# Upper Limbs Industrial Exoskeletons: an Objective and Subjective Evaluation Method

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**Abstract** Work-related musculoskeletal disorders (WMSDs) pose substantial health and economic challenges, affecting a significant portion of the workforce. This study investigates the efficacy of the PAEXO Shoulder exoskeleton in addressing WMSDs during repetitive arm movements, a common risk factor in various industries. Through a comprehensive evaluation utilizing objective measures such as surface electromyography (sEMG), Blood Volume Pulse (BVP), Electrodermal Activity (EDA), and joint angles, alongside subjective assessments including perceived exertion and user questionnaires, the study sheds light on the exoskeleton's impact on worker well-being. Preliminary results suggest a reduction in muscle contraction and physiological parameters indicate decreased fatigue when utilizing the exoskeleton during tasks. Furthermore, from the results concerning the joint angles, the exoskeleton proved to preserve natural shoulder movement while maintaining user comfort. The subjective feedback from participants aligns with the objective findings, indicating reduced fatigue and favorable experiences with the exoskeleton's usability and functionality. These findings suggest the potential of the PAEXO shoulder exoskeleton technology in promoting worker health, yet emphasize the need for further research to confirm its efficacy in real work settings over extended periods.

## 1 Introduction

Work-related musculoskeletal disorders (WMSDs) are the primary cause of health issues for workers in various sectors and occupations throughout Europe [1]. These issues not only impact workers' health but also have economic repercussions for businesses and social costs for countries [2]. About three out of five workers in the EU report experiencing WMSDs, which mainly affect the back and upper and lower

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limbs. The most common types are back pain and upper limb muscle pain, accounting for 43% and 41% of reported cases respectively [3]. The extended maintenance of uncomfortable arm positions, like overhead holding and repetitive movements, are acknowledged as primary risk factors for upper limb WMSDs, due to biomechanical stress, especially on the shoulder joints [1]. Despite the increasing automation in industries, manual activities still play a crucial role. Therefore, the well-being of workers in this sector is of vital importance. In this context, emerging wearable technologies such as passive exoskeletons have shown promise as solutions to provide physical support during demanding tasks [4]. Indeed, as reported in many studies [5, 6, 7], these technologies have the potential to mitigate the onset of physical problems, thereby reducing injuries and the risk of developing WMSDs. There is a critical need to develop methodologies for assessing biomechanical risk in scenarios where such technologies are used, particularly during repetitive tasks that involve raising the arms above the head. This article addresses this need by presenting experimental results evaluating the effectiveness of an upper limb exoskeleton. Several metrics were considered to assess how its support affects muscle activity, physiological state, and subjective perception of physical and mental fatigue.

## 2 Materials and Methods

The purpose of this study is to quantify the potential benefits of using the PAEXO Shoulder exoskeleton, developed by Ottobock (Duderstadt, Germany), during specific tasks. Designed to alleviate upper limb strain during repetitive or prolonged arm movements involving lifting or holding objects, this preliminary study will evaluate the performance of the exoskeleton in simulated industrial tasks in a laboratory setting. Using established acquisition protocols and both objective and subjective analysis of participant data, the study aims to determine the impact of using the exoskeleton compared to performing the tasks without it, with future plans to extend the evaluation to real-world scenarios.

Objective measurements include the recording of muscular activity through surface electromyographic signals (sEMG) using the BTS FREEEMG 1000 system. This system, with a sampling frequency of 1000 Hz, captures signals in real time and wirelessly transmits them to the BTS EMG-analyser software. Electrodes were strategically placed on the Erector Spinae Longissimus (ES), Deltoideus Medialis (DM), Trapezius Descendens (TD) and Biceps Brachii (BB) muscles. Electrodes were placed on the skin following SENIAM recommendations [8]. The first objective metric that was calculated was the Root Mean Square (RMS) of the EMG signals and to do this, the data were processed using a 4th-order Butterworth bandpass filter (20 Hz - 450 Hz), rectified, and normalized based on maximum contraction during the task. The integrated EMG (iEMG), which has been shown in the literature to gradually increases with the progress of muscle fatigue, was also chosen as an objective measure [9]. Specifically, iEMG is defined as the area under the curve of the rectified EMG signal. Therefore, to obtain this value, the integral of the absolute value of the raw EMG signal has been computed. Moreover, Blood Volume Pulse (BVP) and Electrodermal Activity (EDA) were recorded using the Empatica E4 wristband on the non-dominant hand, with sampling rates of 64 Hz and 4 Hz, respectively. EDA is a measure of the increase in sweat activity and skin conductance due to stimuli that activate the sympathetic nervous system, and studying this parameter makes it possible to analyse stress and exertion during task performance. Both signals were subjected to a filtering process to remove artefacts. In particular, the heart rate (HR) was extracted from this filtered BVP signal for further analysis of physiological function. Finally, to assess joint angle variations, shoulder flexion/extension (flex/ext) angles were examined using the Optitrack Motion Capture system at a sampling rate of 360 Hz.

On the other hand, subjective evaluations involved administering two questionnaires. The first utilized the Borg Rating of Perceived Exertion (RPE) 0-10 scale to estimate participants' perceived fatigue during task execution [10]. The second questionnaire, completed after both trials (with and without exoskeleton), consisted of 16 questions rated on a 0-10 scale, categorized into Confidence (CO), Cognitive Load (CL), Functionality (FU), and Physical Effort (PE). These categories respectively measure the participants' self-assurance, mental effort, perception of the exoskeleton's effectiveness, and physical strain experienced during task execution.

## 2.1 Testing Protocol definition and employed tools

For the purpose of this analysis, ten male participants without orthopaedic problems were involved (Mean & SD: Age: 27.6 years ± 5.4; Stature: 181 cm ± 8.0; Mass: 80.4 kg ± 16.9; Body Mass Index: 24.4 ± 3.4). All participants provided informed consent to participate in the study.

The testing protocol steps are illustrated in Fig. 1. Initially, each subject is given a period of time to become familiar with the exoskeleton and the test procedure is explained. Subsequently, the choice of the trial is randomized, that is whether to start with or without the exoskeleton (exo or noexo). For the objective analysis, the first step is the Fatigue Test, which involves the acquisition of EMG, BVP and EDA signals. 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.

On the other hand, for the subjective analysis, the Perceived Fatigue Scores are recorded during task execution. The second step of the objective analysis is the Motion Test. The subject is provided with a suit with markers on it, in order to acquire joint angles with the motion capture system. At this stage, frontal and overhead drilling are simulated for a duration of 100 seconds per trial. Once the test has been performed with and without the exoskeleton, the subject is asked to complete the Post-experimental Questionnaire.

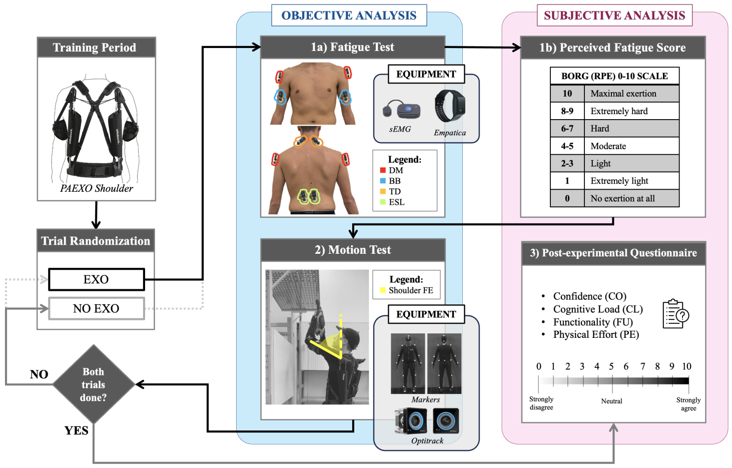


**Fig. 1** Block diagram of the testing procedure: training period, trial randomization, objective analysis (1a. Fatigue Test; 2. Motion Test) with the employed equipment, subjective analysis (1b. Perceived Fatigue Score, 3. Post-experimental Questionnaire).

## 3 Results and Discussion

This section presents a comprehensive analysis of the outcomes obtained from both objective and subjective perspectives. It starts with the objective analysis, examining quantitative measurements and physiological responses to assess the impact of exoskeleton assistance on muscle activity and fatigue. Following this, the subjective analysis explores participants' perceptions of the exoskeleton's usability, functionality, and its effect on physical exertion, offering insights into user satisfaction.

### 3.1 Objective Analysis

Fig. 2 illustrates the results obtained for the parameters considered in the objective analysis. To simplify reporting, the results are presented relative to the dominant side of the subjects (from the right-hand side sensors for right-handed subjects and from the left-hand side sensors for left-handed subjects). In particular, concerning the Fatigue Test, in Fig. 2(a), one can observe the box plots relative to the RMS as a percentage of the maximum contraction for each muscle considered. It is evident how performing the task while wearing the exoskeleton leads to a reduction in both mean (dashed line) and median (solid line) muscle contraction, and this difference is statistically significant according to the Mann-Whitney test. This reduction can be attributed to lower muscle fatigue due to the assistance provided by the exoskeleton.

In addition to the RMS, the iEMG was also calculated from the electromyographic signal. Table 1 shows for each considered muscle of each subject the area under the

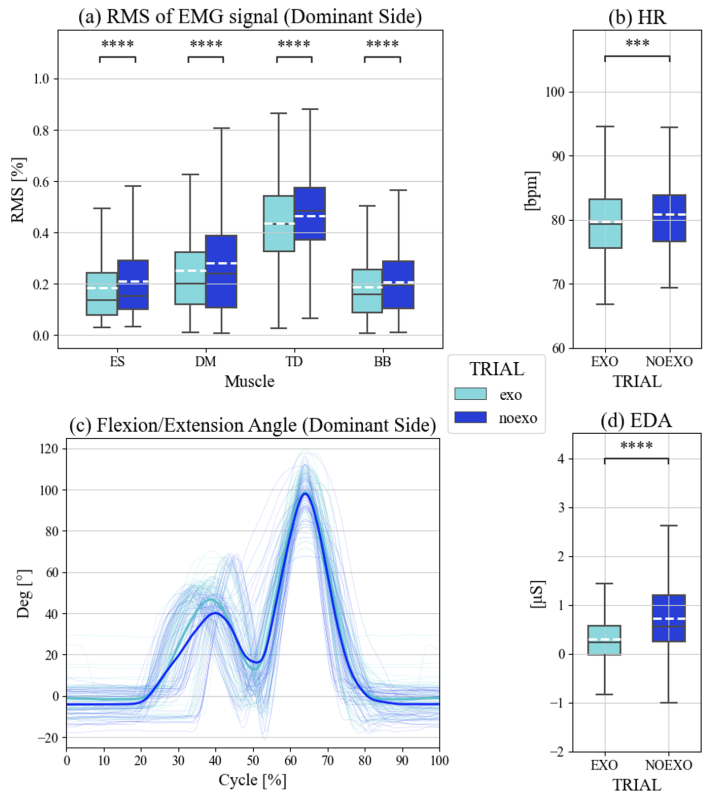


**Fig. 2** Box plots of (a) RMS of muscle activity, (b) heart rate, and (d) electrodermal activity, where the dotted lines represent the mean and the solid lines represent the median, stars indicate statistically significant differences resulting from Mann-Whitney-Wilcoxon two-sided test (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, ****$p < 0.0001$); (c) overlapping plots of Shoulder flex/ext angles within a cycle during the repetition of frontal and overhead drilling, where the thicker lines represent the average trends.

signal curve obtained in the trial with the exoskeleton and without the exoskeleton. Since it is understood that as fatigue increases, the area under the curve increases accordingly, the difference between the iEMG values obtained in the two trials is also computed. A positive difference indicates that the use of the exoskeleton contributed to a reduction in muscle fatigue. The most interesting results are found for DM and TD, where the differences in the two trials are considerable for almost all subjects. Regarding ES, being a compensatory muscle for the shoulder, the minimal positive differences indicate that the exoskeleton, by relieving the strain on the shoulder, does not overload the compensatory muscles of the back. As for BB, despite the RMS box plots showing a smaller contraction using the exoskeleton, there is a majority of negative differences. This discrepancy is attributed to the iEMG being defined by the integral of the raw signal, coupled with the electrodes being in a critical area

**Table 1** Results of the iEMG obtained for each subject for the muscles analysed in the trial with the exoskeleton (exo), without the exoskeleton (noexo), and, in the last column (Diff), the difference obtained by the subtraction iEMG(noexo) - iEMG(exo).

Integrated EMG (iEMG)

| *Subjects* | *ES* | | | *DM* | | | *TD* | | | *BB* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *exo* | *noexo* | ***Diff*** | *exo* | *noexo* | ***Diff*** | *exo* | *noexo* | ***Diff*** | *exo* | *noexo* | ***Diff*** |
| *S1* | 1.8 | 2.3 | **0.5** | 5.6 | 4.5 | -1.1 | 16.3 | 2.2 | -14.1 | 10.4 | 5.6 | -4.9 |
| *S2* | 4.9 | 4.7 | -0.2 | 11.8 | 22.6 | **10.8** | 18.0 | 20.3 | **2.3** | 14.6 | 10.8 | -3.8 |
| *S3* | 3.5 | 4.1 | **0.6** | 16.5 | 40.2 | **23.7** | 31.6 | 38.7 | **7.2** | 12.3 | 11.5 | -0.7 |
| *S4* | 3.6 | 3.6 | **0.0** | 10.6 | 20.0 | **9.4** | 61.9 | 83.2 | **21.3** | 12.5 | 13.0 | **0.4** |
| *S5* | 1.5 | 1.4 | -0.1 | 12.0 | 14.9 | **2.9** | 26.9 | 34.8 | **8.0** | 11.9 | 11.2 | -0.7 |
| *S6* | 3.8 | 3.7 | -0.1 | 7.6 | 12.8 | **5.1** | 23.2 | 33.4 | **10.3** | 17.1 | 13.3 | -3.8 |
| *S7* | 3.0 | 3.4 | **0.4** | 11.7 | 13.7 | **1.9** | 39.8 | 63.0 | **23.2** | 7.3 | 12.4 | **5.1** |
| *S8* | 9.7 | 7.9 | -1.8 | 12.9 | 17.0 | **4.0** | 31.8 | 48.5 | **16.8** | 32.6 | 18.5 | -14.1 |
| *S9* | 3.2 | 3.7 | **0.5** | 9.4 | 12.7 | **3.4** | 43.6 | 29.8 | -13.8 | 15.5 | 23.0 | **7.5** |
| *S10* | 4.1 | 2.1 | -2.0 | 3.0 | 3.8 | **0.8** | 33.7 | 39.4 | **5.7** | 7.6 | 10.1 | **2.5** |

with frequent collisions with the exoskeleton bands. Therefore, the authors believe that the results shown in the table for the iEMG of BB are not reliable.

The fatigue test analysis is enhanced by the acquisitions obtained with the Empatica E4, which provide the HR and EDA results shown in Fig. 2(b) and Fig. 2(d). In both cases, there is a significant reduction in the parameters when measured with the exoskeleton. As these parameters are directly correlated with fatigue, the results obtained further confirm the effectiveness of the exoskeleton in reducing effort during task performance.

On the other hand, as far as the results of the Motion Test are concerned, Fig. 2(c) shows the trend of the shoulder flex/ext angle in terms of percentage of the task cycle. It can be seen that this trend is similar in the two trails, resulting in an imperceptible variation of the angle during the movement performed in the two configurations. This demonstrates a solid transparency by the exoskeleton which operates in a manner that seamlessly integrates with the wearer's movements, offering support and assistance while minimizing interference and without altering natural motion.

### 3.2 Subjective Analysis

As far as the subjective analysis is concerned, Table 2 shows the averages of the scores expressed by the participants, both in terms of the Perceived Fatigue score and the Post-experimental questionnaire. Specifically, the Perceived Fatigue scores reveal that performing the task without the exoskeleton was more demanding, as evidenced by the overall average at the bottom. This indicates a 26.67% reduction in perceived fatigue when using the exoskeleton. In the Post-experimental questionnaire, the averages of the ratings given by each subject are presented, maintaining the distinction between the four categories. Overall, a score of 7/10 was given, indicating that the exoskeleton proved to be easy to use, functional, and had a positive effect on physical effort. Consequently, the final user rating, after all the tests performed, aligns with and reinforces the results of the parameters collected and described above.

**Table 2** Perceived fatigue (exo, noexo) score and post-experimental questionnaires in four categories: Confidence (CO), Cognitive Load (CL), Functionality (FU) and Physical Effort (PE) and TOT as the mean of the four. The last row reports Mean (sd).

| *Subjects* | ***Perceived fatigue*** | | ***Post experimental*** | | | | |
|---|---|---|---|---|---|---|---|
| | *exo* | *noexo* | *CO* | *FU* | *CL* | *PE* | *TOT* |
| *S1* | 5.0 | 7.5 | 6.5 | 5.6 | 6.8 | 5.3 | 6.1 |
| *S2* | 7.0 | 10.0 | 7.0 | 7.2 | 6.5 | 7.3 | 7.0 |
| *S3* | 5.0 | 7.5 | 7.5 | 7.0 | 6.7 | 7.3 | 7.1 |
| *S4* | 4.0 | 7.8 | 5.0 | 6.6 | 8.5 | 7.0 | 6.8 |
| *S5* | 6.5 | 7.3 | 6.5 | 7.5 | 6.1 | 7.2 | 6.8 |
| *S6* | 4.5 | 5.3 | 5.5 | 5.0 | 5.0 | 5.0 | 5.1 |
| *S7* | 2.5 | 2.5 | 10.0 | 8.8 | 6.8 | 7.3 | 8.2 |
| *S8* | 3.0 | 4.5 | 7.0 | 6.4 | 6.2 | 6.3 | 6.5 |
| *S9* | 3.0 | 4.0 | 7.5 | 8.0 | 8.3 | 7.3 | 7.8 |
| *S10* | 3.0 | 4.0 | 8.5 | 7.8 | 8.0 | 9.0 | 8.3 |
| ***Mean** (sd)* | **4.4** (1.5) | **6.0** (2.3) | **7.1** (1.4) | **7.0** (1.1) | **6.9** (1.1) | **6.9** (1.1) | **7.0** (1.0) |

## 4 Conclusion

This study aimed to examine the potential effectiveness of the PAEXO Shoulder exoskeleton in addressing work-related musculoskeletal disorders (WMSDs) during repetitive and prolonged arm movements. Analysis revealed notable reductions in muscle contraction and fatigue, particularly in the DM and TD muscles. Physiological measures such as BVP and EDA indicated a decrease in heart rate and skin conductance among participants using the exoskeleton, suggesting its potential to alleviate physiological stress. Furthermore, the exoskeleton allowed natural shoulder movement during simulated industrial tasks, without imposing restrictions on flex/ext angles. Subjectively, participants reported a 26.67% decrease in fatigue and were positive about the exoskeleton, finding it easy to use, functional and reducing physical effort. Overall, the findings suggest the potential of the PAEXO Shoulder exoskeleton in promoting worker health. However, despite the promising results, future reasearch, including larger-scale studies conducted over extended periods and in real work settings, will be necessary to provide more conclusive evidence on the efficacy of the PAEXO Shoulder exoskeleton in mitigating WMSD risks associated with repetitive arm movements.

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**Competing Interests** The authors have no conflicts of interest to declare that are relevant to the content of this chapter.

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