific database Science Direct, PubMed, IEEE Xplore and in the public document repositories of the US Occupational Safety and Health Agency (OSHA) [15] and the European Occupational Safety and Health Agency (EU-OSHA) [16]. Research studies, conference proceedings, literature reviews, guidelines, research projects, and reports, were included in this study. Figure 1 illustrates an upward trend in the number of publications related to exoskeletons over the period from January 2011 to March 2023. The picture shows a steady increase in the number of publications each year, indicating a growing interest in this topic among scholars and practitioners. This trend indicates that the subject of occupational exoskeletons is gaining increased attention from the scientific community as well as authorities like as the US OSHA and the EU-OSHA, which is expected to lead to new breakthroughs and improvements in the field, in the near future.

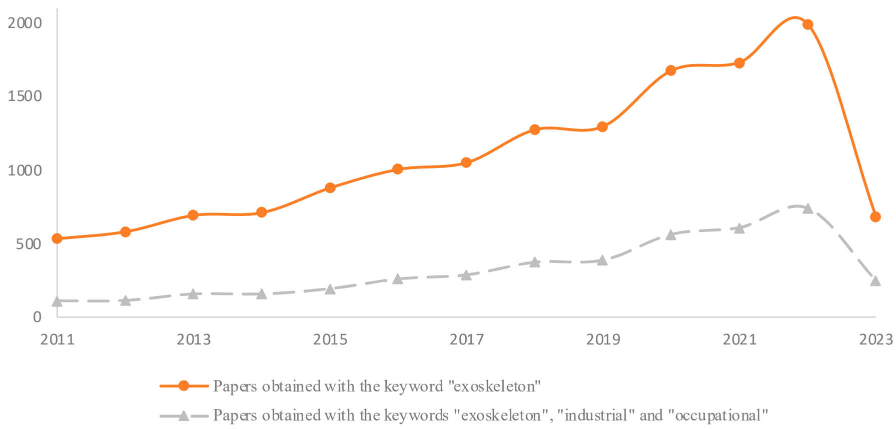

Figure 1. Publication trends on the topic of occupational exoskeletons from January 2011 to March 2023.

The keywords adopted for the search are "exoskeleton", "industrial" and "occupational". A total of 4197 documents was collected using the combination of such three keywords, of which 121 were included in this study (Figure 1). The selection of this limited amount of publications from the literature (4%) was based on the article selection protocol in Figure 2, for considering only those that align with the objectives of the present study. Specifically, the article selection protocol consisted of three phases. The first contained the inclusion criteria related to the characteristics of the article: language (i.e., English); type of document (i.e., research studies, conference proceeding, review, guideline, research project, or report); year (i.e., published from January 2011 to March 2023). The second phase of the protocol employed an inclusion condition for the extraction of the documents that focused on the interaction between the user and the occupational exoskeleton, while disregarding publications that solely focus on exoskeleton development and design stages. The condition was verified by reading the document title and the abstract. Then, in order to identify the aspects related to the objective of the literature review, four research questions were elaborated:

Q1 "Which parameters were analyzed to investigate the interaction between the user and the exoskeleton?"; Q2 "What were the effects of using the exoskeleton on the user's health and safety?"; Q3 "Did the use of the exoskeleton have a demonstrable impact on the operator's job performance during the defined task?"; Q4 "What was the impact of the exoskeleton on user acceptance and perceptions?". These research questions guided the inclusion condition in the third phase of the protocol and the documents were thoroughly read. Data from the 121 documents that met the inclusion criteria and conditions were analyzed and organized according to the research questions Q1, Q2, Q3 and Q4. Hence, data on the exoskeletons investigated in the selected publications were categorized based on the type of exoskeleton (active, passive or hybrid), the technology readiness level (prototype or commercial device), and the supported body area (e.g., spine, lower limbs and upper limbs). An assumption is made on the findings in this paper, i.e., the present review synthesizes information gathered from various studies that have examined the utilization of exoskeletons across different types and sectors, in regard to the impact on workers' health, safety, performance and acceptance. Data on the same exoskeleton that appeared in multiple papers, e.g., in a research paper and in a review study, were included in the present research once. The full list of the 121 publications included in this research is in the document Appendix A.

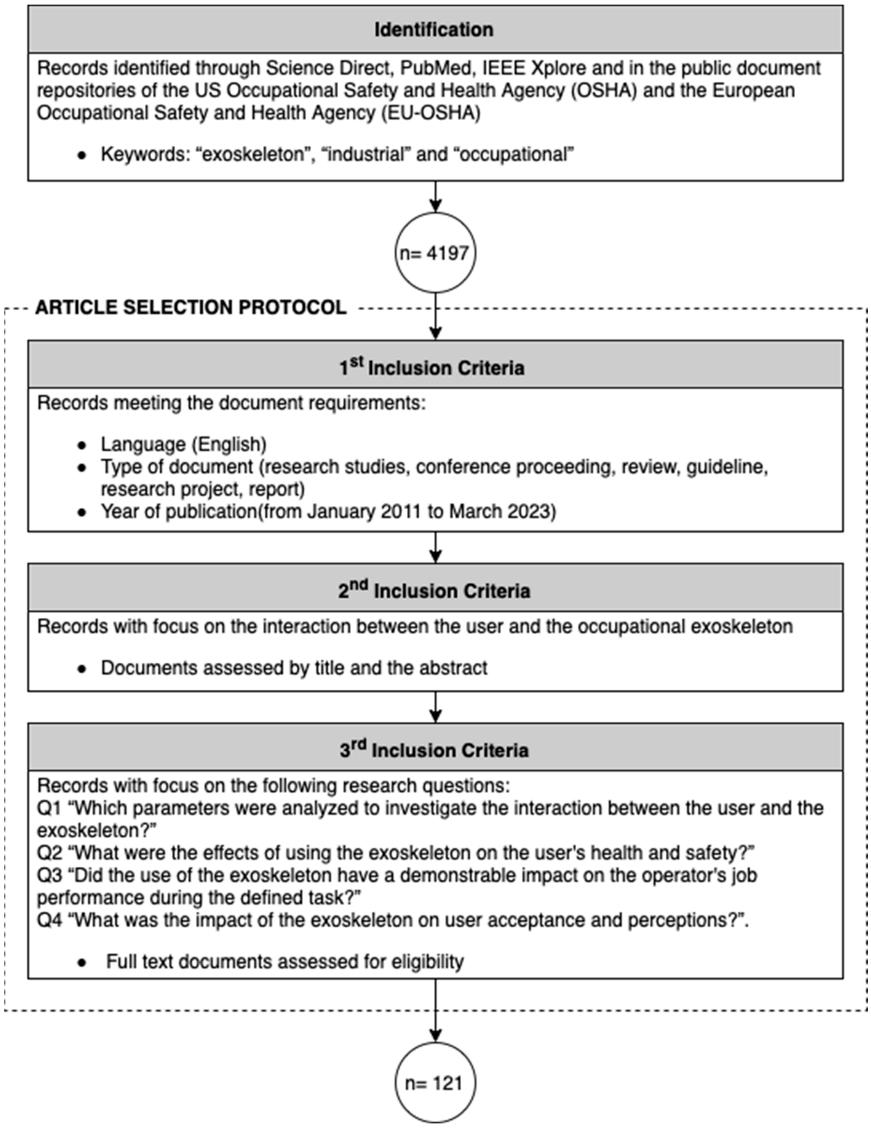

Figure 2. The article selection protocol adopted in the research.

3. Results

A total of 263 occupational exoskeletons were investigated in the selected documents, of which 171 were prototypes and 92 were exoskeletons proven in operational environment. The 61% of these exoskeletons were passive while the remaining devices were mostly active exoskeletons (37%) and hybrid devices (2%). The majority of the articles focused on passive exoskeletons due to their greater usability. Passive exoskeletons are more cost-effective than active ones as they do not require batteries or electronic components, making them lighter and not constrained by charging requirements, which can limit movement for active exoskeletons connected to the grid or make them heavy due to large batteries. The use of active exoskeletons appears to limited to tasks where a passive exoskeleton cannot be used.

3.1. Supported Body Areas and Investigated Parameters

Figure 3 illustrates that the parts of the body most commonly supported by occupational exoskeletons in the documents analyzed are: various parts of the spine (lumbar, trunk, and thorax) and the entire spine, as well as the lower and upper limbs.

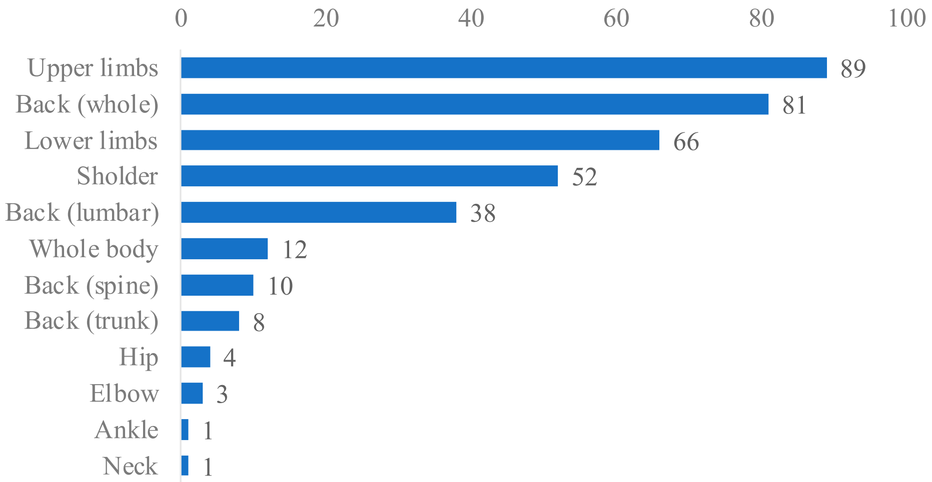

Figure 3. Body areas supported by the occupational exoskeleton, and number of studies that investigated the use of an occupational exoskeletons supporting each specific body area.

These parts of the body are also the most sensitive to MSDs. Some studies suggested that occupational exoskeletons have the potential to reduce the risk of developing MSDs in these locations, by providing support and reducing the load on the musculoskeletal system. About the 10% of the occupational exoskeletons investigated were tested in industrial facilities, while most of the applications were from laboratory studies. The factors analyzed in the documents investigated in the study are in Figure 4. In the articles analyzed, the topics that received the most attention, in order, are: user discomfort and perceived usability, muscle activation, kinematics, and metabolic consumption. These findings provide insight into the areas where research is most focused and, consequently, which factors are deemed most significant to those studying the interaction between exoskeletons and users. Muscle activation is a key metric because exoskeletons work by providing additional support to the wearer's muscles. Electromyography (EMG) is a technique used to measure and evaluate the electrical activity generated by the muscles during contraction. EMG is a useful method for assessing the success of exoskeletons in lowering muscle activation levels, which can indicate reduced physical strain on the user. It can also aid in identifying places where exoskeleton design and configuration may need to be changed to optimize their effects on muscle activation.

The user's comfort and discomfort during exoskeleton use is particularly important to evaluate, since it might influence their willingness to continue using the device. To examine the impressions of users during and after the usage of occupational exoskeletons, interviews and questionnaires with both open-ended and closed-ended questions are frequently utilized. In particular, questionnaires and annotations of impressions during usage were the most commonly used approaches in the research examined in the present study. Questionnaires are extensively used because they allow for uniform data gathering and may be delivered to a large sample size with ease. Open-ended questions are frequently included in questionnaires to allow participants to offer more thorough feedback.

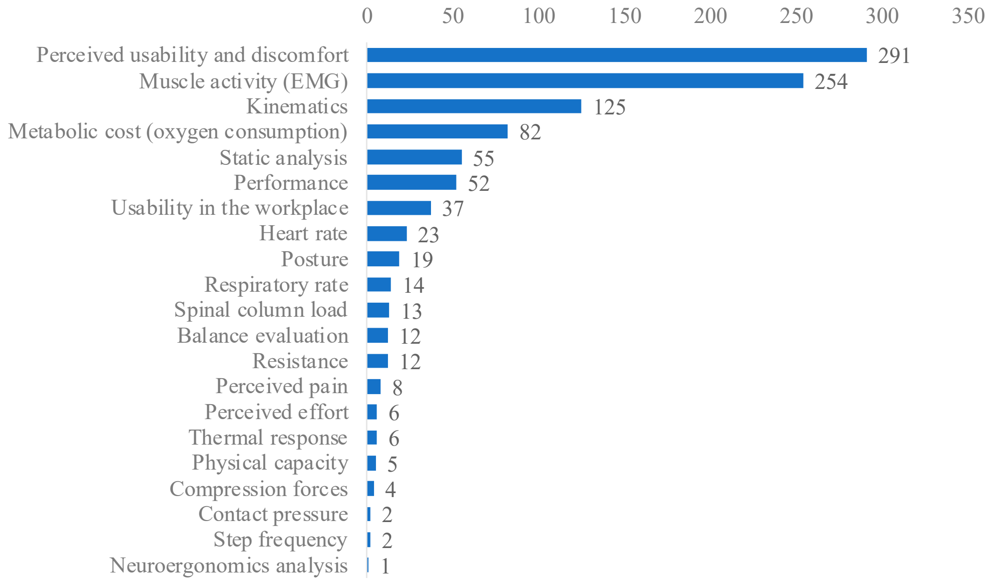

Figure 4. Parameters investigated during the testing of the exoskeletons in the reference studies, and number of studies with focus on each specific parameter.

The methodologies adopted in the questionnaires to obtain users' subjective ratings include: the Borg's scale to assess the rate of perceived exertion [17]; the local perceived pressure to evaluate the musculoskeletal pressure of the parts of the body that are in contact with the exoskeleton [18]; the visual analog scale and the numeric rating scale to measure the pain intensity [19] and the pain severity [20]; the system usability scale to assess the perceived usability [21]; and the Likert scale to collect the level of agreement and disagreement of users on a symmetric agree-disagree scale for a series of statements [22]. Questionnaires are convenient and easy to administer, but they may suffer from response bias or may not capture the full range of experiences and perceptions of the user. On the other hand, annotations of perceptions during use provide more detailed and personalized feedback, but they may be time-consuming to analyze and may not be feasible for larger sample sizes. Overall, the choice of methodology for assessing personal perceptions about exoskeletons should be carefully considered based on the research question and the specific population being studied. Combining multiple methods may also provide a more comprehensive understanding of the user's experience with the exoskeleton. Kinematic analysis is important to understand how the exoskeleton affects the wearer's movement and posture, while metabolic consumption is a measure of the energy expenditure required to use the exoskeleton.

The most recent research on occupational exoskeletons recommends which conditions and tasks are most suitable for the implementation of an exoskeleton, as well as which type of exoskeleton is best suited for certain work. Exoskeletons can be effective in applications that require repeated or difficult actions or involve significant weights. The best exoskeleton for a specific job is decided by the task's unique requirements, such as the range of motion, amount of force, and level of dexterity required. Furthermore, variables such as the exoskeleton's weight and size, convenience of usage, and cost must be addressed. By carefully considering these criteria, it is possible to select an exoskeleton that is both effective and practical for a certain task. It is also important to determine the circumstances and tasks for which exoskeletons are most beneficial, as well as the type of exoskeleton most suited for the intended function. In conclusion, when evaluating the use of exoskeletons in occupational settings, it is important to investigate various parameters such as health, safety, performance and user acceptance, considering the type of exoskeleton (active, passive or hybrid), the technology readiness level (prototype or commercial device) and the supported body area.

3.2. Evidence from the Literature on the Health Implications of Occupational Exoskeletons

The aspects of health addressed in the literature on occupational exoskeletons are diverse. Hence, this section reports those that have been observed most frequently in the recent literature. Figure 5A shows the number of studies that reported health improvements, health deterioration or no variation in the health conditions, in case of active, passive or hybrid exoskeletons. As for active exoskeletons, in most cases, it was observed an improvement in health, in line with the general trend (Figure 5A).

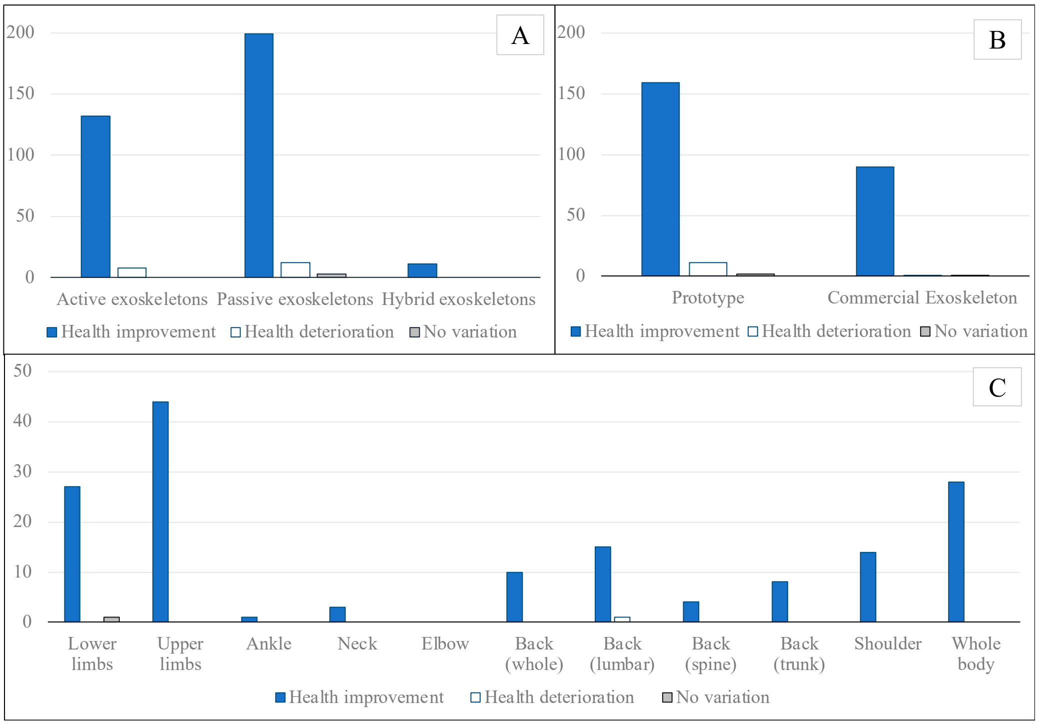

Figure 5. Studies that reported health improvements, health deterioration or no variation in the health conditions, in case of active, passive or hybrid exoskeletons (**A**); prototypes and commercial exoskeletons (**B**); studies that reported health improvements, health deterioration or no variation in the health conditions, in case of exoskeletons supporting different body areas (**C**).

Many active exoskeletons allow a reduction of loads on the body part they assist, without transferring the weight to other parts such as joints, as they have actuators that provide energy and contribute to lifting loads. This has been demonstrated both by user perceptions and electromyography, which have shown a decrease in muscular usage [6,23,24]. Another important aspect of active exoskeletons is the reduction of energy consumed by the user during work activities, which allows a decrease in both effective effort, as demonstrated by the decrease in metabolic consumption, and perceived effort [25]. Finally, active exoskeletons allow the attenuation of intense and repeated stresses on joints to prevent tendinopathies [26]. The negative effects on health from active exoskeletons are few, with the most important one not referring to a particular case but applicable to many application fields, which is the transfer of loads from the shoulder to the waist. In these cases, there is no reduction in loads as expected, while it was reported a decrease in agonist muscles and an increase in antagonist muscles in the case of the shoulder [27,28]. Recent studies show that passive exoskeletons can support the body part for which they were designed without putting too much strain on other body parts [29,30]. In contrast to active exoskeletons, load redistribution can be less efficient since there are no energy-providing components, thus it must be discharged someplace, although in many circumstances, this can be done without overloading other body sections. Passive exoskeletons are therefore preferable when there is a need to transport low loads. Thanks to passive exoskeletons, the load can be redistributed during movements, avoiding load peaks that can damage muscles, causing, for example, tears or contractions [31–35]. Another positive aspect of these exoskeletons is the decrease in metabolic consumption during lifting. Some studies reported a slight increase during walking, but this has no effect on the ultimate result, allowing the user to be less fatigued [36].

Passive exoskeletons, like active exoskeletons, can reduce acute and repetitive pressures on arm muscles to avoid tendinopathies [26]. Finally, passive exoskeletons allow greater movement stability, improving the user's balance and comfort [37]. Negative aspects on health are instead lower and concern more particular cases. The most common cases involve passive shoulder exoskeletons, which, as with active ones, cause a decrease in agonist muscles and an increase in antagonist muscles, as well as, in some cases, an increase in body temperature, particularly in hot environments, resulting in a deterioration of working conditions [28,38]. Although results cannot be drawn at a general level due to the small number of hybrid exoskeletons investigated, only positive reactions have been observed for these devices, corresponding with those shown for passive exoskeletons.

Regarding prototypes and commercially available exoskeletons, improvements in health conditions are observed in most cases for both types (Figure 5B). In the long run, the user became less motivated to utilize the exoskeleton unless forced by the organization. Among the most common issues are those with shoulder exoskeletons, which produce an increase in antagonist muscles activity and a decrease in agonist muscles [28]. Some passive spinal exoskeletons provide less thrust than the back, increasing the load instead of reducing it, and for some exoskeletons, there is no possibility of using them in hot places as the user's thermal response has been negative [38,39]. These exoskeletons cause excessive perspiration, rendering them unsuitable for usage at work. The development of these exoskeletons will need to focus on appropriate materials so that they may be employed in a variety of circumstances.

Figure 5C shows the number of studies that reported health improvements, health deterioration or no variation in the health conditions, in case of exoskeletons supporting different body areas. The studies reviewed in this research generally lack consideration of the long-term effects associated with the use of exoskeletons. Consequently, establishing clear and unambiguous conclusions about the long-term impact of exoskeleton use on health becomes difficult. Unlike the case of a lumbar exoskeleton, which demonstrated a deterioration in the user's health, the health conditions appear to be improving in all other studies. The most frequently reported benefits for the upper limbs include a reduction in mechanical energy and a variation in joint torque trajectories [40], a decrease in muscle peak activity by up to 52.5% and 60.6% for the shoulder and 29% and 16% for the lower trunk [31], and a reduction in muscle activation during lifting and static tasks [29]. For the back, the most frequent benefits of exoskeletons supporting this body part are a significant reduction in loads imposed on passive tissues of the vertebral column in the curved posture, without significantly increasing the loads on the hip, knee, and ankle joints, a reduction in the mean peak and mean muscle activation of back and leg muscles, and reductions in EMG for all back muscles and leg muscles [30,33]. Exoskeletons supporting the lower limbs provide better mechanical stability for both static and dynamic tasks, and reduce muscle fatigue [41,42]. For integral support of the whole body, exoskeletons reduce muscle fatigue and metabolic consumption. For the shoulder, the advantages of exoskeletons include a reduction in the maximum load on shoulder muscles without significantly affecting either the quality or the maximum acceptable force [43], a decrease in muscle fatigue, and improved function of the assumed postural angle [44], as most passive exoskeletons are designed to increase support with increasing angles, just as the risk increases with increasing angle from the neutral position.

3.3. Evidence from the Literature on the Impact of Occupational Exoskeletons on Workers' Safety

In the case of active exoskeletons, safety evaluations have shown both improvement and worsening in safety conditions [23,28,45] (Figure 6A). Improvements are often related to prolonged use and emergency situations where the exoskeleton is controlled to prevent injury to the user.

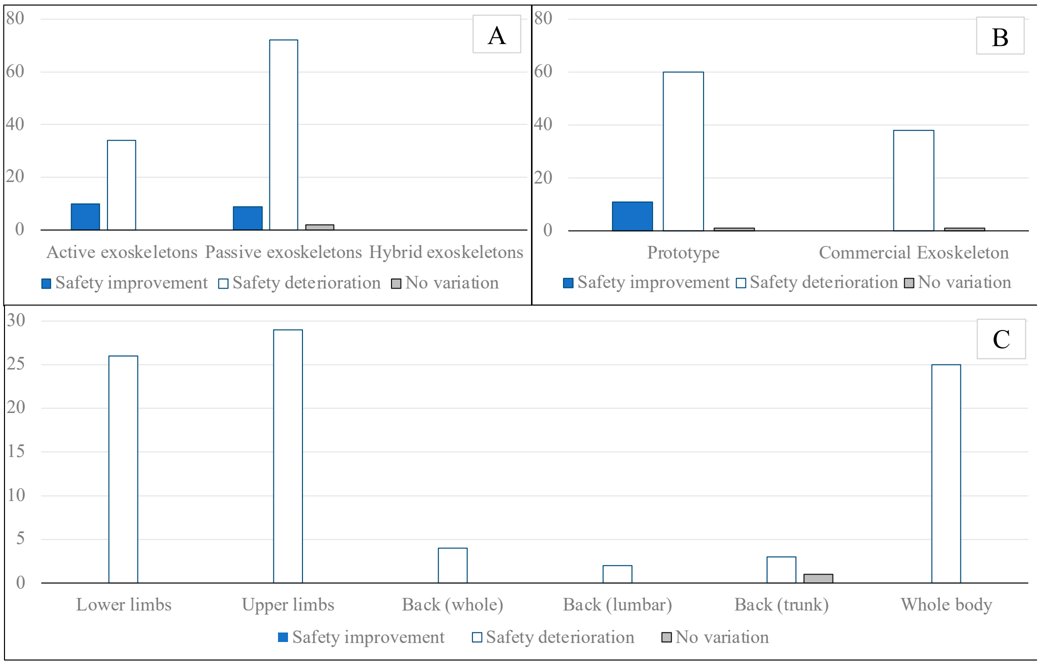

Figure 6. Studies that reported safety improvements, safety deterioration or no variation in the safety conditions, in case of active, passive or hybrid exoskeletons (**A**); studies that reported safety improvements, safety deterioration or no variation in the safety conditions, in case of prototypes and commercial exoskeletons (**B**); studies that reported safety improvements, safety deterioration or no variation in the safety conditions, in case of exoskeletons supporting different body areas (**C**).

However, concerns exist over potentially negative effects on leg muscle activity, discomfort, and muscle deconditioning [29], as well as the assistance with shoulder elevation which may impact muscle coordination and increase the risk of tendon injuries [26]. Passive exoskeletons, on the other hand, have mostly shown deteriorating safety conditions (Figure 6A). Concerns are raised about prolonged use causing muscle weakness, the rigidity of the structure hindering normal body movement, and the potential for the exoskeleton to interfere with other parts of the body [32,46]. In situations where external disturbances occur, such as collisions with colleagues, passive exoskeletons are not recommended [47,48]. However, there have been limited instances where the use of passive exoskeletons has resulted in improved safety conditions, such as with arm support exoskeletons [28]. Safety in wearable robotics should be ensured by monitoring both feedback and control signals, as well as implementing corrective controllers to maintain system stability [49].

Regarding prototypes and commercially available exoskeletons, variations in safety conditions are observed in different cases for both types (Figure 6B). The main aspects that affect safety when using exoskeletons, whether in prototype or commercial form, are the biomechanical advantage in terms of spinal load reduction, the energy consumption required [29], and the potential muscle weakness and coordination loss that can result from prolonged and intensive use [26,32]. Still, there have been more cases of worsened safety conditions than of improved or unchanged ones. In prototype exoskeletons, safety improvements have been rare and have focused mainly on methods to block the exoskeleton in emergency situations [45], as well as on ensuring that the positive effects of reduced muscular activity outweigh the negative effects, such as increased antagonistic muscular activity [28,49]. The joints that have been most studied in the case studies discussed in the articles, with regards to safety considerations, are the lower limbs, the upper limbs, the back and the whole body (Figure 6C). The negative aspects that have been mostly considered for lower limb exoskeletons are potential negative effects associated with increased leg muscle activity, high levels of discomfort and muscle deconditioning [29]. Bosh et al. (2016) suggested that using the exoskeleton with the knees in an excessively extended position for long periods may shift a health risk from the back to the knees [50]. According to Park et al. (2022), the usage of exoskeletons with strong external torques can reduce walking energy and increase the danger of falling [51], while Antwi-Afari et al. (2021) reported no changes in safety conditions of the trunk [52]. For exoskeletons that support the whole body, negative safety aspects for users include potential effects associated with increased leg muscle activity, high levels of discomfort, and muscle deconditioning [29]. In prolonged lifting and lowering work, increased leg muscle activity could require greater oxygen uptake [29]. Finally, the use of passive exoskeletons for the upper body reduces muscle activity [53]. However, the negative effects mainly considered for safety are the weakening of trunk muscles [32] and the pressure that occurs in the arm, which systematically exceeds the threshold for adequate blood flow and can therefore cause long-term harm [54].

3.4. Evidence from the Literature on the Effects of Occupational Exoskeletons on Work Performance

Variations in work performance, both positive and negative, are largely dependent on the type of task being performed. This aspect is critical for determining the appropriate exoskeleton to use in different work settings; however, as Figure 7 illustrates, it has been given little attention in scientific publications. In general, the results from the studies in the literature on the effects of occupational exoskeletons on work performance, e.g., productivity, are more negative than positive. It is worth remembering that these data primarily come from laboratory testing in controlled environments, and therefore have limited precision in terms of productivity outcomes. The limited evaluations can also be attributed to the recent emergence of this technology. People are not yet accustomed to using it, and in most cases, it prevents them from working at normal speeds without the exoskeleton. In the future, with advancements in technology and adaptation by users, these data will undoubtedly improve if exoskeletons are used on a larger scale. Regarding active exoskeletons, almost all cases evaluated for productivity showed a decrease in performance, except for one case where repetitive lifting was required [41]. The cases where productivity decreased were due to hindrance of lower limbs and an increase in errors when increasing the production rate [55]. However, there were a considerable number of cases where the use of active exoskeletons did not affect productivity, but rather had an impact on quality. Moderate evidence shows that completion times for tasks did not increase for the active exoskeletons examined in the studies [24]. As for passive exoskeletons, there were more cases where productivity decreased than increased or remained unchanged [31,32]. For example, Bosch et al. (2016) found that, with passive exoskeletons, the endurance time for static trunk holding was three times higher ($p < 0.001$, $t = 5.96$) when using the exoskeleton (9.7 ± 4.9 min) compared to the situation without an exoskeleton (3.2 ± 1.8 min) [50]. This suggests that wearing the exoskeleton during manual activities increased the endurance time of the subject group from 3.2 to 9.7 min. This could be of practical importance, because workers would be able to work for a longer period of time without experiencing unpleasant, distracting, and eventually harmful sensations. Also, Näf et al. (2018) found that passive exoskeletons appeared to simplify manual activities requiring to bend forward as much as possible with extended knees [56]. Finally, passive exoskeletons can assist people in many production settings involving assembling, packing, stitching, and material manual handling [57]. Cases of decreased productivity could pertain to several work sectors. Alternatively, if the same number of lifts are performed, the cumulative load could increase [35]. Passive exoskeletons, according to Baldassarre et al. (2022), are not a one-size-fits-all solution for employees or job duties and tend to demonstrate their potential more in static activities [54].

The fact that an exoskeleton is a prototype or a commercially available model does not inherently affect its impact on productivity. However, Figure 7B suggests an interesting observation: in commercial exoskeletons, there is only one case in which productivity decreases, as opposed to prototype exoskeletons in which productivity losses are much greater than cases in which productivity increases or remains unchanged. Unlike the previous case, in which the type of exoskeleton, whether passive, active, or hybrid, appeared to directly affects productivity due to design differences, the fact that an exoskeleton is a prototype or a commercially available model does not directly influence its productivity. The significant difference observed between the two cases is because a competitive exoskeleton on the market should not negatively impact productivity, otherwise companies will not be interested in purchasing it. On the other hand, a prototype exoskeleton serves to study new user support methods and is not primarily intended for sale.

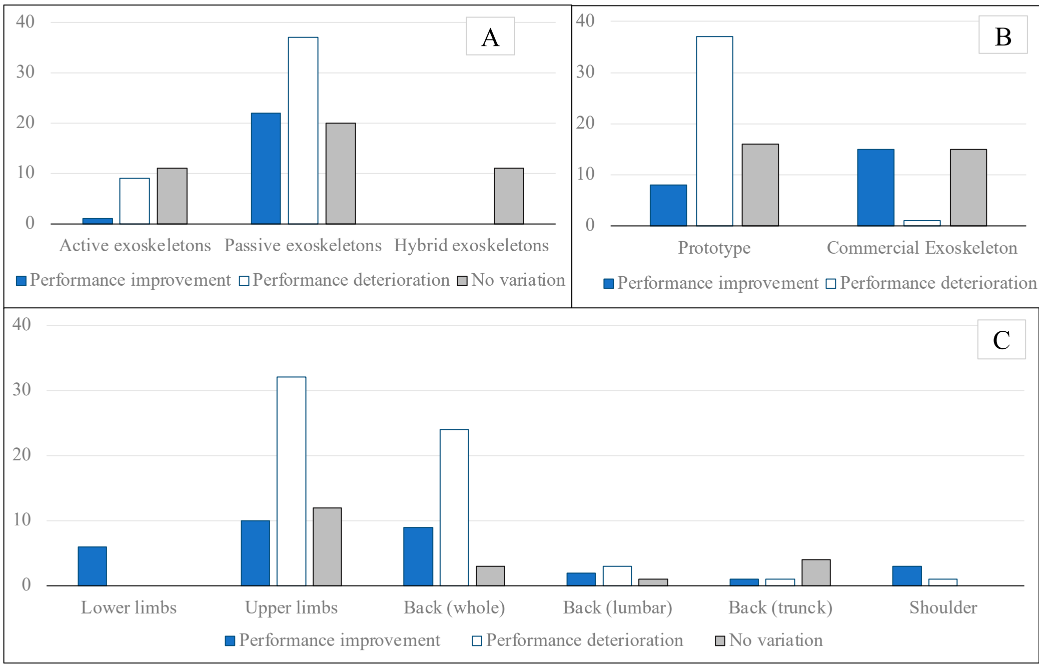

Figure 7. Studies that reported performance improvements, performance deterioration or no variation in the performance conditions, in case of active, passive or hybrid exoskeletons (**A**); studies that reported performance improvements, performance deterioration or no variation in the performance, in case of prototypes and commercial exoskeletons (**B**); studies that reported performance improvements, performance deterioration or no variation in the performance conditions, in case of exoskeletons supporting different body areas (**C**).

In terms of productivity, the body parts that have been most closely considered in the literature investigating the impact of exoskeleton on work performance are, in order: upper limbs, back (including the dorsal, trunk, and lumbar regions), lower limbs, and shoulders (Figure 7C). The upper limbs and, following them, the back are the body parts where it is observed the highest number of performance impairments. This is because they are the most invasive exoskeletons and tend to greatly impede movements. Examining the body parts that have been most closely considered in terms of productivity, it is possible to identify cases where improvements and impairments in performance are observed. For the upper limbs, cases of productivity improvement include: a decrease in drilling errors, an increase in speed during welding and painting [31,32], an increase in the average time of holding a static posture [50], improvement in mid-to-high height activities, and improvement in assembly, packaging, sewing, and Manual Material Handling (MMH) in various production contexts [57]. As for the impairments in performance, it was observed an increase in movement compensation time by 1 s during luggage handling, which, when multiplied by the number of movements made throughout the day, made the exoskeleton unusable [58]. It was also observed that upper limb exoskeletons tend to show their potential more in static activities than in dynamic ones, where they can impede the regular course of work [54]. Cases of performance improvement for the back include jobs that require static resistance of the trunk while bent forward, thereby increasing the duration of this position [50], jobs that require bending with the legs and remaining low, such as squatting and stopping movements [59], and assembly, packaging, sewing, and MMH activities in various production contexts [57]. As for impairments in performance, it was observed that back support exoskeletons hinder the regular course of work due to their bulky size or because the activity requires particular movements that are hindered by the exoskeleton [54]. In the cases where lower limb exoskeletons were considered in terms of productivity, only situations where there was an improvement in productivity are indicated. Specifically, these include a decrease in load by using a passive exoskeleton [60], an increase in repetitive lifting performance by healthy adults [41], and an improvement in range of motion that promoted stability and comfort [61]. Finally, cases of increased productivity are indicated for the shoulder, except for one case where productivity loss occurred as a result of a slowdown in a positioning work activity [62]. However, since this is an isolated case, it has little relevance for an overall evaluation of this type of exoskeleton. Other studies show that exoskeletons for the shoulder allow an increase in work performance by improving resistance to static positions and pressure during work [63].

3.5. User Acceptance

This section describes the improvements, deteriorations, or lack of variation in the subjective opinions of users based on the type of actuation, developmental stage, and body part supported by the exoskeleton. Subjective opinions have not been deeply investigated in scientific articles. In many cases, scientific publications preferred to focus on objective data rather than exploring user perceptions. However, it should be noted that many of these trials were conducted in controlled environments such as laboratories, and that individual opinions may have been less relevant as the trials were quite removed from real-life work scenarios. Nonetheless, a deep investigation of subjective considerations would have certainly helped to provide a more precise idea of the users' perception of exoskeletons. Based on the data collected, it is possible to assume that the use of exoskeletons has not resulted in a negative perception by users, as in most cases, evaluations were either neutral or positive (Figure 8).

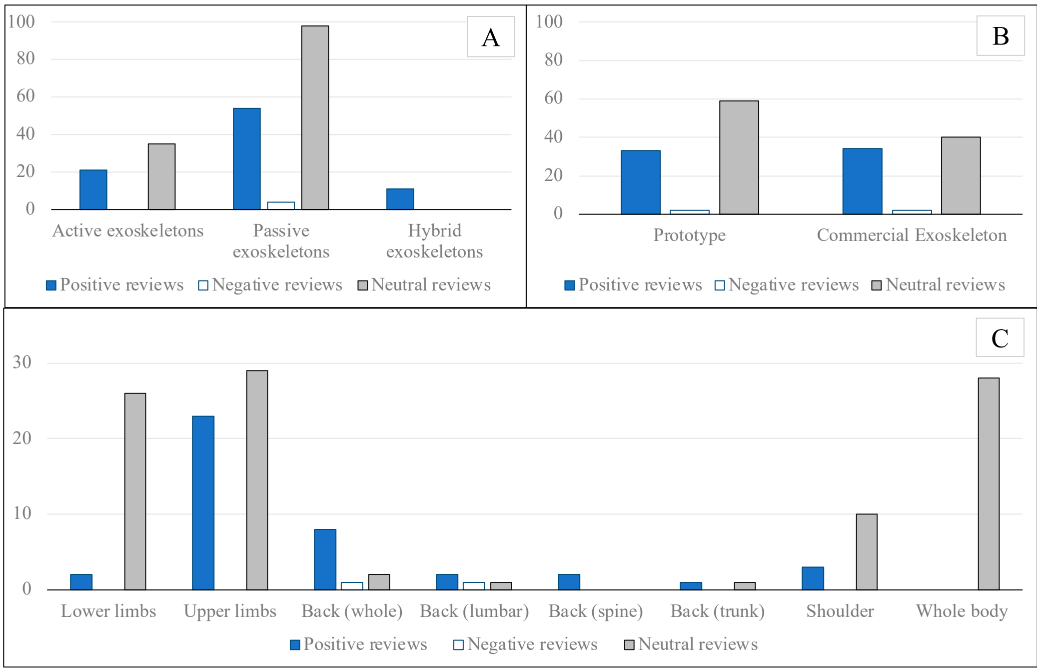

Figure 8. Studies that reported positive reviews, negative reviews or neutral reviews, in case of active, passive or hybrid exoskeletons (**A**); studies that reported positive reviews, negative reviews or neutral reviews, in case of prototypes and commercial exoskeletons (**B**); studies that reported positive reviews, negative reviews or neutral reviews, in case of exoskeletons supporting different body areas (**C**).

Regarding active exoskeletons, the cases analyzed have resulted in either positive or neutral evaluations by users (Figure 8A). Positive reviews refer to a decrease in perceived discomfort when using the exoskeleton compared to performing the same task without it [6,24,26,55]. In neutral evaluations, users did not perceive any difference in discomfort with or without the use of the exoskeleton. For passive exoskeletons, in some cases the users have given negative evaluations. In these cases, users have reported on multiple occasions that the weight of the exoskeleton caused strong pressure on a body part, reducing comfort. Positive and neutral evaluations reported for passive exoskeletons are similar to those for active exoskeletons, where a decrease in perceived discomfort with the exoskeleton or no perceived difference is reported without further evaluation. In the case of hybrid exoskeletons, evaluations are only positive, as the studies reported a good effect on reducing fatigue in the activities for which they are used.

The rate of positive perceptions was higher in case of commercially available exoskeletons, compared to the positive perceptions collected during the experimental studies with prototypes (Figure 8B). This might be because in many cases, these devices were used in work environments for sufficiently long periods where the user's opinion was collected.

As the evaluations conducted in such case studies were not in-depth and were rather superficial, it is not possible to further explore these results. However, the results obtained regarding positive, negative, and neutral evaluations in prototype exoskeletons are quite consistent with those of commercially available exoskeletons.

Figure 8C shows the body parts that have received the most attention of the users, i.e., the upper limbs, the whole body and the lower limbs. For these body areas, the evaluations are mostly neutral. In case of exoskeletons supporting the shoulder, a small proportion of users have given positive feedback.

In the case of the back, the evaluations are more balanced, with both positive and neutral feedback, as well as negative feedback. Specifically, negative evaluations for the back were concentrated on exoskeletons that support the entire back and the lumbar region, as these areas are particularly difficult to support without risking excessive pressure that reduces user comfort.

3.6. A Systematic Approach for Adopting Occupational Exoskeletons

Based on the evidence presented, a 6-step approach for adopting occupational exoskeletons can be outlined as in Table 1.

Table 1. 6-step procedure for the adoption of occupational exoskeletons.

Step 1. Assess Workplace Requirements
1.1 Conduct a comprehensive analysis of the workplace, considering specific tasks and contexts. 1.2 Identify unique requirements and challenges faced by the company, including the analysis of historical injury occurences and consultation with the workforce. 1.3 Evaluate potential benefits and limitations of exoskeletons in addressing these requirements.
Step 2. Focus on Supported Body Areas
2.1 Analyze the data on upper limb, shoulder, lower limb, whole body, and back support exoskeletons. 2.2 Assess the safety, health benefits, performance improvements, and user acceptance associated with each supported body area. 2.3 Identify specific tasks or job roles where exoskeletons can enhance efficiency and reduce errors.
Step 3. Select Exoskeleton Type
3.1 Determine the type of exoskeleton (active, passive, or hybrid) based on the identified needs and safety considerations. 3.2 Consider the impact on health, performance, and user acceptance.
Step 4. Design and Ergonomics Optimization
4.1 Improve exoskeleton design and ergonomics to mitigate trunk muscle weakening, reduced blood flow, and other potential issues. 4.2 Ensure long-term safety and user comfort by considering customization and adjustment options.

Table 1. *Cont.*

Step 5. Gradual Implementation and Performance Evaluation
5.1 Implement the selected exoskeletons gradually, limiting their use to a selected sample of workers and tasks and considering organizational factors. 5.2 Monitor performance variations and evaluate the impact on productivity. 5.3 Address any issues that may arise during the implementation phase.
Step 6. Continuous Improvement
6.1 Conduct ongoing analysis and adjustments to optimize exoskeleton effectiveness and usability. 6.2 Monitor and evaluate long-term effects, comfort levels, and user acceptance in the workplace. 6.3 Improve exoskeletons' design, comfort, and functionality for specific tasks and users.

3.6.1. Step 1. Assess Workplace Requirements

The first step involves a detailed evaluation of the workplace and the identification of the unique demands and barriers that the organization experiences. This involves assessing the activities performed, the conditions in which they occur, and the company's specific demands. The aim is to understand out how exoskeletons can meet these requirements and constraints. Conducting a comprehensive assessment of the workplace is a critical component of this activity. This includes evaluating the physical demands of the task as well as the repeated movements required. It also entails assessing the safety risks connected with existing work procedures.

By identifying the unique requirements and challenges faced by the company, it becomes possible to assess the potential benefits and limitations of exoskeletons in addressing these needs. This step also includes the analysis of historical injury occurrences over an extended duration with the aim to discern recurrent patterns. Additionally, it marks the commencement of the consultation phase with the workforce.

During this phase, the reasons for implementation, the implementation process, and any potential issues or concerns that warrant resolution before execution are discussed. Overall, this step allows for making informed decisions and planning the implementation of occupational exoskeletons. Companies may acquire a comprehensive understanding of their unique demands and establish the potential usefulness of exoskeletons in satisfying those needs by undertaking a full assessment of workplace requirements.

3.6.2. Step 2. Focus on Supported Body Areas

In Step 2, the goal is to analyze the available data on different supported body areas for exoskeletons, which include upper limb, shoulder, lower limb, whole body, and back support. The analysis involves assessing the safety, health benefits, performance improvements, and user acceptance associated with each supported body area. Safety considerations are of utmost importance. The analysis should focus on the reported safety outcomes, including any potential risks, such as muscle weakness and activation, restricted movements, or balance issues, associated with the use of exoskeletons in that particular area.

Understanding the safety implications will help in making informed decisions regarding the adoption of exoskeletons for specific body areas. Health benefits should also be assessed. This involves examining the impact of exoskeletons on reducing physical strain, muscle fatigue, and metabolic demand. The analysis should also explore the reported performance variations with the use of exoskeletons in different supported body areas. This may include investigating productivity enhancements, such as improved accuracy, increased range of motion, or better task performance, observed in specific tasks or job roles. Furthermore, the analysis should include examining the reported user evaluations for each supported body area. This involves considering feedback on comfort, ease of use, and overall satisfaction with the exoskeletons. Understanding user preferences and acceptance levels will help in identifying specific tasks where exoskeletons are more likely to be accepted and perceived positively by workers.

3.6.3. Step 3. Select Exoskeleton Type

The focus of Step 3 is on determining the most suitable type of exoskeleton based on the identified company needs and safety considerations. This decision involves considering the impact of different exoskeleton types on factors such as muscle activity, coordination, productivity, and user acceptance, as reported in previous studies. The selection process should consider the specific needs and requirements identified during the workplace assessment. Considerations should be given to the tasks and contexts in which the exoskeleton will be used. For example, tasks involving repetitive lifting may benefit from an active exoskeleton, while tasks with potential collisions may require avoiding passive exoskeletons. Safety considerations play a crucial role in the selection process. The impact on muscle activity and coordination should be carefully evaluated, as increased muscle fatigue or compromised coordination can pose safety risks.

Work performance, such as productivity, is another important aspect to consider. Understanding the potential impact on productivity is essential to assess the overall value of adopting a particular exoskeleton type. This is possible by identifying key performance indicators, i.e., number of produced units in a given time, that should be assessed and compared before and after the adoption of the exoskeleton. User acceptance is a significant factor for the successful adoption of exoskeletons.

Previous studies have reported a wide range of user evaluations, using different methodologies. Considering user feedback and preferences can help ensure the selected exoskeleton type aligns with the comfort and acceptance levels of the workers. By carefully considering the reported effects of active, passive, and hybrid exoskeletons on muscle activity, coordination, productivity, and user acceptance, companies can make an informed decision on the most appropriate type of exoskeleton for their specific needs and safety considerations.

3.6.4. Step 4. Design and Ergonomics Optimization

Step 4 addresses the limitations and safety concerns identified in relation to exoskeletons, with the aim to optimize their design and ergonomics. This might include making adjustments to the workplace and materials to improve the functioning and usability of the exoskeletons. Customization and modification options should be addressed to guarantee long-term safety and user comfort. Individual preferences and requirements should be accommodated by exoskeletons and workplaces. This may include including aspects that allow for personalization and adjustments to provide the best fit and comfort for each user. By providing flexibility in the design, it becomes possible to meet the unique requirements of different individuals and enhance overall user satisfaction. By implementing improvements based on the analysis of observed issues, companies and safety professionals can enhance the long-term safety, usability, and comfort of exoskeletons for the workers. This contributes to a more effective integration of exoskeletons in the workplace and improves the overall experience of workers utilizing these devices.

3.6.5. Step 5. Gradual Implementation and Performance Evaluation

In Step 5, the focus is on the gradual implementation of the selected exoskeletons and the evaluation of their performance. The implementation process involves introducing the exoskeletons gradually, limiting their initial use to a selected sample of workers and specific tasks. To begin the implementation, a careful selection is made to identify a sample group of workers and tasks that are well-suited for the initial use of exoskeletons. This Step includes the screening of individual users for health and safety risk factors, such as underlying health conditions. By limiting the implementation to a smaller sample, it allows for closer monitoring and assessment of the exoskeletons' performance in the workplace. During the implementation phase, it is important to closely monitor and evaluate the performance variations associated with the use of exoskeletons. This includes assessing their impact on productivity, comparing it to the pre-exoskeleton performance, and identifying any improvements or challenges that arise. By systematically evaluating performance, it becomes possible to gather valuable data and insights on the effectiveness of the exoskeletons in enhancing productivity. Addressing any issues that may arise during the implementation phase is crucial. It is important to maintain open lines of communication with the workers using the exoskeletons and encourage feedback. Any challenges or concerns that arise should be promptly addressed and resolved to ensure a smooth and successful implementation process. This may require making changes and adjustments to the existing work procedures and providing additional training or support for the workers. This step includes the analysis of organizational factors, focusing on change management processes. Also, this step highlights potential areas for improvement and ensures that exoskeletons are effectively integrated into the work processes.

3.6.6. Step 6. Continuous Improvement

The last step, Step 6, underlines the need of continued efforts to enhance the efficacy and usefulness of exoskeletons in the workplace. Continuous monitoring entails measuring elements such as user health, comfort levels, and workplace acceptance. By collecting data and feedback throughout time, it is possible to identify any potential concerns that might arise and implement measures to mitigate them. Usability is another critical aspect that needs continuous attention. This may involve refining the ergonomics, materials, or adjustability features of the workplace to enhance user experience and ensure optimal fit and comfort. By continuously seeking to improve effectiveness, usability, and user experience, the adoption and integration of exoskeletons in the workplace can continue to evolve and provide long-term benefits for workers and organizations alike. Finally, these devices necessitate customization to cater to the specific requirements of each individual. This customization is crucial to mitigate the risk of exacerbating injuries, minimize discomfort, and enhance safety.

4. Discussion

4.1. Active, Passive or Hybrid Exoskeletons?

Safety concerns on the use of active exoskeletons primarily focused on increased leg muscle activity required to support the weight of the exoskeleton, suggesting the need for more frequent breaks to prevent muscle fatigue and potential effects on coordination, particularly in the shoulder, which could increase the risk of WMSDs and injuries. In terms of performance, in most cases active exoskeletons did not contribute to increased productivity. Regarding user acceptance of active exoskeletons, the results are encouraging. In positive evaluations, users reported reduced discomfort when performing tasks with the exoskeleton compared to without it. In neutral evaluations, users did not perceive any difference in discomfort with or without the active exoskeleton.

Regarding the safety of passive exoskeletons, the majority of cases (87%) showed a deterioration in safety conditions, while a small percentage (10%) demonstrated an improvement, and a minor portion (3%) reported no change. Concerns regarding the deterioration of safety conditions were mainly related to weakened trunk muscles, restricted movements due to the rigid structure of the exoskeleton, and an increased risk of balance loss and falls. Passive exoskeletons are generally not recommended for tasks involving potential collisions with objects or individuals due to the increased risk of injuries. However, passive exoskeletons have largely positive effects on health, including supporting the targeted body part without imposing excessive strain on other areas, reducing peak loads, and decreasing metabolic consumption during lifting. Negative health effects primarily involve shoulder muscles' imbalance and increased body temperature in hot environments. In terms of performance, passive exoskeletons generally show a tendency towards deterioration, although the data is better compared to active exoskeletons. Overall, the acceptance of passive exoskeletons appears to be favorable, with fewer criticisms compared to active exoskeletons. The inclusion of hybrid exoskeletons in the analysis in this study is based on a limited number of instances found in scientific articles. However, the insufficient analysis of these instances hinders the provision of positive or negative evaluations regarding safety, health, performance, and subjective opinions of users.

4.2. Insights on Occupational Exoskeletons Based on the Supported Body Areas

Based on the available information regarding upper limb support exoskeletons, there are several suggestions for the use of occupational exoskeletons in this context. Given the safety outcomes observed in the literature, it is crucial to address the weakening of trunk muscles and the potential for reduced blood flow in the arm's human-machine interface. The observed positive health outcomes, such as decreased mechanical energy, altered joint torques, and reduced muscle activity during lifting and static conditions, highlight the potential for exoskeletons to alleviate physical strain and promote better musculoskeletal health. Therefore, their use should be encouraged in tasks where repetitive or strenuous upper limb movements are involved. Overall, the use of upper limb support exoskeletons in occupational settings should be carefully implemented, with attention to safety, health benefits, task-specific performance improvements, and user comfort. Similarly, occupational exoskeletons for shoulder support appear to offer potential benefits for worker health and productivity. The studies reviewed indicate that these exoskeletons can reduce muscle load and fatigue, improve postural function, and enhance work performance. However, safety considerations for shoulder exoskeletons have not been extensively studied, so caution should be exercised when implementing these devices in the workplace. In terms of practical applications, it may be beneficial to consider implementing these exoskeletons in jobs that require repetitive or sustained overhead work, such as assembly line work or construction. It may also be useful to conduct further research to evaluate the long-term effects of using these exoskeletons, as well as to optimize their design and functionality for specific work tasks.

Benefits of lower limb exoskeletons include decreased load using passive exoskeletons, increased performance in repetitive lifting tasks for healthy adults, and improved range of motion promoting stability and comfort. These exoskeletons have demonstrated potential for improving user health, reducing muscle fatigue, and enhancing performance. Further research and development are warranted to optimize the design, comfort, and usability of lower limb exoskeletons for specific occupational tasks, ensuring a safe and effective integration in the workplace.

Occupational exoskeletons for whole body support have shown potential in improving user health by reducing muscle fatigue and metabolic demand. Based on the information provided, it is suggested to consider the application of occupational exoskeletons for whole body support in tasks that involve extended periods of physically demanding work or repetitive movements. Further research and development efforts are necessary to evaluate the impact of whole-body exoskeletons on performance metrics and to ensure their compatibility with various occupational tasks. Additionally, it is recommended to conduct user evaluations to assess the usability, comfort, and acceptance of these exoskeletons in real-world work environments.

Regarding back support exoskeletons, the negative results outlined in the investigated studies can be attributed to the adverse effects of using exoskeletons with high external forces on walking energy and fall risk. Exoskeletons that effectively reduce loads on the spine while minimizing constraints on natural movements have demonstrated potential for improving user health and productivity. The improvements observed were attributed to significant reductions in loads on passive tissues of the curved spine, without significantly increasing loads on the hip, knee, and ankle joints.

Additionally, reductions in average peak and muscle activation of back and leg muscles were observed during MMH. Performance improvements were noted in tasks requiring sustained trunk flexion, increasing the duration of this position, squatting and stooping movements and various production activities such as assembly, packaging, sewing, and MMH. Performance deteriorations were attributed to bulky exoskeletons that hindered work activities or restricted specific movements required for the task. Regarding occupational exoskeletons for hip, ankle, neck, and elbow support, they are relatively uncommon, and there are insufficient cases in the available scientific literature for a comprehensive analysis.

While studies have explored the short-term impact and immediate benefits of exoskeleton use, there is a significant gap in knowledge regarding their sustained effectiveness and potential risks over extended periods. Moreover, the potential for adaptation or habituation to exoskeletons by the human body over time remains uncertain. Longitudinal studies tracking workers' health, safety, and ergonomic outcomes over an extended duration are necessary to fill this research gap. These studies should evaluate the sustained impact of exoskeleton use on reducing MSDs, as well as potential unintended consequences or new risks that may emerge over time.

In most cases where user perception evaluations were collected, the user judgments were not explicitly stated, but rather only whether the user perceived an increase or decrease in discomfort sensation when using the exoskeleton, providing a brief evaluation. This limitation prevented a more in-depth analysis of user evaluations, as most cases used rating scales such as Likert or Borg scales, which did not allow users to elaborate on their judgments. Another limitation is due the limited duration of the trials, which could have influenced people's judgments, i.e., as most of the studies were conducted in a controlled environment, the average duration of the trials was limited, ranging from a few minutes to a couple of hours. This duration is not representative of the actual duration of a work shift, nor it is compatible with the time required to detect any potential negative effects of working with an exoskeleton for an extended period of time.

5. Conclusions

This study offers a contribution to the safe, effective, and appropriate adoption of exoskeletons in the workplace. By combining the latest scientific research in the field of exoskeleton technology and occupational exoskeletons, the step-wise approach proposed in this study aims to maximize the potential benefits and reduce the possible risks for workers and employers alike. The findings in this research suggest that the use of exoskeletons in occupational settings holds promise for improving worker safety and well-being, particularly in relation to MSDs. However, caution is warranted, as the evidence regarding the effectiveness of exoskeletons in reducing the risk of MSDs is lacking. To ensure the reduction of MSDs, it is crucial to understand the long-term implications of exoskeleton implementation in occupational settings. Factors such as prolonged use, extended work shifts, and repeated movements may have different effects on the body compared to short-term interventions. Additionally, comprehensive research should consider the individual factors that can influence long-term outcomes, such as worker characteristics, task requirements, and exoskeleton design features. By investigating these variables, researchers can identify best practices, optimal usage patterns, and potential limitations or contraindications for different populations and work environments.

Future studies should prioritize longitudinal investigations to gain a comprehensive understanding of the sustained impact and potential risks associated with exoskeleton use, thereby ensuring the development of evidence-based guidelines for their implementation in promoting worker health and safety. Standardized testing protocols should be developed for consistent evaluation. Integration with other technologies, like artificial intelligence, can enhance effectiveness.

The field of occupational exoskeleton research faces several challenges. Future directions should include the development of standardized testing protocols to ensure consistent and reliable evaluation of exoskeleton performance. Further advancements in materials and exoskeleton designs can contribute to improved ergonomic fit and user comfort. Collaboration between researchers, industry, and end-users is crucial for advancing the field of occupational exoskeletons. Such partnerships can facilitate the translation of research findings into practical solutions that address the specific needs and requirements of different industries and work environments. Overall, continued investment in research and development is necessary to mitigate risks, optimize benefits, and enhance the overall well-being and productivity of workers.

Finally, ongoing research and development should strive to address specific challenges and requirements identified in different work contexts. By understanding the unique needs of each company and the tasks performed, it becomes possible to develop tailored solutions that effectively address those requirements. This may involve collaborating with industry experts, conducting field studies, and leveraging emerging technologies to push the boundaries of exoskeleton design and performance. By emphasizing continuous research and development, companies can stay at the forefront of exoskeleton technology. This allows for the refinement and optimization of exoskeletons based on evolving needs and advancements. By continuously seeking to improve effectiveness, usability, and user experience, the adoption and integration of exoskeletons in the workplace can continue to evolve and provide the promised long-term benefits for workers and organizations alike.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

No.	Authors	Year	Title	Document Type	DOI
1	Gumasing et al.	2023	Factors influencing the perceived usability of wearable chair exoskeleton with market segmentation: A structural equation modeling and K-Means Clustering approach	Research study	https://doi.org/10.1016/j.ergon.2022.103401
2	Qingcong and Chen	2023	Adaptive cooperative control of a soft elbow rehabilitation exoskeleton based on improved joint torque estimation	Research study	https://doi.org/10.1016/j.ymssp.2022.109748
3	Madinei and Nussbaum	2023	Estimating lumbar spine loading when using back-support exoskeletons in lifting tasks	Research study	https://doi.org/10.1016/j.jbiomech.2023.111439
4	De Bock et al.	2023	Passive shoulder exoskeleton support partially mitigates fatigue-induced effects in overhead work	Research study	https://doi.org/10.1016/j.apergo.2022.103903
5	Chittar et al.	2023	Experimental investigations on waist supportive passive exoskeleton to improve human comfort	Conference proceeding	https://doi.org/10.1016/j.matpr.2022.09.086
6	Iranzo et al.	2022	Assessment of a Passive Lumbar Exoskeleton in Material Manual Handling Tasks under Laboratory Conditions	Research study	https://doi.org/10.3390/s22114060
7	Le Tellier et al.	2022	Objective and Subjective Evaluation of a Passive Exoskeleton for Upper Limbs	Research study	https://doi.org/10.20944/preprints202111.0512.v1
8	Baldassarre et al.	2022	Industrial exoskeletons from bench to field: Human-machine interface and user experience in occupational settings and tasks	Review	https://doi.org/10.3389/fpubh.2022.1039680
9	Van Der Have et al.	2022	The Exo4Work shoulder exoskeleton effectively reduces muscle and joint loading during simulated occupational tasks above shoulder height	Research study	https://doi.org/10.1016/j.apergo.2022.103800
10	Chun Lung So et al.	2022	Biomechanical assessment of a passive back-support exoskeleton during repetitive lifting and carrying: Muscle activity, kinematics, and physical capacity	Research study	https://doi.org/10.1016/j.jsr.2022.08.017
11	Weckenborg et al.	2022	Harmonizing ergonomics and economics of assembly lines using collaborative robots and exoskeletons	Research study	https://doi.org/10.1016/j.jmsy.2022.02.005
12	Linnenberg and Weidner	2022	Industrial exoskeletons for overhead work: Circumferential pressures on the upper arm caused by the physical human-machine-interface	Research study	https://doi.org/10.1016/j.apergo.2022.103706
13	Bances et al.	2022	Applicability of Exoskeletons in Timber Prefabrication: actions for exoscheleton research	Conference proceeding	https://doi.org/10.1016/j.procir.2022.05.133
14	Tetteh et al.	2022	Effects of passive exoskeleton support on EMG measures of the neck, shoulder and trunk muscles while holding simulated surgical postures and performing a simulated surgical procedure	Research study	https://doi.org/10.1016/j.apergo.2021.103646
15	Dos Anjos et al.	2022	Changes in the distribution of muscle activity when using a passive trunk exoskeleton depend on the type of working task: A high-density surface EMG study	Research study	https://doi.org/10.1016/j.jbiomech.2021.110846
16	Longo et al.	2022	Human Ergonomic Simulation to Support the Design of an Exoskeleton for Lashing/De-lashing operations of Containers Cargo	Conference proceeding	https://doi.org/10.1016/j.procs.2022.01.390
17	G. Cesarelli et al.	2022	Gait analysis to quantitatively classify Ataxia and Parkinson's disease patients: a pilot study using tree-based Machine Learning algorithms	Research study	https://doi.org/10.1016/j.gaitpost.2022.09.057
18	Park et al.	2022	Effects of using a whole-body powered exoskeleton during simulated occupational load-handling tasks: A pilot study	Research study	https://doi.org/10.1016/j.apergo.2021.103589
19	Liao et al.	2022	Proxy-based torque control of motor-driven exoskeletons for safe and compliant human-exoskeleton interaction	Research study	https://doi.org/10.1016/j.mechatronics.2022.102906
20	Pacifico et al.	2022	Exoskeletons for workers: A case series study in an enclosures production line	Research study	https://doi.org/10.1016/j.apergo.2022.103679

No.	Authors	Year	Title	Document Type	DOI
21	Park et al.	2022	Effects of back-support exoskeleton use on gait performance and stability during level walking	Research study	https://doi.org/10.1016/j.gaitpost.2021.11.028
22	Park et al.	2022	Wearing a back-support exoskeleton impairs single-step balance recovery performance following a forward loss of balance—An exploratory study	Research study	https://doi.org/10.1016/j.jbiomech.2022.111352
23	Pinho and Forner.Cordero	2022	Shoulder muscle activity and perceived comfort of industry workers using a commercial upper limb exoskeleton for simulated tasks	Research study	https://doi.org/10.1016/j.apergo.2022.103718
24	Hull et al.	2022	Design and preliminary evaluation of two tool support arm exoskeletons with gravity compensation	Research study	https://doi.org/10.1016/j.mechmachtheory.2022.104802
25	Zelik et al.	2022	An ergonomic assessment tool for evaluating the effect of back exoskeletons on injury risk	Research study	https://doi.org/10.1016/j.apergo.2021.103619
26	Zheng et al.	2022	Critical review on applications and roles of exoskeletons in patient handling	Review	https://doi.org/10.1016/j.ergon.2022.103290
27	Roveda et al.	2022	User-Centered Back-Support Exoskeleton: Design and Prototyping	Conference proceeding	https://doi.org/10.1016/j.procir.2022.05.019
28	Moulart et al.	2022	Subjective assessment of a lumbar exoskeleton's impact on lower back pain in a real work situation	Research study	https://doi.org/10.1016/j.heliyon.2022.e11420
29	Jorgensen et al.	2022	The impact of passive shoulder exoskeletons during simulated aircraft manufacturing sealing tasks	Research study	https://doi.org/10.1016/j.ergon.2022.103337
30	Jorgensen et al.	2022	Influence of different passive shoulder exoskeletons on shoulder and torso muscle activation during simulated horizontal and vertical aircraft squeeze riveting tasks	Research study	https://doi.org/10.1016/j.apergo.2022.103822
31	Pang et al.	2022	Estimation of the interaction force between human and passive lower limb exoskeleton device during level ground walking	Research study	https://doi.org/10.1016/j.birob.2022.100056
32	Chittar et al.	2022	Waist-Supportive Exoskeleton: Systems and Materials	Conference proceeding	https://doi.org/10.1016/j.matpr.2022.02.455
33	Rimmele et al.	2022	Motor variability during a repetitive lifting task is impaired by wearing a passive back-support exoskeleton	Research study	https://doi.org/10.1016/j.jelekin.2022.102739
34	Madinei et al.	2022	A novel approach to quantify the assistive torque profiles generated by passive back-support exoskeletons	Research study	https://doi.org/10.1016/j.jbiomech.2022.111363
35	De Bock et al.	2022	Benchmarking occupational exoskeletons: An evidence mapping systematic review	Review	https://doi.org/10.1016/j.apergo.2021.103582
36	Shaoping Bai	2022	User-centered development and performance assessment of a modular full-body exoskeleton (AXO-SUIT)	Research study	https://doi.org/10.1016/j.birob.2021.100032
37	Elprama et al.	2022	An industrial exoskeleton user acceptance framework based on a literature review of empirical studies	Review	https://doi.org/10.1016/j.apergo.2021.103615
38	Shing Man et al.	2022	Effects of passive exoskeleton on trunk and gluteal muscle activity, spinal and hip kinematics and perceived exertion for physiotherapists in a simulated chair transfer task: A feasibility study	Research study	https://doi.org/10.1016/j.ergon.2022.103323
39	McFarland et al.	2022	Level of exoskeleton support influences shoulder elevation, external rotation and forearm pronation during simulated work tasks in females	Research study	https://doi.org/10.1016/j.apergo.2021.103591
40	Gillette et al.	2022	Electromyography-based fatigue assessment of an upper body exoskeleton during automotive assembly	Conference proceeding	https://doi.org/10.1017/wtc.2022.20
41	Wang et al.	2021	Evaluation of a Passive Upper-Limb Exoskeleton Applied to Assist Farming Activities in Fruit Orchards	Research study	https://doi.org/10.3390/app11020757
42	Dezheng et al.	2021	The Assist Performance Test of Industrial Passive Waist-assistant Exoskeleton on Fatigue during a Repetitive Lifting Task	Research study	https://doi.org/10.1088/1742-6596/1748/6/062039

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43	Pesenti et al.	2021	Towards a Functional Performance Validation Standard for Industrial Low-Back Exoskeletons: State of the Art Review	Review	https://doi.org/10.3390/s21030808
44	Qu et al.	2021	Effects of an industrial passive assistive exoskeleton on muscle activity, oxygen consumption and subjective responses during lifting tasks	Research study	https://doi.org/10.1371/journal.pone.0245629
45	Kozinc et al.	2021	Comparison of Subjective Responses of Low Back Pain Patients and Asymptomatic Controls to Use of Spinal Exoskeleton during Simple Load Lifting Tasks: A Pilot Study	Research study	https://doi.org/10.3390/ijerph18010161
46	Song et al.	2021	Multijoint passive elastic spine exoskeleton for stoop lifting assistance	Research study	https://doi.org/10.1177/17298814211062033
47	Drees et al.	2021	Methodology for a task-specific and personalised development of an initial exoskeleton design	Conference proceedings	https://doi.org/10.1017/pds.2021.469
48	Liu et al.	2021	The effects of a passive exoskeleton on human thermal responses in temperate and cold environments	Research study	https://doi.org/10.3390/ijerph18083889
49	Simon et al.	2021	Kinematic effects of a passive lift assistive exoskeleton	Research study	https://doi.org/10.1016/j.jbiomech.2021.110317
50	Rusu et al.	2021	A generic hybrid human/exoskeleton digital model towards digital trasformation of exoskeletons-integrated workplaces	Conference proceedings	https://doi.org/10.1016/j.procir.2021.11.301
51	Schwerha et al.	2021	Adoption potential of occupational exoskeletons in diverse enterprises engaged in manufacturing tasks	Research study	https://doi.org/10.1016/j.ergon.2021.103103
52	Park et al.	2021	Effects of two passive back-support exoskeletons on postural balance duringquiet stance and functional limits of stability	Research study	https://doi.org/10.1016/j.jelekin.2021.102516
53	Sun et al.	2021	Model-free prescribed performance fixed-time control for wearable exoskeletons	Research study	https://doi.org/10.1016/j.apm.2020.09.010
54	Antwi-Afari et al.	2021	Assessment of a passive exoskeleton system on spinal biomechanics and subjective responses during manual repetitive handling tasks among construction workers	Research study	https://doi.org/10.1016/j.ssci.2021.105382
55	Madinei et al.	2021	Effects of back-support exoskeleton use on trunk neuromuscular control during repetitive lifting: A dynamical systems analysis	Research study	https://doi.org/10.1016/j.jbiomech.2021.110501
56	Luger et al.	2021	A passive back exoskeleton supporting symmetric and asymmetric lifting in stoop and squat posture reduces trunk and hip extensor muscle activity and adjusts body posture—A laboratory study	Research study	https://doi.org/10.1016/j.apergo.2021.103530
57	Chae et al.	2021	Systematic usability evaluation on two harnesses for a wearable chairless exoskeleton	Research study	https://doi.org/10.1016/j.ergon.2021.103162
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59	Yan et al.	2021	Development and testing of a wearable passive lower-limb support exoskeleton to support industrial workers	Research study	https://doi.org/10.1016/j.bbe.2020.12.010
60	Zhu et al.	2021	Exoskeletons for manual material handling—A review and implication for construction applications	Review	https://doi.org/10.1016/j.autcon.2020.103493
61	Proud et al.	2020	Exoskeleton Application to Military Manual Handling Tasks	Review	https://doi.org/10.1177/0018720820957467
62	Pacifico et al.	2020	An Experimental Evaluation of the Proto-MATE: A Novel Ergonomic Upper-Limb Exoskeleton to Reduce Workers' Physical Strain	Research study	https://doi.org/10.1109/MRA.2019.2954105
63	Del Ferraro et al.	2020	The Effects of Upper-Body Exoskeletons on Human Metabolic Cost and Thermal Response during Work Tasks—A Systematic Review	Review	https://doi.org/10.3390/ijerph17207374
64	Thamsuwan et al.	2020	Potential exoskeleton uses for reducing low back muscular activity during farm tasks	Research study	https://doi.org/10.1002/ajim.23180
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66	Baltrush et al.	2020	Passive Trunk Exoskeleton Acceptability and Effects on Self-efficacy in Employees with Low-Back Pain: A Mixed Method Approach	Research study	https://doi.org/10.1007/s10926-020-09891-1
67	Liu et al.	2020	Functional Evaluation of a Force Sensor-Controlled Upper-Limb Power-Assisted Exoskeleton with High Backdrivability	Research study	https://doi.org/10.3390/s20216379
68	Glock et al.	2020	Assistive devices for manual materials handling in warehouses: a systematic literature review	Review	https://doi.org/10.1080/00207543.2020.1853845
69	Steinhilber et al.	2020	The use of exoskeletons in the occupational context for primary, secondary, and tertiary prevention of work-related musculoskeletal complaints	Guideline	https://doi.org/10.1080/24725838.2020.1844344
70	Madinei et al.	2020	Biomechanical assessment of two back-support exoskeletons in symmetric and asymmetric repetitive lifting with moderate postural demands	Research study	https://doi.org/10.1016/j.apergo.2020.103156
71	Poliero et al.	2020	Applicability of an Active Back-Support Exoskeleton to Carrying Activities	Research study	https://doi.org/10.3389/frobt.2020.579963
72	Yin et al.	2020	Effects of a passive upper extremity exoskeleton for overhead tasks	Research study	https://doi.org/10.1016/j.jelekin.2020.102478
73	Kim et al.	2020	Assessing the potential for "undesired" effects of passive back-support exoskeleton use during a simulated manual assembly task: Muscle activity, posture, balance, discomfort, and usability	Research study	https://doi.org/10.1016/j.apergo.2020.103194
74	Alabdulkarim et al.	2020	Effects of a Wearable Carriage Aid on Whole-Body Physiological Measures and Balance	Research study	https://doi.org/10.3390/app10228076
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79	Jorge E	2020	Wearable sensor array design for spine posture monitoring during exercise incorporating biofeedback	Research study	https://doi.org/10.1109/TBME.2020.2971907
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81	Yang et al.	2020	Lower limb exoskeleton gait planning based on crutch and human-machine foot combined center of pressure	Research study	https://doi.org/10.3390/s20247216
82	Wu et al.	2020	SIAT-WEXv2: a wearable exoskeleton for reducing lumbar load during lifting tasks	Research study	https://doi.org/10.1155/2020/8849427
83	Koopman et al.	2019	Effects of a passive exoskeleton on the mechanical loading of the low back in static holding tasks	Research study	https://doi.org/10.1016/j.jbiomech.2018.11.033
84	Yang et al.	2019	Spine-inspired continuum soft exoskeleton for stoop lifting assistance	Research study	https://doi.org/10.48550/arXiv.1907.02562
85	Baltrusch et al.	2019	The effect of a passive trunk exoskeleton on metabolic costs during lifting and walking	Research study	https://doi.org/10.1080/00140139.2019.1602288
86	Fox et al.	2019	Exoskeletons. Comprehensive, comparative and critical analyses of their potential to improve manufacturing performance	Review	https://doi.org/10.1108/JMTM-01-2019-0023
87	Ringhof et al.	2019	Does a passive unilateral lower limb exoskeleton affect human static and dynamic balance control?	Research study	https://doi.org/10.3389/fspor.2019.00022
88	Wijegunawardana et al.	2019	ChairX: a robotic exoskeleton chair for industrial workers	Research study	https://doi.org/10.1109/ICORR.2019.8779501

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89	Hensel and Keil	2019	Subjective evaluation of a passive industrial exoskeleton for lower-back support: a field study in the automotive sector	Research study	https://doi.org/10.1080/24725838.2019.1573770
90	Theurel and Desbrosses	2019	Occupational exoskeletons: Overview of their benefits and limitations in preventing work-related musculoskeletal disorders	Review	https://doi.org/10.1080/24725838.2019.1638331
91	Marino	2019	Impacts of Using Passive Back Assist and Shoulder Assist Exoskeletons in a Wholesale and Retail Trade Sector Environment	Research study	https://doi.org/10.1080/24725838.2019.1645057
92	McFarland and Fischer	2019	Considerations for Industrial Use: A Systematic Review of the Impact of Active and Passive Upper Limb Exoskeletons on Physical Exposures	Review	https://doi.org/10.1080/24725838.2019.1684399
93	Toxiri et al.	2019	Back-Support Exoskeletons for Occupational Use: An Overview of Technological Advances and Trends	Review	https://doi.org/10.1080/24725838.2019.1626303
94	Wei et al.	2019	The effects of a passive exoskeleton on muscle activity and metabolic cost of energy	Research study	https://doi.org/10.1080/01691864.2019.1707708
95	Lowe et al.	2019	ASTM F48 Formation and Standards for Industrial Exoskeletons and Exosuits	Research study	https://doi.org/10.1080/24725838.2019.1579769
96	Alemi et al.	2019	A passive exoskeleton reduces peak and mean EMG during symmetric and T asymmetric lifting	Research study	https://doi.org/10.1016/j.jelekin.2019.05.003
97	Von Glinski et al.	2019	Effectiveness of an on-body lifting aid (HALÒfor care support) to reducelower back muscle activity during repetitive lifting tasks	Research study	https://doi.org/10.1016/j.jocn.2019.01.038
98	Alabdulkarim and Nussbaum	2019	Influences of different exoskeleton designs and tool mass on physical T demands and performance in a simulated overhead drilling task	Research study	https://doi.org/10.1016/j.apergo.2018.08.004
99	Glitsch, U. (IFA)	2019	Analysis of the effectiveness of exoskeletons	Report	617.0-IFA:617.81
100	De Vries et al.	2019	The effectivity of a passive arm support exoskeleton in reducing muscle activation and perceived exertion during plastering activities	Review	https://doi.org/10.1080/00140139.2020.1868581
101	Babic et al.	2019	SPEXOR: Design and development of passive spinal exoskeletal robot for low back pain prevention and vocational reintegration	Research study	https://doi.org/10.1007/s42452-019-0266-1
102	Cortell-Tormo et al.	2019	Lumbatex: A Wearable Monitoring System Based on Inertial Sensors to Measure and Control the Lumbar Spine Motion	Research study	https://doi.org/10.1109/TNSRE.2019.2927083
103	Simpson et al.	2019	The role of wearables in spinal posture analysis: a systematic review	Review	https://doi.org/10.1186/s12891-019-2430-6
104	Bogue et al.	2018	Exoskeletons—a review of industrial applications	Review	https://doi.org/10.1108/IR-05-2018-0109
105	Toxiri et al.	2018	Rationale, Implementation and Evaluation of Assistive Strategies for an Active Back-Support Exoskeleton	Research study	https://doi.org/10.3389/frobt.2018.00053
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107	Luger et al.	2018	Subjective Evaluation of a Passive Lower-Limb Industrial Exoskeleton Used During simulated Assembly	Research study	https://doi.org/10.1080/24725838.2018.1560376
108	Kim and Nussbaum	2018	A Follow-Up Study of the Effects of An Arm Support Exoskeleton on Physical Demands and Task Performance During Simulated Overhead Work	Research study	https://doi.org/10.1080/24725838.2018.1551255
109	Miura et al.	2018	The hybrid assistive limb (HAL) for Care Support successfully reduced lumbar load in repetitive lifting movements	Research study	https://doi.org/10.1016/j.jocn.2018.04.057
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112	Ranavolo et al.	2018	Wearable monitoring devices for biomechanical risk assessment at work: Current status and future challenges—A systematic review	Review	https://doi.org/10.3390/ijerph15092001
113	Näf et al.	2018	Passive Back Support Exoskeleton Improves Range of Motion Using Flexible Beams	Research study	https://doi.org/10.3389/frobt.2018.00072
114	Hill et al.	2017	What are user perspectives of exoskeleton technology? a literature review	Review	https://doi.org/10.1017/S0266462317000460
115	Bonicatto	2017	Esoscheletro e Riduzione del Sovraccarico Biomeccanico per l'Arto Superiore	Research study	https://doi.org/10.13135/2532-392X/2480
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121	Ulrey and Fathallah	2013	Subject-specific, whole-body models of the stooped posture with a personal weight transfer device	Research study	https://doi.org/10.1016/j.jelekin.2012.08.016

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