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MAIN CHALLENGES IN THE IMPLANTATION OF EXOSKELETONS ACCORDING TO APPLICABILITY CRITERIA. SELECTION, EVALUATION AND VALIDATION PROCESS

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Abstract
Background: To reduce the mechanical exposure of workers and their physical load, the use of exoskeletons has become nowadays a valuable preventive tool, although their implementation should be considered taking into account different applicability criteria. **Objective**: The implantation of exoskeletons in companies must follow the principles of preventive activity. The aim of this study is to design an effective management process, integrating the need for these equipment and the way in which they will be selected and implemented. **Method**: A literature search using PUBMED, Web of Science and Scopus was carried out to investigate the challenges in the implantation of exoskeletons in companies, focusing on selection, evaluation and the validation process of exoskeletons. **Results**: Results show that, before considering the implementation of the use of an exoskeleton, the job must be assessed and the risk factors correctly identified. After selecting a particular exoskeleton model, it is essential to validate it with objective parameters. Having passed the final validation, a test process about the use of the exoskeleton in the workplace must be designed to achieve reliable results. Also, is important to analyze the possible risks derived from the use of the exoskeletons. **Conclusions**: An effective process to implant exoskeletons leads to the optimization of man-machine integration and an increase in productivity in the company. In any case, exoskeletons are currently in a process of constant improvement, both in design and functionality, so it seems necessary to establish the bases to advance in their legal standardization.

Keywords: Ergonomics, Exoskeleton, Occupational Health, Assessment, Risk management

Introduction

It is known that an increasing number of professionals are exposed to forced postures, given that in many sectors of activity there are tasks that require lifting, pushing or manually handling loads, which are carried out during a significant amount of work time. The impact of such work affects not only the lower back but also the shoulder area when loads are lifted overhead (Duffield et al, 2017). In order to adapt such working conditions, especially for those workers who are especially sensitive, it is important to appreciate the possibility of optimizing the conditions of the task, and also to consider the evolution of the technique (WHO, 2021). In this context, exoskeletons offer a series of possibilities to reduce the negative effects derived from manual tasks, specifically those related to musculoskeletal disorders, so that they can reduce muscular stress at work or help workers with physical disabilities (Bosch et al, 2016). In order to respect ergonomic principles, and to reduce the mechanical exposure of workers and their physical load, the use of exoskeletons has become a valuable tool, although at the moment there are no standards on the use of exoskeletons in an industrial environment (Poggensee et al, 2021). In short, and for all of the above, it is evident that any action that implies an improvement in working conditions constitutes a preventive measure of the first order to be considered within the field of ergonomics applied to prevent the appearance of work-related musculoskeletal disorders (Theurel et al, 2019), and that their implementation should be considered taking into account different applicability criteria.

Definition and classification of exoskeletons

An exoskeleton is the personal support system that affects the body mechanically. However, there is a general consensus that exoskeletons can be defined as mechanical structures external to the body. Another equally accepted definition refers to exoskeletons as those portable external devices that are placed on the user's body, used to increase their capabilities (Bosch et al, 2016). Considering the fundamental premise that an exoskeleton, as a wearable technology that assists human movement, reduces the physical stress applied to the user and mitigates the risk of developing work-related musculoskeletal disorders, different types of exoskeleton have been designed to date to respond to these conditions (de Looze et al, 2016). It should also be noted that exoskeletons have different fields of application and operating principles; therefore, for optimal performance, the type of exoskeleton, the tasks performed and the different periods of use must be assessed (Bogue, 2015). Regarding the classification of exoskeletons, depending on the articulation mechanism, they can be active or passive (Lee et al, 2012). Active exoskeletons have mechanisms that actively provide energy to the human body, while passive exoskeletons have the ability to accumulate energy derived from human movement and then discharge it, in order to facilitate the performance of a certain action. In the case of active exoskeletons, these have mobile parts driven by motors to assist the movements made by the worker, reducing their fatigue. In any case, its high weight means that its use is not widespread to date (Kim et al, 2021). For their part, passive exoskeletons use the energy generated by the movement of the user, without providing an external supply of energy, and currently are the most widely used to reduce the load supported by the back at a lumbar level (Baltrusch et al, 2020). Once the types of exoskeleton are known, is relevant to take into account that the implantation of the exoskeleton in the company must follow the principles of preventive activity, and that its use must help to minimize the risk without generating newhazards for its users (INSST, 2021). Simultaneously, a management process must be designed, integrating the need to have these equipment and the way in which they will be selected, evaluated and implemented, a process that we will describe below.

General considerations for implanting and selecting exoskeletons

Before implanting an exoskeleton it should be considered first that it does not replace the rest of the preventive measures that have been implemented in the company, and that it is designed for a series of specific tasks; that is, it is not valid for all situations (Flor et al, 2021). Similarly, the use of an exoskeleton must be voluntary, and its use by people with physical limitations must be done with caution (Pesenti et al, 2021).

Regarding the selection of the exoskeleton, it is recommended to develop a process based on three well-differentiated phases, in order to implement it correctly. In the first one, it must be determined whether or not it is really necessary to use an exoskeleton. The decision to integrate an exoskeleton into a workplace must be the result of a specific risk assessment that indicates that it is the best possible preventive measure. In the second phase, once the need for use has been estimated, the exoskeleton that best suits the wearer of the exoskeleton must be selected, counting on the opinion of all the users. Finally, in the third phase, it must be verified whether the safety and health of workers after its use has been improved. This last consideration is in line with the achievement of an effective protection of the safety and health in the company, which will also improve the efficiency and productivity of professionals (INSST, 2021).For all that said, the aim of this study is to design an effective management process, integrating the need for these equipment and the way in which they will be selected and implemented.

Material and Methods

This article is based on a narrative revision. A literature search using PUBMED, Web of Science and Scopus was carried out, using the keywords “exoskeletons”, “selection” and “validation”, including a systematic review investigating the challenges in the implantation of exoskeletons in companies, focusing on selection, evaluation and the validation process of exoskeletons, in relation to the most recent studies published in the last five years. Eligibility criteria were based on the type of intervention exoskeletons and the selection and validation results obtained in each study.

Results and Discussion

Application of exoskeletons in companies

In our literature search it was found that when a risk assessment determines that the physical load risk factors can be improved through the use of exoskeletons, passive devices can be used, as they allow a distribution of the pressure supported by the lumbar spine, unloading part of the tension in the legs. Although that currently passive type exoskeletons have the greatest implantation, however, by modifying the part of the body that receives the load, such equipment can generate overexertion in other parts of the body (Spada et al, 2017). Based on various studies, its use has been associated with a significant reduction in the stress borne by the spine, although on occasions, when shifting the weight to other segments of the body, it has been detected a considerable increase in the load that the legs must bear, an aspect which may require a specific design for certain tasks that involve lifting loads (De Bock et al, 2022). Related to the risk factor of manual handling of loads are also the postures necessary to carry out the work, whether they are postures maintained or forced when making efforts, which can experience a significant improvement when exoskeletons are introduced in the production process. Likewise, actions such as job redesign or organizational changes should not be forgotten, all of which are measures aimed at reducing the loads that the back supports at the lumbar level (Coenen et al, 2014).

Implantation of exoskeletons in the workplace

As it can be seen in Figure 1, results of our research are synthesized in the flow diagram, where the exoskeleton implantation process is explained. For a correct implantation of exoskeletons in the workplace, it must first be taken into account what their function is and the destination of their use. The fundamental function of an exoskeleton is the correction of bad postural habits, the correction of fatigue during repeated movements with the same pattern, and the correction of fatigue associated with relevant muscular efforts. Taking this parameter into account, the appropriate job profile must be chosen for the implantation of a certain exoskeleton. As for its use, it should be limited to positions with inappropriate postures, with very repeated movement requirements or that follow the same pattern or with significant requirements in terms of force, either during load handling, pushing or pulling (Bogue, 2018).

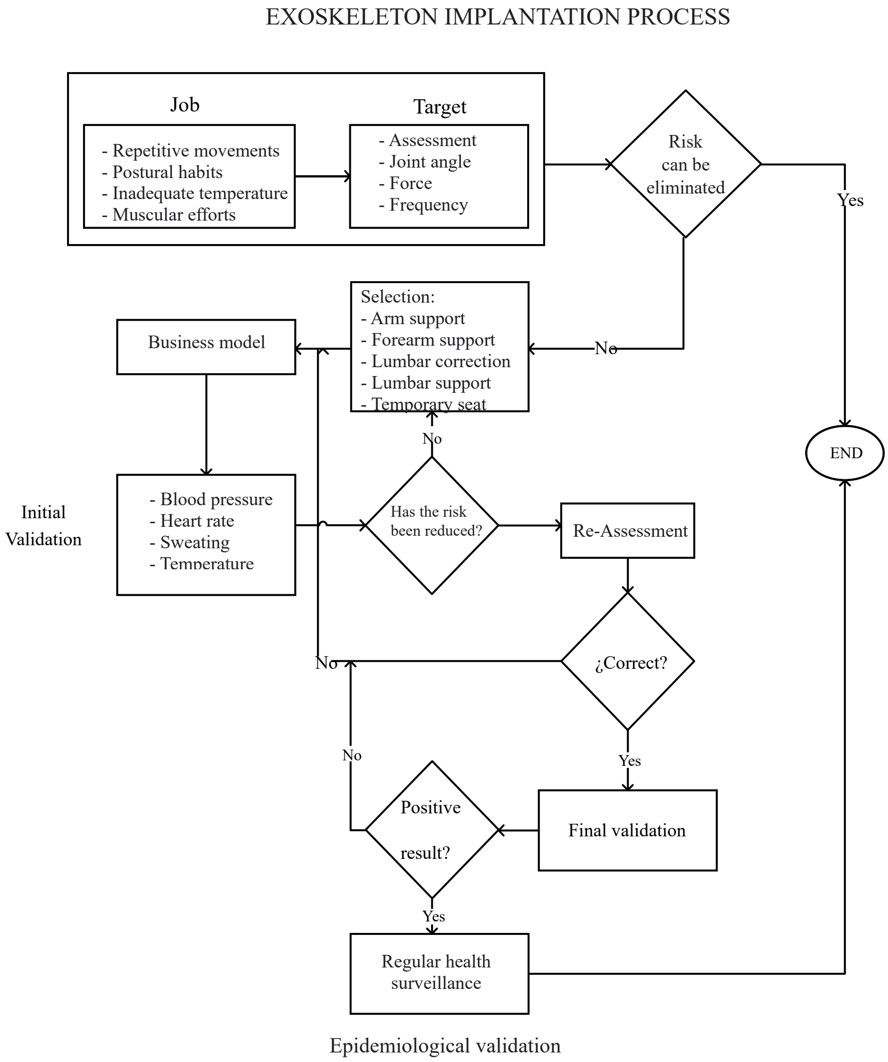

Figure 1*. Exoskeleton implantation process (prepared by the authors)*

Prior evaluation and supplementary input

The studies consulted, according to the premises indicated in the methodology, indicate that before considering the implementation of the use of an exoskeleton, the job must be assessed and the risk factors correctly identified, such as frequency, joint angles, load weights or temperature (Al-Otaibi, S.T., 2015). Once its origin has been detected, an attempt will always be made, as a first option, to eliminate the risk origin; that is, to reduce movements, to vary the angles adopted by the joints or to reduce the weights handled. Only if the process prevents eliminating the risk at its source, the use of an exoskeleton must be considered (Bostelman et al, 2017).

As soon as the assessment has been carried out and the risks identified, the deviation that needs to be corrected must be defined. There are several options available, specifically forearm support, arm support for elevated tasks, lumbar support for lifting loads, lumbar postural correction during squatting tasks and posterior supports that allow temporary seating during a static posture (Bridger et al, 2018). It is the function of the risk prevention manager in the company to select the type of exoskeleton that is sought for the characteristics of the position adopted (Amandels et al, 2019).

Selection and initial validation

After selecting a particular exoskeleton model, ensuring its effectiveness about the risk factor analyzed, it is essential to validate it, making a comparison between the effort made before and after the use of the exoskeleton during the performance of the tasks. It is essential to locate an objective parameter that is not subjective to the worker, such as opinion or pain perceived, since there areother checkable parameters, as blood pressure, body temperature or heart rate (Madinei et al, 2020). During the validation process, if the risk has not been reduced, it can be necessary to select another exoskeleton model until the most effective model is chosen, according to the most appropriate characteristics for the evaluated job position (Pesenti et al, 2021).

Re-evaluation and final validation

In the moment in which the process is finished, the position must be re-evaluated, since this type of device can generate situations not previously contemplated, such as additional weights, reduced mobility or response capacity, localized pressure in the support zone or electrical interference. It is important to analyze the possible risks derived from the use of this new element. The criterion is that it should never be accepted to reduce the ergonomic risk at the cost of generating new risks of another nature, such as entrapment or overload (Toxiri, 2018).

Once all the stages have been passed, after adopting the use of an exoskeleton for a given risk and task, the final validation of its use must proceed. In each case, a test process must be designed for a significant period of time to achieve results with a certain reliability. Again, the use of objective parameters will be essential, as established in the initial validation process. Only after having passed the final validation, the use of the exoskeleton in the workplace can be established and approved (Shin et al, 2019).

Finally, the health surveillance of all those workers who see their body balance compromised or varied with the use of an exoskeleton must not be forgotten. It is necessary to design a medical protocol to periodically verify that this imbalance is not causing any type of overload or residual tension in other joints or parts of the body. In any case, the data must be analyzed globally to obtain an epidemiological validation (EU-OSHA, 2019). If all these phases are not scrupulously followed, the implantation of an exoskeleton in a worker may not only be ineffective from a preventive point of view but, most seriously, it can generate risks of the same magnitude as those being treated (Keyserling, 2017).

Main challenges in the implementation of exoskeletons

Whether it is the type of active or passive exoskeleton, both must meet certain requirements to proceed to commercialization. On one hand, there are exoskeletons for medical purposes, regulated by medical devices regulations, and on the other hand there are exoskeletons used in the work environment with mechanical regulations for the commercialization and commissioning of machines, specifically those referring to active exoskeletons, since they have moving parts driven by motors (Chen et al, 2015). Furthermore, when we talk about the industrial application of exoskeletons, we must consider that their use is quite recent, and that many of the investigations have only been carried out in a laboratory environment.

Another of the challenges in the implantation of exoskeletons is related to the safety of the user, since the equipment accompanies the movements of the worker, so that it should not generate added discomfort, unwanted movements or incorrect postures. The exoskeleton also limits the natural balance of the body, and makes it difficult to adopt movements to avoid objects or imperfections in the terrain (Torricelli et al, 2020). In addition, a possible interaction between personal protective equipment and an exoskeleton must be taken into account when they are used simultaneously, or when the batteries used in the case of active exoskeletons create an additional risk (Kermavnar et al, 2021).

All these conditions can present problems that affect ergonomics during use. A decrease in muscle tone may occur, for which a non-prolonged use of the exoskeleton should be considered, together with the performance of strengthening exercises for those parts of the body that are affected. That is why the adaptation of the exoskeleton to the person is especially relevant, specifically in the shoulder or waist supports, since there may be problems with sweating or chafing in the support areas, for which it is necessary to reduce the weight of the device on the extent possible (Ferreira et al, 2020).

Conclusions

The opportunity to use exoskeletons in companies seems clear, both from the point of view of safety and health and from the point of view of productivity. The integration of new technologies within the framework of Industry 4.0 is also one of the strong points of exoskeletons, so it seems appropriate to check the introduction of exoskeletons in production processes, both in terms of reducing work-related musculoskeletal disorders as well as in relation to reducing the costs of injuries incurred (Villarroya et al, 2020). Exoskeletons are, from the point of view of lumbar protection, a relevant preventive measure within the industrial environment. In addition, and unlike other measures adopted in the field of safety and hygiene, the improvement of productivity, the optimization of man-machine integration and the possibility of taking full advantage of new technologies, make exoskeletons to be considered as an investment and not as an expense in the field of safety and health.

Finally, it should be specified that, in general terms, the use of exoskeletons to improve the ergonomic design of workplaces should always be the last resort. Only when the different collective protection measures to avoid these occupational risks are exhausted, is when it will be possible to provide exoskeletons to workers. That is, as long as technical or organizational measures offer possibilities to improve the design of a workplace at an ergonomic level, the use of exoskeletons should not be implemented. In addition, although it is true that exoskeletons can be a measure to improve working conditions, their implementation must be accompanied by the different principles of preventive action, checking at all times that they effectively control the risk of suffering from musculoskeletal disorders and that their implementation does not imply the appearance of new risks among the professionals who use them.

Limitations

Exoskeletons are currently in a process of constant improvement, both in design and functionality, so it seems necessary to establish the bases to advance in the field of its legal standardization. In absence of such standardization, this work proposes an initial management system that can serve as a provisional help to articulate the whole process for its implantation, so its use must take into account those conditions.

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