Investigating the efficiency of a passive back-support exoskeleton in manual picking tasks

G. Ashta*, S. Finco*, D. Battini*, A. Persona*

* *Department of Management and Engineering, University of Padova, Stradella San Nicola 3, 36100 – Vicenza – Italy (gjulio.ashta@phd.unipd.it, serena.finco@unipd.it, daria.battini@unipd.it alessandro.persona@unipd.it)*

Abstract: The Industry 5.0 paradigm complements the well-known Industry 4.0 paradigm and aims to focus research and innovation on social impacts and sustainability. Industry 5.0 proposes a shift of focus from technology-centred to human-centred design approaches for the modern workplace to enable the workers to achieve physical, psychological and cognitive resilience dealing with the new concept of Operator 5.0. Passive exoskeletons, which represent one of the emerging technologies, are suitable for industrial deployment due to their simplicity and low cost. Previous investigations evaluated the physical benefits of passive exoskeleton use during various tasks. These studies measured and demonstrated the capability of back-support exoskeletons to reduce back muscular demand in order-picking tasks, which are labour-intensive and challenging to automatize. For these reasons, passive back-support exoskeletons could be deployed to support the operators. However, the literature still has not proposed models to enable the analysis of exoskeleton deployment from a time effectiveness point of view to support managerial decisions. Nevertheless, this gap could be reduced by investigating exoskeletons' effects on muscular fatigue and the related rest allowance (RA). RA represents the amount of time required to cover the fatigue (muscular or cardiovascular) spent in executing tasks. The higher the fatigue, the higher the rest allowance. Thus, by investigating exoskeletons' effects on rest allowance, we can identify the pros and cons of using exoskeletons while executing tasks. For these reasons, in this paper, we propose a methodological approach for evaluating the time effectiveness of exoskeleton deployment for picking tasks based on its effects on picking times and RA.

Keywords: Industry 5.0, Exoskeletons, Rest Allowance, Picking

I. INTRODUCTION

In the last years, manufacturing and logistics (M&L) systems have been facing the transition from the well-known Industry 4.0 paradigm to the Industry 5.0 one. The new Industry 5.0 paradigm increases the focus on the social impact of modern industry and places the worker's well-being at the centre of the production processes [1]. On the other hand, over the years, Industry 4.0 has focused on efficiency and flexibility improvement of production with digitalization [2]. In such a context, Industry 5.0 does not replace but complement Industry 4.0 since it aims to drive research and innovation to achieve the transition to a human-centred sustainable and resilient industry. Such a type of transition becomes strategic in labour-intensive M&L systems where, despite the trend to automation, several tasks need to be performed manually due to the high flexibility, agility, judgment and other series of skills that cannot be automatised and served by robots [3,4]. In the new scenario in which the technology needs to be adapted to the workers, wearable supportive devices such as exoskeletons gained interest over the last years to support and achieve the operators' physical resilience [5]. These devices could be actively actuated (active exoskeletons) or can be entirely passively powered using elastic components (passive exoskeletons) [6]. Nevertheless, passive exoskeletons have lower complexity and cost than active ones and are easy to use. For these reasons, they are most accessible for large industrial use [7]. Passive exoskeletons demonstrate their capability to reduce operators' physical workload in industrial tasks by decreasing the activity of the supported muscular groups [5] as well as the compression of lumbar vertebrae [8].

Moreover, the passive back-support exoskeleton Laevo has recently been certified as a PPE (Personal Protective Equipment) by the European Union [9]. However, standardized testing and comparison methods are still missing [10,11]. Additionally, the current literature does not focus enough on their impact on productivity and efficiency. Finally, decision support models to drive deployment decisions are missing [12].

For this reason, in this work, we aim to reduce this gap by proposing a methodological approach whose goal consists of leading managers in selecting or not passive back support exoskeletons for picking and material handling tasks. We investigate time performances and the required RA related to muscular fatigue. Most of the existing studies are focused on investigating the effects of wearing an exoskeleton by measuring the muscle activity generally expressed as a percentage of the maximum voluntary contraction (MVC) [13,14] or RMS (Root Mean Square) amplitude of the signal [15]. However, as stated by El Ahrache Imbeau [16], the muscle activity spent in executing any task can be used as an input parameter to define the necessity to have or not a RA.

Further, this work focuses on order picking and material handling tasks since they are still performed manually and represent some of the most labour-intensive activities in M&L fields [17].

The paper is structured as follows. Section 2 reports the current state of the art. Section 3 describes the methodological approach. Section 4 presents a numerical application. Finally, Section 5 reports conclusions.

II. State of the Art

Several works studied the effects of passive exoskeletons in material handling and order-picking tasks [5]. Further, in this field, back-support exoskeletons were the most deployed [12].

Ogunseiju et al. [18] investigated the efficacy of two StrongArm exoskeletons, the V22 and Flx, in material handling tasks using an EMG-driven biomechanical model of the spine. They found that both exoskeletons resulted in similar stress on the L5/S1 joint, with the Flx limiting the range of motion and increasing task performance time by 20%. In the case of spring powered passive back-support exoskeletons, the Laevo was majorly deployed and tested in simulated and real tasks. Motmans et al. [19] studied the effect of the Laevo exoskeleton on order-picking activities in a dairy company. They found that it reduced erector spinae activity by 9-12% and improved workers' perceived physical workload, although more energy was required for downward movements. Cardoso et al. [20] and Kinne et al. [21] also reported positive feedback for the Laevo exoskeleton in order picking tasks, with a decrease in NASA TLX subdimensions except for mental workload. Users perceived the task as easier when using the exoskeleton but reported interference, movement limitations, and discomfort in various body regions. Flor et al. [22] concluded that the Laevo was best suited for workstations with heavy lifting and low diversity of mobility. Giustetto et al. [23] and dos Anjos et al. [24] found that the Laevo resulted in lower discomfort, doubled endurance times, and a 10% decrease in back muscle activity in static tasks. Luger et al. [25,26] and Iranzo et al. [27] investigated the performance of the Laevo in dynamic tasks. They found decreased heart rate, increased hip and knee flexion, decreased trunk activity up to 28%, and a slight reduction in range of motion due to the constriction provided by the exoskeleton.

Moreover, the time to complete lifting and fastening increased between 2% and 8%. Schmalz et al. [8] assessed the Paexo Back, a newly introduced back-support exoskeleton. They found that it resulted in a 9% reduced oxygen consumption, reduced muscle activity in the back and thighs by up to 18%, and reduced peak and mean compression forces at L4/L5 (21%) and L5/S1 (20%). Qu et al. [28] investigated an IPAE exoskeleton allowing load-carrying bypassing the arms. They found reduced erector spinae activity in isolated lifting and effective relief of the arms in dynamic lifting. However, users reported pressure on the shoulders, wrists, and thighs and no oxygen consumption differences. Lastly, Yandell et al. [29] investigated the Hero Wear Apex, a modular soft suit, in a distribution centre for various activities. They found reduced back muscle activity by around 10% and that workers were satisfied with the soft suit, reporting comfort and natural movement.

Nevertheless, the main focus of the studies is the evaluation of exoskeletons through their effect on muscle activity measured with electromyography (EMG). The trend to use EMG for the assessments is maintained, extending literature to other M&L tasks [30]. Investigating the current state-of-the-art methods to support managerial deployment decisions of passive back-support exoskeletons in M&L systems. In particular, their impact on productivity remains very few investigated. As reported below, the effect of passive back support exoskeletons was investigated twice for material handling and picking.

Moreover, passive exoskeletons are claimed to reduce fatigue [13] and physical workload [6] but models translating these biomechanical and ergonomic parameters into the time domain are still absent. However, operators' fatigue can be evaluated as an additional time through RA [16,31]. Further, they can convert the fatigue reduction effect of exoskeletons in the time domain.

Several models for RA evaluation have been proposed over the years. RA is defined as a percentage of the holding time required to perform the task without interruption. According to [16] RA can be computed by considering local fatigue (e.g., muscle fatigue) or global fatigue (e.g., cardiovascular fatigue) according to the type of task the worker is asked to perform.

Since the effects of wearing an exoskeleton are related to a specific body part, we focus on local fatigue. In such a context, four models are widely used in the literature to compute RA: [32], [33], [34], [35]. In Rohmert's [32] and Milner's [33] models, holding time is expressed as a fraction of the maximum holding (or endurance) time (MHT or MET). The Rose et al. [34] model uses MHT directly. Finally, Byström and Fransson-Hall [35] use the %MVC value to define the proper RA. Further, in [32] and [35], no fatigue, thus RA, arise if %MVC is lower than 15%.

MHT is linked to the %MVC as defined by Ma et al. [36]. Different models have been developed and validated over the years, specific for the lower or upper body part or more generic, aiming to consider the whole body. Further, the MHT models are constructed using different mathematical models, mainly power and negative exponential functions. Moving on the %MVC is measured through electromyography (EMG) signals collected by applying sensors in the muscle mainly involved while performing tasks.

III. Methodological approach

According to the literature review section, there is a lack of models translating in the time domain the physiological relieving effect of passive exoskeletons when performing manual M&L tasks. For this reason, we propose a methodological approach by combining time performances and muscular activity effects on RA while wearing or not an exoskeleton.

According to [37,38] the positive effects of wearing an exoskeleton are task-dependent. Thus, this study is focused on order picking and material handling activities. This approach (see Fig. 1) aims to assess if a back-support passive exoskeleton is suitable for a given order-picking activity in terms of time efficiency. To do this, it is necessary to:

I. Evaluate how exoskeletons affect the time performances of operators in order picking sub-tasks like picking, moving, placing and walking.
II. Evaluate the effects of exoskeletons by measuring the effects on muscle activity for each task (e.g., %MVC)
III. Evaluate the effects of muscle activity on RA according to the models proposed by the literature [16].

The methodological approach is illustrated in Fig.1. It consists of four parallel phases that evaluate the two scenarios with and without the exoskeleton deployment. In the first phase, in common with the two scenarios, is necessary to collect all the data of the picking process, such as the items' positions, the average weight o items to pick, the average speed of the worker involved in the picking process and the average distance between items to pick. Further, in the second phase of the approach, a picking times analysis has to be done experimentally with the worker to evaluate his time performances in picking, moving, placing and walking with and without the exoskeleton worn to consider improvements or penalizations given by the wearing of the exoskeleton. In phase 3, the RA values are computed for conditions without the exoskeleton (3a) and with the exoskeleton (3b) by considering the muscle activity and local fatigue. In phases 4a (without exoskeleton) and 4b (with exoskeleton), the total picking times can be computed by combining the experimental data from phase 2 with the RAs calculated in phases 3a and 3b.

For the evaluation of the RA, The model proposed by Rose et al. [34] has been chosen for this application. It considers the %MVC and computes RA for %MVC lower than 15%. By considering [34], the RA is defined as follows:

$$(1) \qquad RA = 3 \cdot MHT^{-1.52} \cdot 100$$

Where MHT could be computed using the model of Mannenica (1986) for back muscles:

$$(2) \qquad MHT = 32.7859e^{-4.9 \cdot fMVC}$$

And $fMVC = \%MVC/100$

%MVC values were measured by different studies in the literature showing significant decreases when material handling was performed with exoskeleton support [6]. Reductions of the %MVC were up to 35% measured in assembly and static forward bending [3]. Moreover, for lifting tasks, the %MVC reduced from 32%MVC to 25%MVC in 5kg lifting using the ergonomic squat movement [39] while it reduced from 35%MVC to 8%MVC when lifting was performed in stoop posture [14] and had a 22% reduction when lifting 10kg in free lifting technique. In particular, this paper considers the %MVC values measured by Antwi-Afari et al. [14] since many workers prefer the stoop lifting style due to its easier operation [40]. They measured an 8%MVC needed to the Lumbar Erector Spinae (LES) for lifting a 5kg weight with the support of a passive exoskeleton and 35%MVC without its support.

Finally, the picking times can be compared to drive the final decision based on production efficiency. If the picking time without an exoskeleton is lower than that with an exoskeleton, the exoskeleton will not be indicated for deployment. Otherwise, its deployment will be convenient if the picking time is lower when using the exoskeleton.

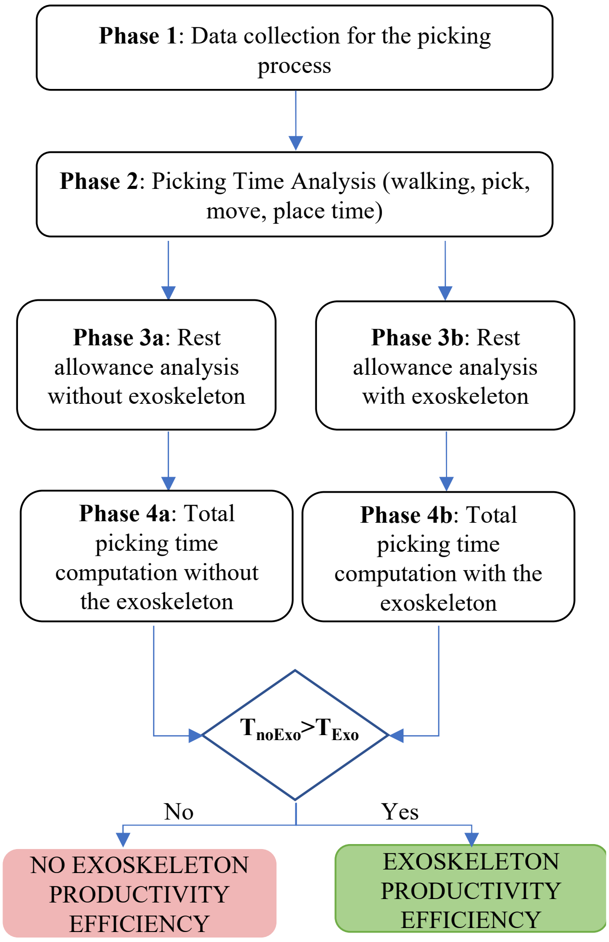

Fig. 1 Methodological approach

In phase 4a the total picking time without exoskeleton can be computed as follows with T(x) values retrieved in Table 1:

$$(3)\ T_{noExo} = \sum_{i=1}^{n} Q(i)\{[T_{pick}(x(i)) + T_{place}(x(i))](1 + RA_{noExo}) + T_{move}(x(i))\} + T_{walk}$$

Where:

$$x(i) = (noExo, pick\ position, pick\ height)$$

Determines the correct location to retrieve the data in Table 1 entering in the "no Exo" line with the position and height of the pick.

While in phase 4b, with the exoskeleton, the total picking time is computed differently. Since the exoskeleton gives support in bent positions such as picking and placing [8] its effect on RA will be charged only with picking and placing times, resulting:

$$(4)\ T_{Exo} = \sum_{i=1}^{n} Q(i) \cdot \{[T_{pick}(x(i)) + T_{place}] \cdot (1 + RA_{Exo}) + T_{move}(x(i))\} + T_{walk}$$

Where:

$$x(i) = (Exo, pick\ position, pick\ height)$$

IV. Numerical Application

In this Section, we apply the methodological approach proposed in Section III to a numerical application.

Phase 1:data collection for the picking process

We simulate the picking process for two picking lists. In both cases, the average weight of the item to pick is 5 kg. The pallets where pick and place items are subdivided into two equivalent areas named "near" and "far" positions. In the "near" position, the picking and placing positions are very close to the worker's area. On the other hand, in the "far" position, the worker assumes a not ergonomic position while performing picking due to the higher distance to pick and place the items (see Fig.2). In this numerical application, we assume to have an empty pallet where to place items so the picked items must be placed at ground level in far position. The picking list consists of one item to pick 5 times and another item to pick 2 times. For item 1 the picking location is near to the working position and at 0.5 m height. Item 2 is picked in a near position but at ground level (height 0 m). The total distance to complete the picking process is 50m.

Phase 2: Picking time analysis

For the picking time analysis is necessary to collect picking, moving, placing and walking values with and without the exoskeleton. The walking time can be set by considering the average speed of the worker with and without the exoskeleton. It is necessary to collect data with and without the exoskeleton for the pick and place activities since their deployment are subject specific [41]. For this reason, for this numerical application, we simulate the pick and place activities on a 27 years old healthy male 175cm tall and 72kg of weight. The Paexo Back exoskeleton developed by Ottobock has been deployed for this laboratory test. The motion data necessary to assess time performances in each sub-tasks was recorded with a Xsens inertial motion capture system as described in Battini et al., (2022).

In particular, the pick and place activity consisted of moving a box 395x295x275mm carrying a load of 5kg from a 1200x800mm picking pallet to an 800x600mm placing pallet positioned 1000mm far. Additionally, two picking heights were simulated: ground level and 500mm. The top view of the experimental setup is shown in Fig. 2. The volunteer (Fig. 3) was asked to perform a pick and place moving the box from the near pick position to the far place position and from the distant pick position to the close place position repeated for a total of 4 times (8 total objects picked and placed). The pick and place activities were repeated for the two picking heights described below with and without the exoskeleton for 4 runs.

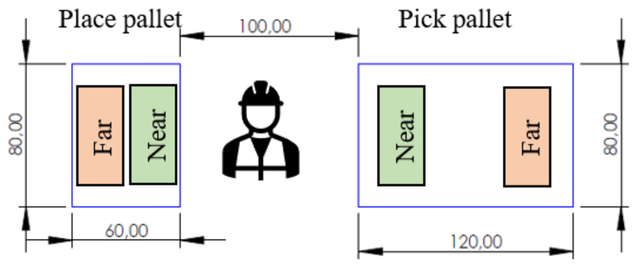

Fig. 2 Top view of the experimental layout

Fig. 3 The volunteer performing the tests

Additionally, the walking activity consisted of a walk in an indoor environment, and the walking speeds were directly took in output of the motion capture system. The deambulatory speeds resulted: v_{noExo}=1.41 m/s and v_{Exo}=1.35 m/s.

In Fig. 3 is reported a frame from the experiment showing the volunteer wearing both the Xsens motion capture system and Ottobock Paexo Back exoskeleton during the pick and place activity.

Phases 3a and 3b: rest allowance analysis without and with exoskeleton

In this phase, the RA is computed for conditions without (3a) and with the exoskeleton (3b). In 3a the %MVC in input to the models is 35%MVC and, using (1) and (2):

$$RA_{noExo} = 20.20\%$$

While, in 3b, with a %MVC of 8% the RA results:

$$RA_{Exo} = 2.70\%$$

In both cases, the RA is computed for pick and place activities since they represent the two activities which are influenced by the exoskeleton as defined in [8]. As we can see, the exoskeleton provides a significant relief on the back muscles since RA is significantly lower compared to the case without the exoskeleton.

Phases 4a and 4b: total picking time computation without and with exoskeleton

According to the collected data and the computed RA is now possible to evaluate the total picking time with and without exoskeleton. Without the exoskeleton using (3) according to phase 4a, the total time results:

$$T_{noExo} = 72.83\text{s}$$

While with exoskeleton, using (4) according to phase 4b, the total picking time results:

$$T_{Exo} = 70.81s$$

In this example, the exoskeleton is preferable for deployment since it guarantees a reduced process time. Its relieving effect on %MVC ensures a much lower RA impacting in the picking and placing times when the support is given despite the higher RA charged to the moving time where the exoskeleton does not provide support. Despite that, a different picking list with the items positioned in the "far" halves of the pallets where the exoskeleton penalized most of the time performances (Table 1) could have resulted in the convenience to not deploy it. For example, by reducing to 1 the quantities to pick for each item we obtain T_{exo}=46.76s (resp. T_{noExo}=45.95s). In this scenario, the picking time with the exoskeleton results

		Hpick [mm]	Hplace [mm]	Near position			Far position		
				Pick [s]	Move [s]	Place [s]	Pick [s]	Move [s]	Place [s]
5kg	No Exo	0	0	2.16	0.79	2.13	1.96	0.94	1.96
		500	0	2.03	1.16	1.55	1.49	1.27	1.42
	Exo	0	0	<u>2.04</u>	**1.10**	<u>1.76</u>	**2.17**	**1.34**	<u>1.76</u>
		500	0	<u>1.86</u>	**1.27**	<u>1.48</u>	**2.40**	**1.40**	**1.54**

Table 1 Experimentally measured picking times. The times improved by the exoskeleton utilization are underlined while the times where the exoskeleton brought penalization are in bold

slightly higher than that one without the exoskeleton. Thus, the exoskeleton is not convenient for improving picking performances.

V. CONCLUSIONS

In this paper, we present a methodological approach to evaluate the impacts of a passive back support exoskeleton on time performance by combining its direct impacts on sub-tasks and indirect effects on time performance through the RA which allows to convert into the time domain the relieving effect of the exoskeleton on back muscles. Moreover, the results of this approach can be used by managers as a decision support tool for evaluating when to deploy or not a passive back support exoskeleton in pick and place activities. As a future development of this approach, more scenarios and weight values could be considered as well as other %MVC values according to the operator features.

REFERENCES

[1] Breque, M., De Nul, L., and Petridis, A. (2021) Industry 5.0 : towards a sustainable, human-centric and resilient European industry. European Commission, Directorate-General for Research and Innovation, .

[2] Battini, D., Berti, N., Finco, S., Guidolin, M., Reggiani, M., and Tagliapietra, L. (2022) WEM-Platform: A real-time platform for full-body ergonomic assessment and feedback in manufacturing and logistics systems. *Computers & Industrial Engineering*. 164 107881.

[3] Bosch, T., van Eck, J., Knitel, K., and de Looze, M. (2016) The effects of a passive exoskeleton on muscle activity, discomfort and endurance time in forward bending work. *Applied Ergonomics*. 54 212–217.

[4] Spada, S., Ghibaudo, L., Gilotta, S., Gastaldi, L., and Cavatorta, M.P. (2017) Investigation into the Applicability of a Passive Upper-limb Exoskeleton in Automotive Industry. *Procedia Manufacturing*. 11 1255–1262.

[5] Ashta, G., Finco, S., Persona, A., and Battini, D. (2022) Investigating exoskeletons applicability in manufacturing and logistics systems: state of the art and future research directions. in: Proceedings of the Summer School Francesco Turco, .

[6] de Looze, M.P., Bosch, T., Krause, F., Stadler, K.S., and O'Sullivan, L.W. (2016) Exoskeletons for industrial application and their potential effects on physical work load. *Ergonomics*. 59 (5), 671–681.

[7] Voilqué, A., Masood, J., Fauroux, J.C., Sabourin, L., and Guezet, O. (2019) Industrial Exoskeleton Technology: Classification, Structural Analysis, and Structural Complexity Indicator. in: 2019 Wearable Robotics Association Conference, WearRAcon 2019, pp. 13–20.

[8] Schmalz, T., Colienne, A., Bywater, E., Fritzsche, L., Gärtner, C., Bellmann, M., et al. (2021) A Passive Back-Support Exoskeleton for Manual Materials Handling: Reduction of Low Back Loading and Metabolic Effort during Repetitive Lifting. *IISE Transactions on Occupational Ergonomics and Human Factors*.

[9] Laevo (2022) First PPE certified exoskeleton in the world! Meet the Laevo FLEX. *Https://Www.Laevo-Exoskeletons.Com/News/First-Ppe-Certified-Exoskeleton-in-the-World-Meet-the-Laevo-Flex*.

[10] Massardi, S., Rodriguez-Cianca, D., Pinto-Fernandez, D., Moreno, J.C., Lancini, M., and Torricelli, D. (2022) Characterization and Evaluation of Human–Exoskeleton Interaction Dynamics: A Review. *Sensors*. 22 (11),.

[11] Pesenti, M., Antonietti, A., Gandolla, M., and Pedrocchi, A. (2021) Towards a functional performance validation standard for industrial low-back exoskeletons: State of the art review. *Sensors (Switzerland)*. 21 (3), 1–23.

[12] Ashta, G., Finco, S., Battini, D., and Persona, A. (2023) Passive Exoskeletons to Enhance Workforce Sustainability: Literature Review and Future Research Agenda. *Sustainability*. 15 (9),.

[13] De Bock, S., Ampe, T., Rossini, M., Tassignon, B., Lefeber, D., Rodriguez-Guerrero, C., et al. (2023) Passive shoulder exoskeleton support partially mitigates fatigue-induced effects in overhead work. *Applied Ergonomics*. 106.

[14] Antwi-Afari, M.F., Li, H., Anwer, S., Li, D., Yu, Y., Mi, H.Y., et al. (2021) Assessment of a passive exoskeleton system on spinal biomechanics and subjective responses during manual repetitive handling tasks among construction workers. *Safety Science*. 142 105382.

[15] Amandels, S., het Eyndt, H.O., Daenen, L., and Hermans, V. (2019) Introduction and testing of a passive exoskeleton in an industrial working environment. .

[16] El ahrache, K. and Imbeau, D. (2009) Comparison of rest allowance models for static muscular work. *International Journal of Industrial Ergonomics*. 39 (1), 73–80.

[17] J.A. Tompkins (2003) Facilities Planning.

[18] Ogunseiju, O., Olayiwola, J., Akanmu, A., and Olatunji, O.A. (2022) Evaluation of postural-assist exoskeleton for manual material handling. *Engineering, Construction and Architectural Management*. 29 (3), 1358–1375.

[19] Motmans, R., Debaets, T., and Chrispeels, S. (2019) Effect of a passive exoskeleton on muscle activity and posture during order picking. .

[20] Cardoso, A., Colim, A., and Sousa, N. (2020) The Effects of a Passive Exoskeleton on Muscle Activity and Discomfort in Industrial Tasks. .

[21] Kinne, S., Kretschmer, V., and Bednorz, N. (2020) Palletising Support in Intralogistics: The Effect of a Passive Exoskeleton on Workload and Task Difficulty Considering Handling and Comfort. .

[22] Flor, R., Gaspar, J., Fujão, C., and Nunes, I.L. (2021) How Workers Perceive LAEVO Exoskeleton Use in Non-cyclic Tasks. .

[23] Giustetto, A., Vieira Dos Anjos, F., Gallo, F., Monferino, R., Cerone, G.L., Di Pardo, M., et al. (2021) Investigating

the effect of a passive trunk exoskeleton on local discomfort, perceived effort and spatial distribution of back muscles activity. *Ergonomics*. 64 (11), 1379–1392.

[24] dos Anjos, F.V., Vieira, T.M., Cerone, G.L., Pinto, T.P., and Gazzoni, M. (2022) Assessment of Exoskeleton Related Changes in Kinematics and Muscle Activity. .

[25] Luger, T., Bär, M., Seibt, R., Rieger, M.A., and Steinhilber, B. (2021) Using a Back Exoskeleton During Industrial and Functional Tasks—Effects on Muscle Activity, Posture, Performance, Usability, and Wearer Discomfort in a Laboratory Trial. *Human Factors*.

[26] Luger, T., Bär, M., Seibt, R., Rimmele, P., Rieger, M.A., and Steinhilber, B. (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. *Applied Ergonomics*. 97.

[27] Iranzo, S., Piedrabuena, A., García-Torres, F., Martinez-De-juan, J.L., Prats-Boluda, G., Sanchis, M., et al. (2022) Assessment of a Passive Lumbar Exoskeleton in Material Manual Handling Tasks under Laboratory Conditions. *Sensors*. 22 (11),.

[28] Qu, X., Qu, C., Ma, T., Yin, P., Zhao, N., Xia, Y., et al. (2021) Effects of an industrial passive assistive exoskeleton on muscle activity, oxygen consumption and subjective responses during lifting tasks. *PLoS ONE*. 16 (1 January),.

[29] Yandell, M.B., Wolfe, A.E., Marino, M.C., Harris, M.P., and Zelik, K.E. (2022) Effect of a Back-Assist Exosuit on Logistics Worker Perceptions, Acceptance, and Muscle Activity. .

[30] De Bock, S., Ghillebert, J., Govaerts, R., Tassignon, B., Rodriguez-Guerrero, C., Crea, S., et al. (2022) Benchmarking occupational exoskeletons: An evidence mapping systematic review. *Applied Ergonomics*. 98.

[31] Calzavara, M., Persona, A., Sgarbossa, F., and Visentin, V. (2019) A model for rest allowance estimation to improve tasks assignment to operators. *International Journal of Production Research*. 57 (3), 948–962.

[32] Rohmert, W. (1973) Problems in determining rest allowances: Part 1: Use of modern methods to evaluate stress and strain in static muscular work. *Applied Ergonomics*. 4 (2), 91–95.

[33] Milner, N. (1985) Modelling fatigue and recovery in static postural exercise. *Clinical Biomechanics*. 1 (1), 29.

[34] Rose, L., Örtengren, R., and Ericson, M. (2001) Endurance, pain and resumption in fully flexed postures. *Applied Ergonomics*. 32 (5), 501–508.

[35] Byström, S. and Fransson-Hall, C. (1994) Acceptability of Intermittent Handgrip Contractions Based on Physiological Response. *Human Factors*. 36 (1), 158–171.

[36] Ma, L., Chablat, D., Bennis, F., and Zhang, W. (2009) A new simple dynamic muscle fatigue model and its validation. *International Journal of Industrial Ergonomics*. 39 211–220.

[37] De Bock, S., Ghillebert, J., Govaerts, R., Elprama, S.A., Marusic, U., Serrien, B., et al. (2021) Passive Shoulder Exoskeletons: More Effective in the Lab Than in the Field? *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. 29 173–183.

[38] Madinei, S., Alemi, M.M., Kim, S., Srinivasan, D., and Nussbaum, M.A. (2020) Biomechanical Evaluation of Passive Back-Support Exoskeletons in a Precision Manual Assembly Task: "Expected" Effects on Trunk Muscle Activity, Perceived Exertion, and Task Performance. *Human Factors*. 62 (3), 441–457.

[39] So, B.C.L., Hua, C., Chen, T., Gao, Q., and Man, S.S. (2022) Biomechanical assessment of a passive back-support exoskeleton during repetitive lifting and carrying: Muscle activity, kinematics, and physical capacity. *Journal of Safety Research*. 83 210–222.

[40] Bazrgari, B., Shirazi-Adl, A., and Arjmand, N. (2007) Analysis of squat and stoop dynamic liftings: Muscle forces and internal spinal loads. *European Spine Journal : Official Publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society*. 16 687–699.

[41] Nussbaum, M.A., Lowe, B.D., de Looze, M., Harris-Adamson, C., and Smets, M. (2019) An Introduction to the Special Issue on Occupational Exoskeletons. *IISE Transactions on Occupational Ergonomics and Human Factors*. 7 (3–4), 153–162.