Test Methods for Passive Exoskeletons for Manufacturing Applications

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Abstract. This study explores the use of passive exoskeletons in modern industries to improve worker well-being and efficiency, particularly in tasks prone to musculoskeletal issues. A protocol has been defined to evaluate two passive exoskeletons (PAEXO back and PAEXO shoulder) through objective and subjective analyses. The first focused on muscle activity, kinematic movements and heart rate; the latter consisted of questionnaires to quantify user impressions. Results indicate that the PAEXO shoulder exoskeleton effectively reduces muscle strain and heart rate while maintaining user comfort. The PAEXO back exoskeleton showed potential but requires protocol refining and a longer familiarization period. Overall, passive exoskeletons hold promise for mitigating musculoskeletal risks and improving worker ergonomics.

Keywords: passive exoskeletons, human factor, motion capture

1 Introduction

Modern industries are adopting human-centred workplace designs and operator 5.0 concepts to customise work environments to improve operators' well-being and workforce efficiency [1]. Passive exoskeletons are emerging as valuable tools for improving the working environment, particularly in tasks involving repetitive or strenuous work that can lead to musculoskeletal issues [2,3], which afflict over 41% of the working population [4,5]. Recent studies show positive effects in the use of exoskeletons [6] for improving workers' biomechanics and researchers are exploring their benefits and developing protocols for their proper utilization [7,8].

In this preliminary study, the authors drafted a protocol to evaluate the effects of two passive exoskeletons during the execution of a repetitive lifting task and an assembly and screwing task by studying muscle activity, kinematic movements and heart rate alongside the subjective impressions of the participants.

2 Materials and Methods

For the purposes of this study, two passive exoskeletons have been taken into account: PAEXO back and PAEXO shoulder, developed by Ottobock (Duderstadt, Germany). The first is designed to reduce the load on the lower back during heavy object lifting; the latter targets the user's upper limb strain during the execution of repetitive or prolonged movements, especially with raised arms.

2.1 Obejctive and subjective analysis

To explore the potential benefits of the two mentioned devices, an objective and subjective analysis was conducted. The objective analysis focused on three main aspects. Initially, an assessment was made to determine if there were differences in muscle contraction between task execution with and without the exoskeleton. Specifically, for the back the following muscles of interest were considered: the Erector Spinae Longissimus (ESL), Erector Spinae Ileocostalis (ESI) and the Semitendinosus (ST). On the other hand, for the shoulder, the Trapezius descendens (TD), the Biceps Brachii (BB), the Deltoid medial (DM) and again the Erector Spinae Longissimus (ESL) were observed. To quantify muscular contraction, electromyographic signals from the muscles were recorded using surface electrodes (sEMG) from the BTS FREEEMG 1000 system. The measured data were then filtered and processed, and finally the Root Mean Square (RMS) value of each signal is calculated. The second aspect assessed in the objective analysis was the subjects' heart rate (HR) in the two study scenarios, and these signals were acquired using the Empatica E4 wristband. In the final stage, an assessment was conducted to identify any potential alterations in movement or posture resulting from exoskeleton usage, with a specific focus on the analysis of flexion-extension angles for the hip and shoulders. The data in this case were acquired using a Motion Capture system (Optitrack). On the other hand, the subjective analysis consists of two separate questionnaires. The first assesses the subjects' perceived fatigue during task execution using the BORG CR-10 scale. The second questionnaire, which is filled in at the end of the two trials (with and without exoskeleton), consists of 16 different questions, to be rated on a 0-10 scale, and divided into four categories: Confidence (CO), Cognitive Load (CL), Functionality (FU) and Physical Effort (PE).

2.2 Testing protocol and experimental set-up

For the purpose of this analysis, 10 male participants were involved, without orthopaedic problems, being 29.6 years old in average. All participants provided informed consent and the study was approved by the ethics committee of the Università Politecnica delle Marche.

Figure1 shows the steps of the testing protocol. Initially, each subject is given a period of time to become familiar with both exoskeletons and the test procedure are explained. Subsequently, the choice of the starting test protocol (back or shoulder) and whether to start with or without the exoskeleton (exo or noexo) is randomized. For the objective analysis, the first step is the fatigue test, which involves the acquisition of EMG and HR signals and the perceived effort scores. For the back, the test consists of the cyclic repetition of a task that includes lifting and stowing a box. The initial weight of the box is 6kg, but it is gradually increased to 12kg and then to 20kg. The exercise is repeated for 5, 4

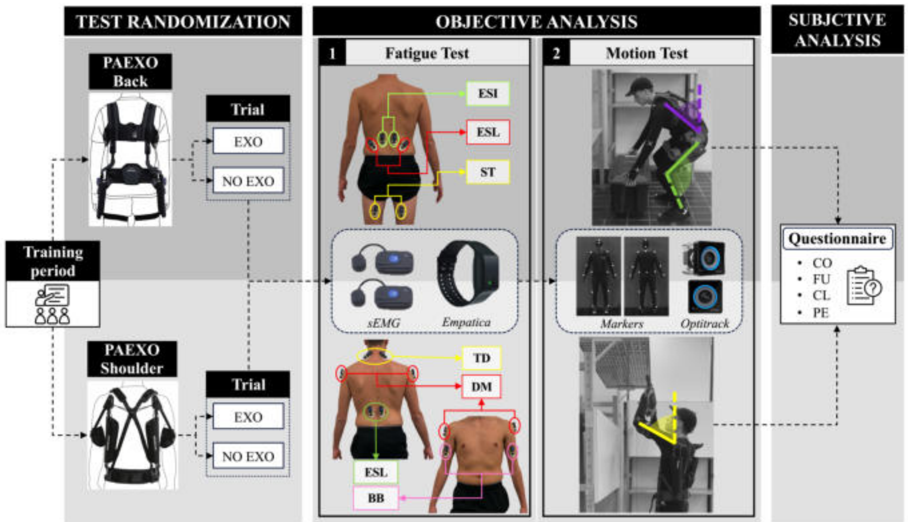

Fig. 1: Testing protocol steps: training period, test randomization, objective analysis (1. Fatigue Test; 2. Motion Test), subjective analysis. At the center, the used devices

and 3 minutes for each weight respectively and between each stage there is a 2-minute break. As for the shoulder, the test consists of three different tasks which require the arms to be kept raised: simulation of screwing, drilling and cabling. Each task lasts 2 minutes and the sequence is repeated twice. The second step is the motion test, aimed at the acquisition of joint angles with the motion capture system. For the back test, the previous exercise is repeated for 100 seconds for each weight. With regards to the shoulder test, only the frontal and overhead drilling simulation is performed for a duration of 100 seconds. At the end of the test, once it has been performed with and without the involved exoskeleton, the subject is asked to complete the post experimental questionnaire.

3 Results and discussion

The muscular activity related to PAEXO back exoskeleton is summarized in Figure2 (a). The most relevant result regards the ST, since for this muscle the plot shows a reduced muscular contraction while wearing the exoskeleton. On the other hand, from a postural point of view, Figure2 (b) shows a significant reduction in the maximal hip flexion angle while using the exoskeleton, which indicates the maintenance of a better posture. However, no influence was found on the heart rate. This result is aligned with the subjective analysis (Table1), in which the exoskeleton does not appear to provide relevant improvements in perceived fatigue [3] and shows an overall score of 5.3 in the post experimental questionnaire, which suggest a discomfort with the exoskeleton. Conversely, the PAEXO shoulder exoskeleton leads to a reduction in the contraction [8] noticeable for all the muscles involved in the analysis (Figure2 (c)) and in the HR. Moreover, it can be observed that the shoulder flexion/extension angles (Figure2(d)) are comparable in the two tested configurations. These results demonstrate that in terms of fatigue and ergonomics, this exoskeleton proves useful in reducing physical effort while remaining comfortable to wear. This is also confirmed by the subjective analysis, which highlights the perception of an overall advantage in performing the task while wearing the exoskeleton (Table1).

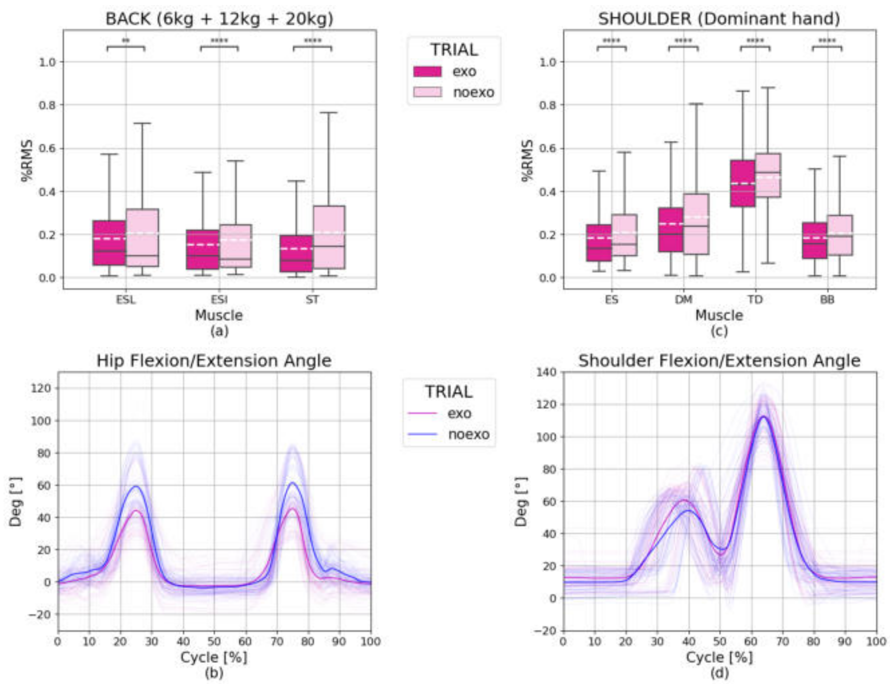

Fig. 2: Box plots of muscle activity (a, c), where the dotted lines represent the mean and the solid lines represent the median, stars indicate statistically significant differences resulting from Mann-Whitney-Wilcoxon two-sided test (*p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001); hip and shoulder joint angles within a cycle (b, d), respectively lifting and stowing the box, and frontal and overhead drilling.

4 Conclusion and future works

The presented work is a preliminary test to assess and refine the employed protocol, methods, and tools, in order to verify its transferability in industrial frameworks. From the initial results, the passive exoskeletons proved to be an effective measure for posture control and muscle overload, potentially reducing the risk of musculoskeletal injuries. The PAEXO back evaluation has highlighted some limits in the implemented protocol. From the users' feedback and from the objective analysis, these limits can be tackled by a longer familiarization period and by a simpler protocol that reproduces a real-case scenario. Conversely, the results concerning the PAEXO shoulder evaluation demonstrate that the use of the exoskeleton can help reduce muscle activity, consequently decreasing cardiac cost.

Table 1: Perceived fatigue (exo, noexo) and post-experimental questionnaires in four categories: Confidence (CO), Cognitive Load (CL), Functionality (FU) and Physical Effort (PE). Each result is expressed in Mean (sd).

	Perceived fatigue		Post experimental				
	exo	*noexo*	*CO*	*FU*	*CL*	*PE*	*TOT*
BACK	5 (2.0)	5.6 (2.1)	5.0 (1.7)	5.5 (1.3)	5.1 (1.2)	5.7 (1.3)	5.3 (1.0)
SHOULDER	4.5 (1.6)	6.25 (2.3)	6.9 (1.3)	6.8 (1.2)	6.7 (1.0)	6.7 (0.9)	6.8 (0.9)

Moreover, the subjects involved in the tests expressed positive effects on the reduction of perceived fatigue. This can be due to the greater intuitiveness of such an exoskeleton, which, compared to the PAEXO back, has been proven effective despite the short familiarization period. Future works will assess how comfortable and practical exoskeletons are when used during everyday non-task-specific movements (e.g. walking) and for performing tasks with collaborative robots.

5 Acknowledgements

The research has been funded by the European Union - NextGenerationEU under the Italian Ministry of University and Research (MUR) National Innovation Ecosystem grant ECS00000041 - VITALITY - CUP I33C22001330007.

References

1. Romero, D., Stahre, J. (2021). Towards the resilient operator 5.0: The future of work in smart resilient manufacturing systems. Procedia CIRP, 104, 1089-1094.
2. De Bock, S., Ampe, T., Rossini, M., Tassignon, B., Lefeber, D., Rodriguez-Guerrero, C., De Pauw, K. (2023). Passive shoulder exoskeleton support partially mitigates fatigue-induced effects in overhead work. Applied Ergonomics, 106, 103903.
3. van Sluijs, R. M., Wehrli, M., Brunner, A., Lambercy, O. (2023). Evaluation of the physiological benefits of a passive back-support exoskeleton during lifting and working in forward leaning postures. Journal of Biomechanics, 149, 111489.
4. Kok, J., De Vroonhof, P., Snijders. J., Roullis, G., Clarke, M., Peereboom, K., Isusi, I., 2019. Work-related MSDs: Prevalence, costs and demograpghics in the EU. Pubblications Office of the European Union.
5. Breque, M., De Nul, L., Petridis, A. (2021). Industry 5.0: towards a sustainable, human-centric and resilient European industry. Luxembourg, LU: European Commission, Directorate-General for Research and Innovation.
6. Lee, J., Kim, D., Ryoo, H. Y., Shin, B. S. (2016). Sustainable wearables: Wearable technology for enhancing the quality of human life. Sustainability, 8(5), 466.
7. Li-Baboud, Y. S., Virts, A., Bostelman, R., Yoon, S., Rahman, A., Rhode, L., Shah, M. (2023). Evaluation Methods and Measurement Challenges for Industrial Exoskeletons. Sensors, 23(12), 5604.
8. Brunner, A., van Sluijs, R., Bartenbach, V., Bee, D., Kos, M., Aryananda, L., Lambercy, O. (2023, May). Effect of a Passive Shoulder Support Exoskeleton on Fatigue During Working with Arms over Shoulder Level. In International Workshop on Medical and Service Robots (pp. 188-197). Cham: Springer Nature Switzerland.