Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 232 (2024) 584–594

Procedia Computer Science

www.elsevier.com/locate/procedia

5th International Conference on Industry 4.0 and Smart Manufacturing

A multi-facet approach to functional and ergonomic assessment of passive exoskeletons

Riccardo Karim Khamaisi[a]*, Margherita Peruzzini[a], Agnese Brunzini[a], Zoi Arkouli[b],Vincent Weistroffer[c], Anoop Varghеese[c], Pietro Alberto Cultrona[d]

[a]*Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via P. Vivarelli, 10 Modena, 41125, Italy*
[b] *Laboratory for Manufacturing Systems & Automation, University of Patras, Rion Patras, 26504, Greece*
[c]*Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France*
[d]*COMAU SpA, Via Rivalta 30, 10095, Grugliasco (TO), Italy*

Abstract

Seeing the innovative character of exoskeletal devices, it appears that there is yet progress to be made in adopting exoskeletons to industry, and to the different users' characteristics and needs. Their validation is mainly focused on technological aspects and seldom researchers presented methodological approaches including both physical and cognitive impact on operators, synergically with functional issues. This study proposes a multi-faced approach to investigate the impact of passive exoskeletons on functional and ergonomic aspects providing a preliminary experimental validation with an industrial task. The approach assesses the physical comfort, muscular fatigue, cognitive workload, and users' technological acceptance, to map the overall user experience (UX). Participants were monitored by a mechanomyogram (MMG) and a motion capture (MoCap) system and a UX questionnaire was administered. Results demonstrated the effectiveness of passive exoskeletons regarding the specific task being strictly related to a correct definition of the level of assistance for each user.

Keywords: Exoskeletons; Ergonomic assessment; User eXperience; Physical comfort

---

1. Introduction

The new-born theory of Industry 5.0 extends the concept of smart factories, introducing the well-being of the worker at the centre of the production process, while remodulating the use of innovative technologies to provide societal

---

* Corresponding author. Tel.: +39-320-8692496.
E-mail address: riccardokarim.khamaisi@unimore.it

10.1016/j.procs.2024.01.058

prosperity beyond jobs and growth [1]. On this line, the academic interest towards assistive devices has increased in several heterogeneous fields, in accordance with a growing attention to the human sphere and the diffusion of human-centred design (HCD) methodologies. Contemporarily, an increasing number of supportive devices are becoming available on the market, together with the widespread adoption of automatized industrial systems and aging of the working population [2]. In addition, the increasing average age of the worldwide population has seen an increase in the appearance of several mobility-impairing disorders, making the demand for rehabilitation and assistive devices a real future priority. Both the industry and the healthcare sector have been specifically affected by such trends, with particular attention to the emerging domain of exoskeletons.

Exoskeletons have been introduced in the industrial environment to reduce biomechanical work-related risk factors due to frequent lifting and forward bending postures as well as operations with lifted arms [3][4]: indeed, in the European Union, the industrial sector is still characterized by high and diversified work intensities, according to the last European Working Conditions Survey [5]. In the 2021 survey, 60% of respondents reported problems with the upper limbs, followed by 53% reporting backache, 51% headaches and 39% problems with the lower limbs. Nearly a third of the respondents reported anxiety. Therefore, health problems related to upper limbs or backaches are the most frequently reported by workers, causing absence from work and loss of productivity.

In this sense, several studies tackled the efficacy of different passive exoskeletons to decrease spinal loading during controlled lifting, bending, and static holding tasks [6] [7]. Although the increased research for automation in industry could be considered an alternative to manual operations, thus solving the ergonomic issue, it must be nevertheless stated that machines cannot achieve the high dexterity of humans, still making them essential in many industrial tasks [8]. Thus, the need for supportive technologies is soon justified. Exoskeletons are not a fix-all technology, considering both workers and job tasks; they tend to disclose most of their potential in static activities while in dynamic tasks they often obstacle regular job experience and performance [9]. In the end, comfort and easiness of use are key factors influencing the final user's experience. In this context, the design of exoskeletons has been well-researched, leading to the establishment of standards such as ISO 13482 for instance, which suggests requirements and guidelines for the inherently safe design, protective measures, and information for use of personal care robots, applicable to exoskeleton too [10].

Nevertheless, rigorous evaluation of exoskeletons in terms of assistance to the users has not been properly tackled yet, whereas the lack of extended validation standards and clear indications specific for the exoskeleton design are limiting their effective introduction in industry. On top of that, such standards must obey different regulations across the world. Recent studies attempted to quantify the benefits of exoskeletons, although a unique evaluation practice has not been defined yet [11]. The same authors identified five domains for the quantification and analysis of the effect of the exoskeleton, respectively functional, force and/or torque, metabolic, subjective, and muscular. Massardi et al. remarked that the interaction between the human and the exoskeleton should always be carefully monitored to avoid the occurrence of unexpected behaviors by one of the actors during the task thus impacting the safety and the system [12]. Contextually, it must be said that their scarce use does not help in the analysis of the long-term implications of exoskeletons, both from a physical point of view and from the cognitive one. Another open issue regarding the exoskeleton involves how these technologies might be considered. They could be listed as Personal Protective Equipment (PPE), or as performance and amplification devices (PAADs). As PPE, exoskeleton could be adopted for the worker's health protection only when all the possible organizational measures to reduce occupational risks are taken and certified according to the Regulation (EU) 2016/425 on personal protective equipment. In some cases, workers considered exoskeletons as a hindrance representing an issue for security. This consideration leads to the need to accurately select the task in which wearing the exoskeleton, as pointed out also by laboratory studies [13] . In this perspective, Karvouniari et al. presented a Virtual Reality simulation-based approach in support of the integration of exoskeletons into industrial application [14]. In this approach, industrial tasks are simulated, and the workers perform as they would in the physical environment with and without exoskeletons while the impact of exoskeletons on the posture of the workers is evaluated with quantified metrics such as the Rapid Upper Limb Assessment (RULA), and the Rapid Entire Body Assessment (REBA) scores. Nevertheless, the final performance of the operators as well as their well-being is impacted by their mental state thus, it is also relevant to investigate the effects of the use of exoskeletons in the cognitive workload [15]. From the existing literature it occurs that securing the dynamic interaction between the human and the exoskeleton's physical interfaces is a crucial point in the reduction of exoskeleton's risk exposure. Ultimately, the target of researchers should be to provide a truly ergonomic physical interface, which translates into a personalized customization of the device according to the individual's own anthropometrics and needs.

The main contribution of this study is to propose a preliminary methodology to assess the overall performance of the exoskeleton by involving both the operator's physical point of view and the cognitive one in order to improve the device supportive experience. This will in turn enable first to identify cases where the provided support is not as effective as expected, and thus, stimulate the improvements of worker-centered exoskeleton design, which is a fundamental starting point for its full industrial acceptance: in fact, machines should adapt to workers and a wearable device must comply not only safety, comfort, usefulness, and usability regulations but also just as importantly, must be attractive and effective for the end user.

The remainder of this paper is structured as follows: material and methods explore the related works in the field of exoskeleton evaluation and the definition of both the experimental setup and the proposed methodology. Results and discussion highlight the relevance of the current study by describing the main outcomes that derived from the combined analysis of the sensor's data and of the questionnaire's outputs.

2. Materials and methods

2.1. Related background

Most of the current literature analyses the biomechanical effects of available exoskeletons on users. In particular, systematic reviews investigated the effects of current industrial exoskeletons on exertion, muscle activity, while only partially dealing with the UX [16]. In [17], an important reduction in the user's acute physical stress and strain in the targeted area is described and a correlation with mean values of metabolic and cardiorespiratory parameters is firstly introduced. Instead, Kermavnar et al. specifically extended the analysis to aspects related to UX and satisfaction [18]. [19] stressed that a major issue when designing exoskeletons is the lack of requirements, guidelines and performance analysis tools. As a concern, the usability and the practical value of exoskeleton technologies need to be adequately tackled to improve human safety and performance while highlighting the importance of better exploring the human-exosystem interaction. Thus, the authors came up with a framework to allow companies and researchers to test the performance of robots and exosystems at any stage of development.

Following, the PRISMA method [20] systematically reviewed the assessment methods of usability and cognitive workload in the use of exoskeletal devices for motor rehabilitation: they scrutinized conventional UX questionnaire methods (e.g., SUS, QUEST, SWAT, and NASA-TLX) demonstrating good psychometric properties and therefore proving appropriateness to assess usability and cognitive workload while performing exoskeleton-based rehabilitation. [21] examined what factors usually influence the use of exoskeletons in terms of contributing to the adoption of industrial exoskeletons. Based on empirical research with potential future end users, the authors designed a framework with factors influencing the acceptance of industrial exoskeletons to be used during the iterative design, development, and evaluation phase of new or existing exoskeletons. This ultimately aims to improve the quality of exoskeletons since it allows designers to consider acceptance factors in the early stage of the design process. Starting from similar conclusions, [22] remarked the need of highlighting ergonomic benefits of exoskeletal devices in the digital world by embedding an active exoskeleton controller to a production and ergonomic simulation software: to achieve such aim, a thorough understanding of the human models and of wearable robotics, especially exoskeleton design principles, is required.

Bearing all this in mind, the authors formulated three research questions (Qi) to guide the following study:

- *Q1: What is the impact of the Level of Assistance on user acceptance?*
- *Q2: Do workers choose the maximum level of assistance as the most effective?*
- *Q3: Do workers prioritize their performance or comfort when assessing their exoskeletal device?*

2.2. The proposed methodology

In order to satisfactorily reply to the stated research questions, the authors have developed a systematic methodology, depicted in Fig. 1, which is founded on principles such as bias avoidance in the evaluation of the user acceptance of exoskeletons and the ideal levels of assistance. For this purpose, a structured testing sequence has been defined, which provides a progressive awareness of the potentialities of the device as well as improves the operator's confidence. The following methodology applies to passive exoskeleton characterized by a multi-stage regulation. Fig. 1 details the workflow adopted throughout the execution of the functional tests, where the feedback of operators is collected by the means of two questionnaires, which have been designed to evaluate the overall user experience, but also the physical comfort that can be achieved while executing a task with the exoskeleton regulated at different levels of assistance (LoA).

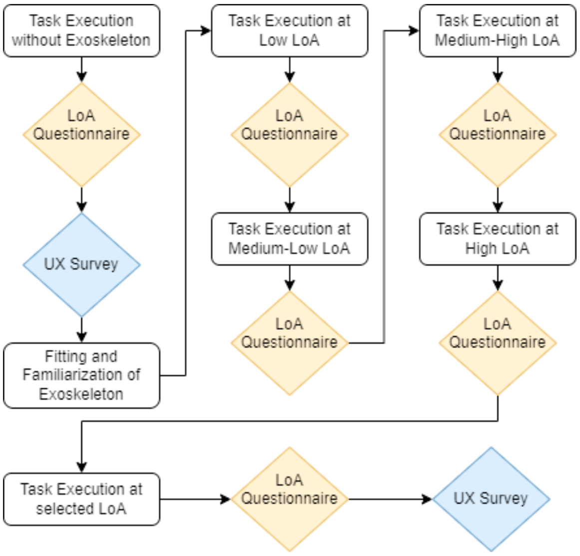


Fig. 1. The UX evaluation methodology adopted throughout the trials.

In more detail, the LoA questionnaire aims to mainly answer the research questions Q2 and Q3 and thus, investigates the operator's physical comfort during the task performed from a subjective point of view, to ultimately establish the best regulation setup of the exoskeleton fitting the user's needs. Moreover, interaction efficacy and subjective preferences on the force's feedback provided by the exoskeleton are examined; a final area is dedicated to suggestions and complaints regarding exoskeleton usability. The UX survey allows to collect demographic data, perceived workload (based on NASA-TLX), body discomfort, inclination to use technology (i.e., exoskeletons in this case). It also investigates the operator's requirements and interactions by task-related questions. In detail, the NASA-TLX [23] questionnaire provides information on how humans subjectively evaluate various aspects of workload for accomplishing a task considering six different dimensions (respectively mental, physical, temporal, performance, effort, and frustration levels). The body part discomfort scale instead is a subjective assessment tool that evaluates the respondent's direct experience of discomfort at different body parts on a 5-points scale (1 = not uncomfortable, 2 = barely uncomfortable, 3 = quite uncomfortable, 4 = very uncomfortable, 5 = extremely uncomfortable). At the end of the UX survey, the operator is asked to express a final judge on a possible everyday use of the exoskeleton.

Firstly, the operator completes the task without any kind of support and evaluates the baseline session by filling in both the questionnaires. Subsequently, after a first hands-on of the exoskeleton and a free-interaction phase, it is needed to evaluate whether the provided support affects the operators' experience. Therefore, the methodology suggests that the operators execute the baseline task several times while wearing the exoskeleton regulated at different levels of assistance (LoA) before selecting the most effective. In order to capture a reasonable spread of levels of support while maintaining a manageable testing duration, a subset of levels of support that adequately represent the exoskeleton's capacity should be defined. In scope of developing a vendor-neutral approach, the levels Low LoA, Medium-Low LoA, Medium-High LoA, and High LoA are proposed: according to the exoskeleton adopted and to its regulation, the medium LoA range could be contextually modified. Ultimately, the operator selects the LoA that has been the most helpful amongst the ones tried on, called "Selected LoA", and undergoes a definitive trial session with the best exoskeleton regulation and retakes the two questionnaires (i.e., LoA and UX). Both questionnaires have been made available as supplemental material.

3. The experimental setup

Alongside the questionnaire, two independent sensor suites are used to evaluate the performance of the operator objectively, with and without the exoskeleton. The first sensor is the ZED 2 stereo camera from StereoLabs [24], which allows for a full-body motion capture in real environments, using its inbuilt hardware and firmware, for a recreation of the human posture. The stereo camera configuration allows the camera to create a rough 3D reconstruction of the scene in front of the camera, which is then used by the AI within the firmware of the camera to find and track the limbs of a human in front of the device. This performs a motion capture of the operators' movements, which allows to track any differences in the posture of the operator that might be apparent when they perform the task using the exoskeleton. The operator's posture data could then be used to compute ergonomics scores such as RULA.

Fig. 2. Example of ZED 2i camera application during the trial session (camera screenshot of the obtained ergonomic evaluation).

The second suite of sensors consists of mechanomyogram-type (MMG) sensors from MOTEN Technologies [25]. They consist of small vibration sensors that are placed in direct contact with the skin of the operators. By detecting the vibrations of the muscles, they can estimate the level of activation of each muscle. This serves as an indication of the level of force that is being applied by the operators but can also be used to estimate the level of muscular fatigue depending on how the data is processed. A total of 6 MMG sensors are used in the study: the sensors provide their data in the form of muscular activation as a percentage of the maximum force applicable by that muscle.

4. Results and discussion

The use case was provided by Idesa, one of the European project Penelope's partners, operating in the Oil&Gas sector [26]. The use case focused on a grinding operation on a pipe, which is currently one of the most physical intensive tasks in the pipes production. The task was performed by four experienced users for approximately 5 minutes for each trial. Each operator signed an informed consent form after a detailed explanation of the study. Errore. L'origine riferimento non è stata trovata. reports the demographic characteristics of the involved operators. They were all males, right-handed (this does not affect the proper use of the grinding tool but is relevant for analysing the muscular activity) and they have never used an exoskeleton before.

Table 1. Demographic data

Operator	Age	Height (cm)	Weight (kg)	Education qualification
Op1	39	168	55	Lower secondary
Op2	44	187	109	Bachelor’s degree
Op3	35	176	80	Lower secondary
Op4	30	168	60	Lower secondary

The tested exoskeleton was the MATE from COMAU [27]. It is a passive exoskeleton providing support for the upper arms in the form of an extra torque for lifting objects at the shoulder level, while it redistributes that lifting force over the back of the operator. There are three main muscle groups that were monitored using the muscle effort sensors – the deltoids at the shoulder, the triceps on the upper arm, and the lumbar muscles at the lower back. The operator can choose among eight levels of assistance. For the trials, the chosen Levels of Assistance were 1 (low), 3 (medium-low), 6 (medium-high) and 8 (high). These levels were deemed to be representative and appropriate for the study's objectives and constraints as they cover the entire spectrum of the exoskeleton’s support capacity enabling a comprehensive evaluation of its efficacy.


(a) (b) (c)

Fig. 3. (a) and (b) shows the experimental site involving grinding operations performed on a pipeline while (c) depicts the MATE exoskeleton.

4.1. Questionnaire’s results

The impact of the anthropometric characteristics (i.e., height, and weight) to the preferred level of assistance by the operators was one of the main aspects investigated. The results are discussed in terms of the Body Mass Index [28], in order to facilitate discussions considering at the same time the weight and height of the operators, which are the two determining factors for the regulation of the exoskeletons in current practice. In general, body types can be clustered into four classes of Body Mass Index, where BMI less than 18.5 is known as the underweight range, 18.5 to 24.9 is known as the healthy weight range, 25 to 29.9 is the overweight range, and higher than 30.0 is the obese range. For the experiment participants three out of the four clusters were observed (Fig. 4.)

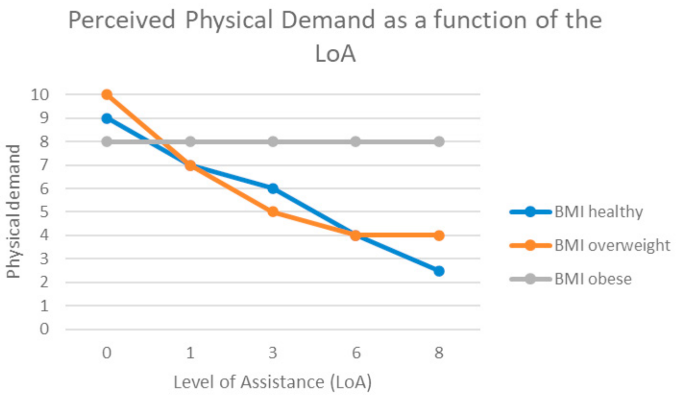


Fig. 4. Perceived physical demand as a function of the LoA for the different classes of Body Mass Index.

It was observed that for the healthy range the higher the LoA the less the operators felt their bodies were working, for the overweight range the perceived effort converged for LoA equal or greater than 6, whereas the variations in LoA did not alter the perceived physical effort for the obese range, as shown in Figure 4. Regarding the prioritization of comfort versus performance, it has been observed that the use of the exoskeleton favors both aspects.

From the UX survey, it emerged that 75% of participants believe that the grinding task, even if it is easy to remember and does not require personal effort, involves a great amount of responsibility. Also, 100% of participants think that the task requires attention and is very physical demanding. Then, the body part discomfort scale was used to investigate how the operators perceive physical discomfort without using the exoskeleton and using the exoskeleton as reported in Figure 5. It seems that the impact of exoskeletons is more intense for the middle back, low back, and shoulders, whereas only slight changes were observed for the head-neck area, arms and buttock. Overall, the exoskeleton seems to decrease the overall physical discomfort perceived by the operator in performing their task.

Concerning the perceived workload over the six domains, mean results of NASA-TLX are shown in Figure 6. As expected, physical demand and effort (which is a combination of physical and mental effort) gained the highest scores, followed by the mental demand. All items decrease using exoskeleton. The overall score decreases from high (range 50-79) without the exoskeleton to rather high (range 30-49) by using the exoskeleton.

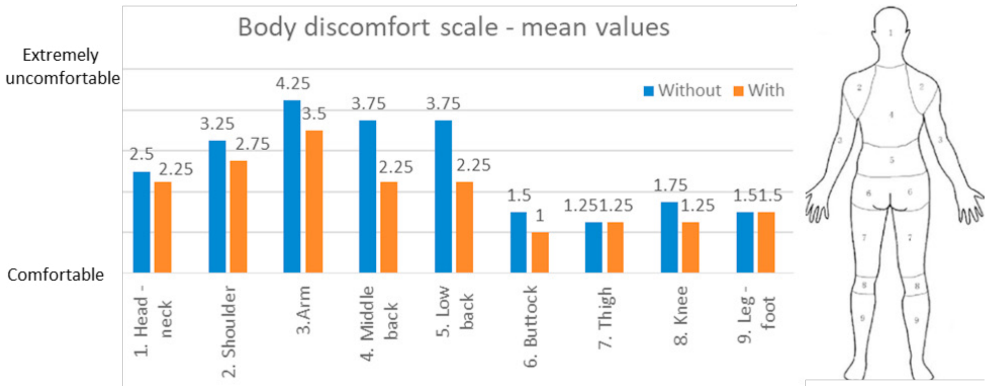
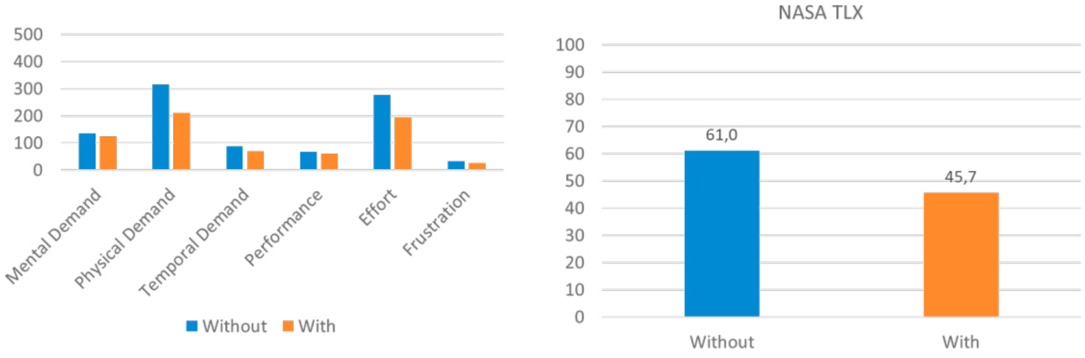


Fig. 5. Body Part Discomfort Scale and Questionnaire results.



(a) (b)

Fig. 6. (a) shows the NASA-TLX mean results for the six domains while (b) the overall mean score.

In the context of assessing whether operator support is needed while using the exoskeletons, the technology self-efficacy questionnaire has been distributed after operators used the exoskeleton. The responders stated that they felt highly confident to use the exoskeleton even if they only had the manuals for reference or no one was around to tell them what to do. As a result, it seems that a session of trying on the exoskeleton would suffice, whereas providing videos of how to use the exoskeleton seems also promising. It is rather not needed to provide support after the exoskeleton has been adjusted to the operators' individual characteristics.

4.2 Sensor Analysis

The output of the MMG sensors is expressed as the percentage of activation relative to the maximum effort applied by each muscle during the recordings. As these maximum values are relative to each operator, each operator's results must be assessed independently.

While interpreting the results, it is useful to understand the four ranges that the muscular efforts fall into:

- Low effort (0% to 25%) - This represents an everyday level of effort, and it can go up to 25% for even everyday actions that use no effort or cause no discomfort.
- Moderate effort (25% to 50%) - This range represents a level of effort where the user is moderately stressing himself. It causes only a minimal level of discomfort and can also generally be ignored for the purposes of this evaluation.
- High effort (50% to 75%) - This range represents the upper ranges of effort, where the user can experience discomfort if they stay at this level for extended periods of time.
- Very High effort (75% to 100%) - This range represents the peak of the effort that the muscle can exert. While it is normal for the muscles to reach this level for sporadic moments while executing tasks, it is extremely unhealthy to remain at these levels for longer periods of time. As such, it is vital to minimize the amount of time the user spends at this level.

The ideal scenario when using the exoskeleton is not necessarily to minimize all the efforts as much as possible, as this is not feasible for a passive exoskeleton. Rather, it is more to minimize the amount of time spent in the Very High effort range. The peaks are more characteristic of the ergonomic limits of the body than the average or moderate values.

For the analysis, the average activation percentage of each of the 6 muscles for each operator was investigated while performing the chosen task: thus, the average muscle activation level of each muscle for each LoA setting on the exoskeleton was established.

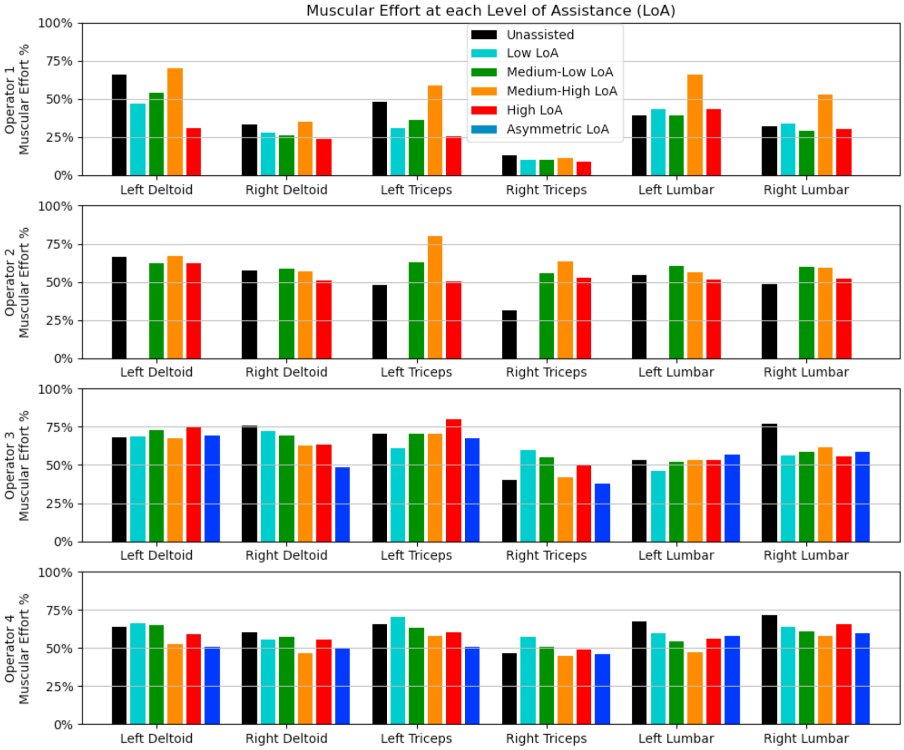


Fig. 7. Individual results for muscular effort from each operator from MMG analysis.

Figure 7 shows the average muscular efforts for each muscle group on the left and the right side of the body, for a total of 6 muscles per operator. It is apparent to see that the use of the exoskeleton has strong effects on the efforts applied by the operator. The most significant point to note is that the effect of wearing the exoskeleton is not always positive. The choice of the LoA has a strong impact upon each of the muscles that were evaluated while performing the task. On the other side, the use of the incorrect LoA can cause a significant increase in the effort applied by each muscle, as in the case of Operator 1 at the medium-high LoA (level 6). On the other hand, this same operator registered encouraging results when he used the lowest LoA (level 1). Conversely, Operator 2, who also had the largest frame among the operators, experienced trouble adjusting to the constraints caused by the exoskeleton. Even without the exoskeleton, he was never in the average Very High effort ranges of his muscles. None of the LoA appears to have given him any significant improvement, and it can be argued that he either performs better without an exoskeleton or requires one that provides higher LoA than what the MATE provides. Operators 3 and 4 both showed healthy reductions in their muscular effort from wearing the exoskeleton, particularly at the medium-high LoA (level 6), which brought them out of the very high effort ranges. Both operators also requested an extra measurement where they used a different LoA on each arm, as the grinding tool is not held symmetrically but rather to one side. This hybrid LoA shows interesting results for optimizing the LoA based on the exact nature of the task, although not enough data is available from this study alone to provide a more meaningful analysis.

It is worth noting that none of the operators were already experienced with using this exoskeleton, and so these results are representative of them using the exoskeleton for the first time. The rigid body of the exoskeleton also influences the choice of pose and posture of the operator, as it restricts spinal movements and encourages keeping the arms at a higher level, at around eye-level. Operators who are not familiar with the usage of the exoskeleton may take some time to adjust their normal operation posture to find one that is comfortable, that takes advantage of the rigidity of the exoskeleton's spine and minimizes the forces on their back. On the same line, the lower arm and the upper arm angles for each of the four operators as tracked by the ZED camera motion capture system reported a progressive decrease which stressed the effectiveness of the exoskeleton in supporting the operator in the upper arm task.

4.3 Research questions analysis

According to the data shown in the previous paragraph, the three research questions have been addressed and answered thoroughly. It must be stated that the current research was performed on a limited user population with previous experience of the chosen task and that it did not tackle all the anthropometric characteristics. Moreover, the proposed methodology was tested only on a single exoskeleton, thus lacking any kind of generality.

Specifically, regarding the correlation between the level of assistance and the user acceptance towards the exoskeleton, no complaints have been encountered: in accordance with the LoA questionnaire, the exoskeleton was not perceived as an obstacle at all, and the general provided force feedback was sufficient. Operators reported that the corresponding level of assistance tested were not completely matching their expectations in term of force feedback, but it did not alter the overall experience and additionally it did not cause an increase of rigidity of the movement. Grinding tools were easily maneuverable while wearing the exoskeletal device: ergonomically, users provided indications on how to improve the support feedback even during non-conventional postures assumed during the task.

As for Q2, the LoA survey underlined how users did not always perceive an increase in efficacy and ergonomics by using the highest level of assistance provided by the exoskeleton, being strictly dependent on the body size.

The last question of the LoA survey compared to the muscle effort results clearly remarked that comfort during usage is of primary importance, both from an ergonomic point of view and a functional one. As mentioned above, operators without prior experience with the usage of the exoskeleton may need some time to adjust the device to their normal operation posture to find the one which is comfortable and effective.

5. Conclusion

The presented study represents a preliminary attempt to investigate in a structured way UX-related aspects when assessing passive exoskeletons with a multi-stage regulation in industrial tasks. A UX survey and a Level of Assistance questionnaire have been appositely prepared, and a precise testing sequence adopted with a commercial passive exoskeleton. The correct definition of the LoA provided by the exoskeleton in terms of comfort seemed decisive for a fruitful working experience: according to the BMI index, different desired LoA were demonstrated to efficiently assist operators during the task without incurring in acceptance issues. People ranging in the obese BMI index cluster did not perceive an improvement in the physical demand with different LoA compared to the other groups.

This work aims to stimulate a greater standardization in the evaluation and interpretation of exoskeletal devices, especially in the industrial environment, by emphasizing user-specific need. A statistical validation is foreseen by expanding the user population to inexperienced people seeing: several exoskeletons will be tested to validate the proposed methodology in an extensive way. The research on the topic will proceed with the integration of physiological parameters as well as the implementation of a task analysis module to define the correct level of assistance. The effect of the determined sequence and the definition of the exoskeleton-specific medium range level of assistance on which the methodology is based should be addressed and further discussed.

Acknowledgements

This research was funded by the European Community under the HORIZON 2020 programme, grant agreement No. 958303 (PENELOPE) and grant agreement No.101091780 (DaCapo).

Supplemental Material

The adopted UX Survey and LoA questionnaire are freely available at the link:
https://drive.google.com/drive/folders/1tw7CD4Y2BTfr9PAFu7VPlhh9bhdDxDEz?usp=sharing

References

[1] Industry 5.0|European Commision. https://ec.europa.eu/info/research-and-innovation/research-area/industrial-research-and-innovation/industry-50_en (accessed May 18, 2023).

[2] Peters, M., and Wischniewski Sascha. (2019) "Impact of Using Exoskeletons on OSH".

[3] Griffith, Lauren E., Shannon Harry S., Wells Richard P., Walter Stephen D., Cole Donald C., Côté Pierre, Frank John, Hogg-Johnson Sheila, and Langlois Lacey E. (2012) "Individual participant data meta-analysis of mechanical workplace risk factors and low back pain". American Journal of Public Health 102:309-318. https://doi.org/10.2105/AJPH.2011.300343.

[4] Coenen, Pieter, Gouttebarge Vincent, Van Der Burght Aafje S.A.M., Van Dieën Jaap H., Frings-Dresen Monique H.W., Van Der Beek Allard J., and Burdorf Alex. (2014) "The effect of lifting during work on low back pain: a health impact assessment based on a meta-analysis." Occupational and Environmental Medicine 71:871–877. https://doi.org/10.1136/OEMED-2014-102346.

[5] European Working Conditions Telephone Survey 2021: Technical report | Eurofound. https://www.eurofound.europa.eu/publications/report/2022/working-conditions-in-the-time-of-covid-19-implications-for-the-future#wp-107972 (accessed August 02, 2023).

[6] Koopman Axel S., Kingma Idsart, Faber Gert S., de Looze Michiel P., van Dieën Jaap H. (2019) "Effects of a passive exoskeleton on the mechanical loading of the low back in static holding tasks." Journal of Biomechanics 83:97–103. https://doi.org/10.1016/J.JBIOMECH.2018.11.033.

[7] Koopman, Axel S., Kingma Idsart, de Looze Michiel P., and van Dieën Jaap H. (2020) "Effects of a passive back exoskeleton on the mechanical loading of the low-back during symmetric lifting." Journal of Biomechanics 102:109486. https://doi.org/10.1016/J.JBIOMECH.2019.109486.

[8] Chryssolouris G, Alexopoulos K, and Arkouli Zoi. (2023) "Artificial Intelligence in Manufacturing Equipment, Automation, and Robots." Studies in Systems, Decision and Control 436:41–78. https://doi.org/10.1007/978-3-031-21828-6_3.

[9] Baldassarre, Antonio, Lulli Lucrezia G., Cavallo Filippo, Fiorini Laura, Mariniello Antonella, Mucci Nicola, and Arcangeli Giulio. (2022) "Industrial exoskeletons from bench to field: Human-machine interface and user experience in occupational settings and tasks." Front Public Health 10:4375. https://doi.org/10.3389/fpubh.2022.1039680.

[10] ISO 13482:2014 - Robots and robotic devices — Safety requirements for personal care robots. https://www.iso.org/standard/53820.html (accessed May 15, 2023).

[11] Pesenti, Mattia, Antonietti Alberto, Gandolla Marta, and Pedrocchi Alessandra. (2021) "Towards a Functional Performance Validation Standard for Industrial Low-Back Exoskeletons: State of the Art Review." Sensors 21: 808. https://doi.org/10.3390/S21030808.

[12] Massardi, Stefano, Rodriguez-Cianca David, Pinto-Fernandez David, Moreno Juan C., Lancini Matteo, and Torricelli Diego. (2022) "Characterization and Evaluation of Human-Exoskeleton Interaction Dynamics: A Review." Sensors 22 (11): 3993. https://doi.org/10.3390/S22113993.

[13] Zhu, Zhenhua, Dutta Amrita, and Dai Fei. (2021) "Exoskeletons for manual material handling – A review and implication for construction applications." Automation in Construction 122:103493. https://doi.org/10.1016/J.AUTCON.2020.103493.

[14] Karvouniari, Anna, Michalos George, Dimitropoulos Nikos, and Makris Sotiris. (2018) "An approach for exoskeleton integration in manufacturing lines using Virtual Reality techniques." Procedia CIRP 78:103–108. https://doi.org/10.1016/J.PROCIR.2018.08.315.

[15] Arkouli, Zoi, Michalos George, and Makris Sotiris. (2022) "On the Selection of Ergonomics Evaluation Methods for Human Centric Manufacturing Tasks." Procedia CIRP 107:89–94. https://doi.org/10.1016/J.PROCIR.2022.04.015.

[16] Bär, Mona, Steinhilber Benjamin, Rieger Monika A., and Luger Tessy. (2021) "The influence of using exoskeletons during occupational tasks on acute physical stress and strain compared to no exoskeleton – A systematic review and meta-analysis." Applied Ergonomics 94:103385. https://doi.org/10.1016/J.APERGO.2021.103385.

[17] Davis, Kermit G., Reid Christopher R., Rempel David D, and Treaster Delia. (2020) "Introduction to the Human Factors Special Issue on User-Centered Design for Exoskeleton." Human Factors 62(3):333-336, https://doi.org/10.1177/0018720820914312.

[18] Kermavnar, Tjasa, de Vries Aijse W., de Looze Michiel P., and O'Sullivan Leonard W. (2021) "Effects of industrial back-support exoskeletons on body loading and user experience: an updated systematic review." Ergonomics 64:685–711. https://doi.org/10.1080/00140139.2020.1870162.

[19] Pietrantoni, Luca, Rainieri Giuseppe, Fraboni Federico, Tušl Martin, Giusino Davide, De Angelis Marco, and Annagrazia Tria. (2019) "Usability of exosystems: A review." CHItaly19: Biannual Conference of the Italian SIGCHI Chapter.

[20] La Bara, Laura Maria A., Meloni Luca, Giusino Davide,and Pietrantoni Luca. (2021) "Assessment Methods of Usability and Cognitive Workload of Rehabilitative Exoskeletons: A Systematic Review." Applied Sciences 11:7146. https://doi.org/10.3390/APP11157146.

[21] Elprama, Shirley A., Vanderborght Bram, and Jacobs An. (2021) "An industrial exoskeleton user acceptance framework based on a literature review of empirical studies." Applied Ergonomics 100:103615. https://doi.org/10.1016/J.APERGO.2021.103615.

[22] Constantinescu, Carmen, Rus Rares, Rusu Claudiu A., and Popescu Daniela. "Digital Twins of Exoskeleton-Centered Workplaces: Challenges and Development Methodology." Procedia Manufacturing 39:58–65. https://doi.org/10.1016/J.PROMFG.2020.01.228.

[23] Hart, Sandra G., and Staveland Lowell E. (1988) "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research." Advances in Psychology 52:139–183. https://doi.org/10.1016/S0166- 4115(08)62386-9.

[24] ZED 2i - Industrial AI Stereo Camera | Stereolabs. https://www.stereolabs.com/zed-2i/ (accessed May 16, 2023).

[25] MOTEN technologies - Homepage. https://www.moten-tech.com/en/ (accessed May 16, 2023).

[26] Idesa :: Ingeniería y Diseño Europeo S.A.. https://www.idesa.net/ (accessed May 16, 2023).

[27] Comau Mate – Fit for workers https://mate.comau.com/ (accessed May 16, 2023).

[28] Messiah, Sarah. (2013). "Body Mass Index." Encyclopedia of Behavioral Medicine, 247–249. https://doi.org/10.1007/978-1-4419-1005-9_729.