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The Effect of an Active Upper-Limb Exoskeleton on Metabolic Parameters and Muscle Activity During a Repetitive Industrial Task

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Miguel Hernandez University's Ethical Committee under Application No. 2017.32.E.OEP.

ABSTRACT In this paper, an experimental evaluation of an active upper-limb exoskeleton, where 12 subjects perform an overhead industrial task with and without the exoskeleton, is presented. The experimental laboratory test has been carried out to analyze the advantages of wearing the exoskeleton to carry out repetitive industrial tasks, assessing whether the proposed device reduces metabolic parameters and the muscular strain. The set of metrics to assess the effects of the exoskeleton included biomechanical parameters, such as electromyographic signals, and metabolic parameters, such as heart rate, heart rate variability, respiratory frequency, tidal volume, ventilation and oxygen consumption. The results show that the developed active upper-limb exoskeleton can reduce cardiorespiratory responses and muscular activity. In addition, statistical data analysis shows significant differences in oxygen consumption, heart rate and effort supported by muscles between conditions (when handling a load of 1.7 kg with and without the exoskeleton). It is observed that, wearing the exoskeleton reduces oxygen consumption by more than 24%, the heart rate decreases by 14%, and muscle activity is reduced by almost 37% in triceps and up to 64% in biceps compare to no wearing. Based on these results, the presented active upper-limb exoskeleton could be potentially useful to reduce muscular strain and fatigue in repetitive overhead tasks.

INDEX TERMS Exoskeletons, wearable robotics, power augmentation, industrial task, ergonomic design, assistive technologies.

I. INTRODUCTION

Work-related musculoskeletal disorders (WRMSDs), especially when they become chronic, are highly prevalent and costly in industrialized countries, constituting one of the leading causes of absenteeism worldwide [1]. They are related to physical exposure or poor ergonomics in the workplace, and cause the sufferer to impact significantly the personal, social and economic spheres [2]. As for the regions of the body most affected by this type of disorder, around 65% of these ailments occur in the upper body (arms, back and neck) [3].

Despite the widespread use of robots and automated systems in the industry, many manual jobs are still performed by the operator himself, especially those requiring human decision-making or dexterity [4], [5]. A possible solution could be the incorporation in the industry of exoskeletons, combining robotics with the human factor, a trend known as Operator 4.0 inside the Industry 4.0 framework, which considers technology augmented workers [6], [7].

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The main objective of industrial-type exoskeletons is to support operators at their workstation, reducing the physical fatigue and discomfort produced by performing repetitive tasks, mainly repetitive overhead motions [8]–[10]. To asses the effect of an exoskeleton on the user, Torricelli *et al.* proposed to evaluate the functional performance and the physical impact of the device on the user [11]. The functional performance is usually assessed through electromyography signals (EMG), physiological measures, biomechanical parameters and information provided by the exoskeleton, such as, position, velocity, force, etc [12]. On the other hand, the physical impact of the device on the user is mainly assessed through subjective measurements, such as, discomfort, usability, donning and doffing time, etc [12].

The present study aims to validate the active upper-limb exoskeleton developed in the framework of the ExIF project (Intelligent Robotic Exoskeleton and Advanced Interface Systems Man Machine for Maintenance Tasks in the Industries of the Future) [13]. This project arises from the need to reduce or eliminate musculoskeletal disorders that appear in the work environment, usually linked to repetitive manual tasks or the adoption of bad postures during work. The main objective of the project is the development of an integral robotic solution for the assistance of arm movements in the industrial field, consisting of an exoskeleton-type robot and an intelligent control system, which will be adapted to different users according to their needs. The robotic system developed has been previously evaluated in simulation environments and experimental laboratory tests [14], [15]. These experimentations have allowed us to see possible improvements of the device, facilitating the redesign of the system and the fabrication of a more evolved prototype, shown in Fig. 1.

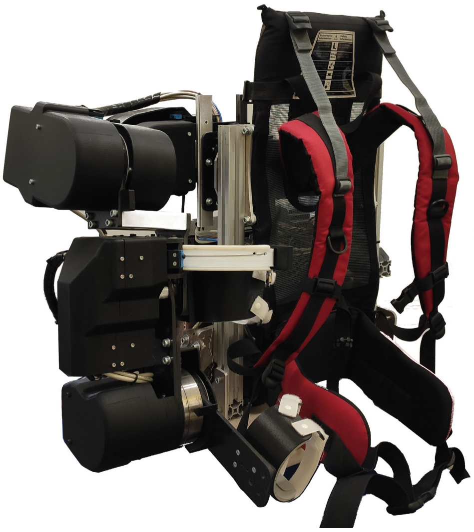


FIGURE 1. Active upper-limb exoskeleton prototype.

The new upper-limb exoskeleton prototype has been validated in depth. In this paper, the effect of an exoskeleton on the user is evaluated performing a dynamic task. Specifically, we carried out the assessment of functional performance through the analysis of EMG and physiological signals of the user. Our hypothesis is that the developed exoskeleton will reduce the metabolic parameters of users when performing a typical industrial task. We have also analyzed the differences in muscle activity of the main muscle groups involved in the task and the differences in some physiological parameters (cardiac responses and respiratory activity).

In order to determine whether there is a reduction in the metabolic cost when carrying out the activity, different measures related to the respiratory activity of the users were analyzed, such as respiratory frequency, tidal volume, ventilation and oxygen consumption. Some methods for determining metabolic cost are described by the International Organization for Standardization 8896 (ISO 8996:2004) [16], with the method based on the measurement of oxygen consumption being considered one of the most accurate. Changes in muscle activity (EMG) were also studied, as well as cardiac responses through pulse rate (HR) and heart rate variability (HRV). These measures are closely related to the intensity level of the activity and can be used to approximate the metabolic cost [17]–[19], which allow us to verify whether the proposed device reduces user fatigue when carrying out the task.

II. MATERIALS AND METHODS

An experimental study was designed to simulate overhead work task close to the real industrial and maintenance tasks. The simulated overhead task, a drilling task, was performed with/without exoskeleton support to evaluate and analyze functional performance through the analysis of EMG and physiological signals of the user.

A. SUBJECTS

Twelve healthy subjects volunteered for the study, 11 male and 1 female. All of them are right-handed, and their ages are between 22 and 42 years (27.6 years ± 5.53 years), with heights ranging between 1.63 and 1.83 m (1.76 m ± 0.56 m), and a weight between 63 and 90 kg (72.4 kg ± 8.16 kg). They provided written, informed consent before participating in the experimentation. This experimentation was approved by the Miguel Hernandez University's Ethical committee and registered with reference number 2017.32.E.OEP.

B. EXPERIMENTAL TASK

The upper-limb exoskeleton has been designed to be anchored to a lower-limb exoskeleton-type structure that transmits the weight of the system to the ground. This is necessary to avoid possible overstressing that may occur due to the incorporation of the upper-limb exoskeleton because of its weight. In previous work it has been analyzed how the incorporation of this structure that transmits the weight of the device to the ground would affect it, which the conceptual design and the simulation carried out in [14] are shown in Fig. 2. The results obtained in this simulation indicate that, when the upper limb exoskeleton is used and all its weight falls on the user, there are overstrains in the lumbar area that would be counterproductive for the person wearing it.

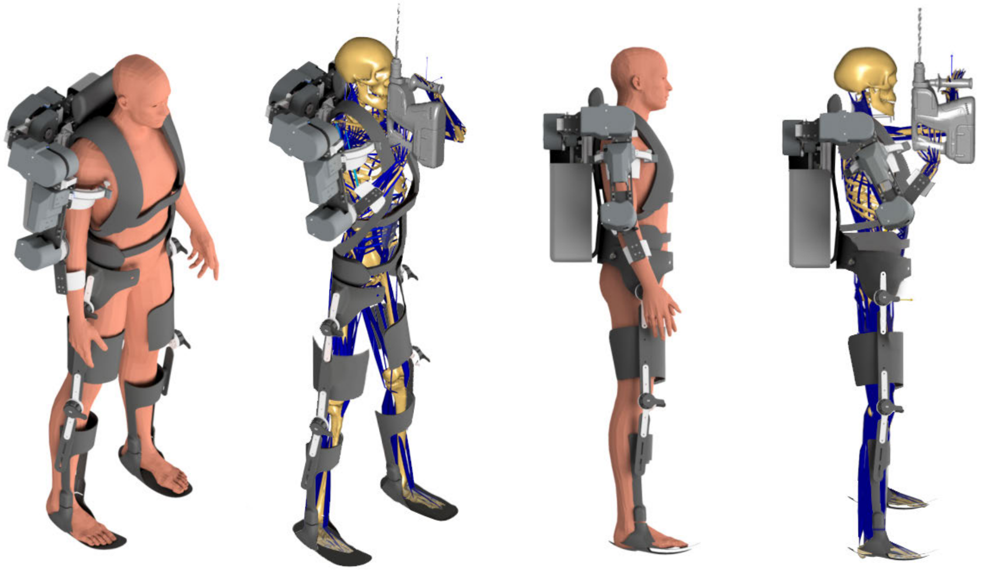


FIGURE 2. **Design and simulation of the complete system.**

However, by adding the robot's weight-bearing structure, these overstrains are considerably reduced.

Since the lower-limb exoskeleton-type structure is still under development and not available to the experimental task, to simulate the effect of its incorporation, the device has been partially anchored to an aluminium profile structure that supports the upper-limb exoskeleton weight. The subjects will stand in front of a screen that will indicate at all times the instructions to follow to carry out the experimentation. The setup was adjusted according to subjects' height, so that all the subjects kept approximately 90 deg of shoulder and elbow flexion angles during the performance of the overhead simulated drilling task.

The task is performed by the subjects under two conditions: 1) without wearing the exoskeleton, namely "no exoskeleton (NE)"; and 2) wearing the active upper-limb exoskeleton, namely "with exoskeleton (WE)," which are carried out randomly so as not to condition the experimental data. The task consists of performing an overhead drilling simulated action, keeping the arm with a shoulder and elbow flexion of 90 degrees, respectively.

The task is composed of 3 movements or states:

- Raise the arm to reach the target position.
- Hold the working position for 5 seconds.
- Lowering the arm to the resting or starting position.

These 3 states compose a trial, which lasts approximately 15 seconds (5 seconds per state). For each of the conditions (NE and WE), 20 repetitions of each trial are performed, first without weight to take reference measurements (No Load), and then with a 1.7 kg drill (Load).

C. SETUP

The experimentation setup can be seen in Fig.3 and Fig.4, where all the devices used in the study are shown. The exoskeleton validated in this study has 4 degrees of freedom to assist the following movements:

TABLE 1. **Maximum ranges of movements and torques of the exoskeleton.**

Movement	Range (degrees)	Maximum Torque (Nm)
sA/A	90° abd / 0° ad	40
sF/E	170° flex / 0° ext	40
sI/E	57° int / 42° ext	15
eF/E	40° flex / 85° ext	20

- Shoulder abduction/adduction
- Shoulder flexion/extension
- Shoulder internal/external rotation
- Elbow flexion/extension

The zero-position has been established as that in which the shoulder has an abduction and flexion of 0 degrees in both joints, maintaining an angle between the upper arm and forearm of 90 degrees. The assistance provided by the exoskeleton is total. We are working in the incorporation of torque sensors at the various joints to implement a control mechanism that should be able to detect the user intention to provide the required support accordingly.

In the simulations previously carried out in AnyBody^{TM} [14], it was verified that the external applied forces do not impose a kinematic pattern which could load the joints excessively.

Table 1 lists the maximum ranges of motion for each degree of freedom and the maximum nominal torque we can exert at each joint.

A button has been incorporated to show the instant at which the target position has been reached, followed by the next state. The VO2 Master Pro mask has also been used to measure the flow of oxygen inhaled and exhaled by the users during the study (VO2 Master Health Sensors Inc.).

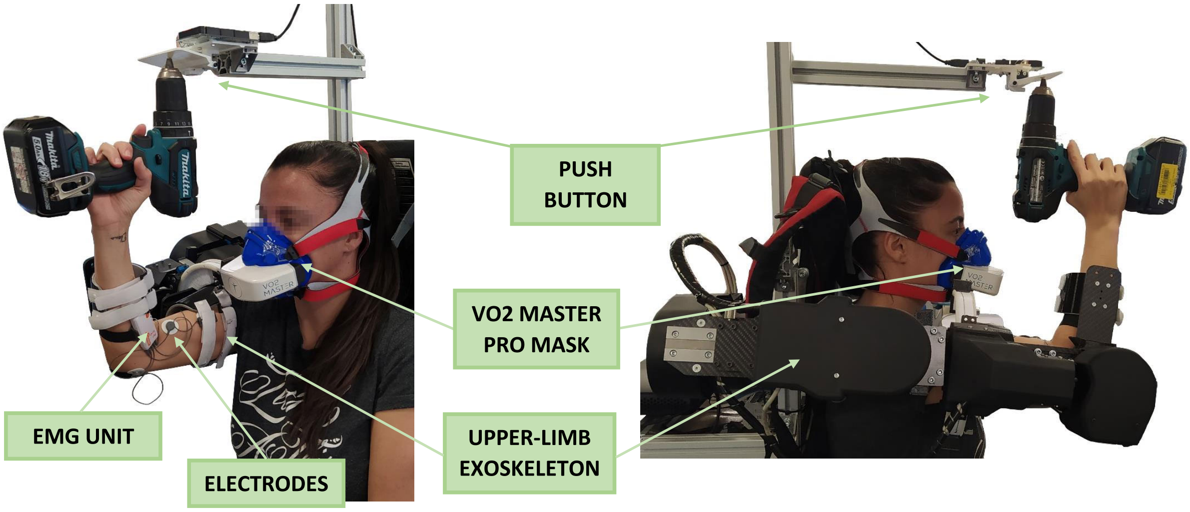


FIGURE 3. Experimental Setup with exoskeleton (WE condition). Some EMG electrodes placement and a Shimmer3 EMG unit to acquire EMG signals are shown. The subject wears a VO2 Master Pro mask to measure the flow of oxygen inhaled and exhaled during the task.

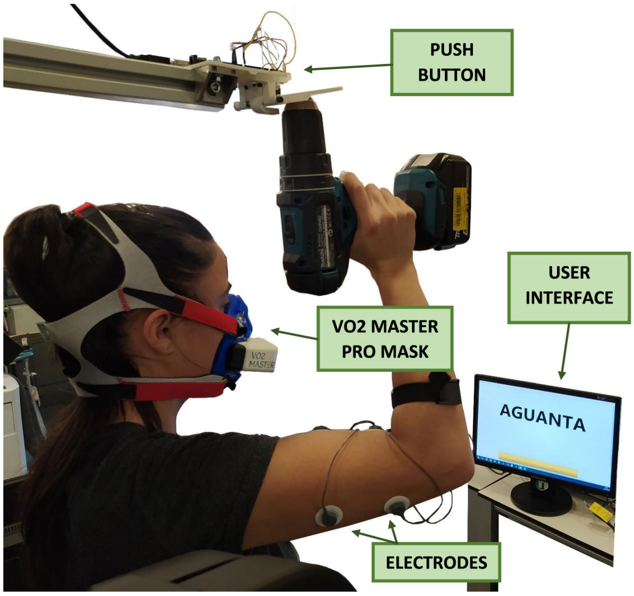


FIGURE 4. Experimental Setup without exoskeleton (NE condition). The push button to mark the instant at which the target position is reached can be seeing in the image.

In addition to these devices, two Shimmer3 EMG units have been used to measure muscle activity [20] (Shimmer Sensing), as previously performed in [14], as well as a Bio-Harness used to measure the ECG signals of the subjects [21].

D. STUDY PROTOCOL

The protocol followed for this study, which lasts a little more than 1 hour, from the time we explain to the subject what the experimentation consists of until the last recovery period is over and we remove all the devices is shown in Fig. 5.

First of all, we explain to the subjects what the experimentation consists of, and we show them the instructions they must follow through the interface displayed on the screen in order to perform the task properly. Then, as can be seen in Fig. 5, we place all the devices involved in the experiment and check that the communication between all the elements work fine.

As it was mentioned above, for each of the conditions (NE and WE), 20 repetitions of each trial are performed, first without weight (No Load), and then with a 1.7 kg drill (Load), making a total of 40 repetitions for each condition. Before starting each block of 20 repetitions, we performed a 3-minute baseline to have the subject's reference data at that moment. During the 3-minute baseline the user is at rest, trying to stay relaxed with the aim of measuring the relaxed state of the person to be used in normalization. At the end of the 20 trials, we gave a 5-minute recovery time before starting the baseline preceding the next block of repetitions. Once the subject has completed the first condition, he/she takes a 10-minute break, time that we take advantage of doffing the exoskeleton, depending on the condition he/she has previously performed. The whole process is then repeated for the second condition.

E. ACQUIRED DATA

1) ELECTROMYOGRAPHY

Muscular activity is closely related to the level of intensity of the performed task, and therefore its increase could have important repercussions on metabolic parameters. The greater the muscular activity, the greater the level of intensity, so that the user must make a greater effort to complete the task [22].

Signal capture by non-invasive electromyography (EMG) sensors has been used to analyze whether there is a reduction in the user's muscle activity during the execution of the task when it is performed with the assistance of the exoskeleton. For this purpose, Shimmer3 units have been used, locating the electrodes in the same muscle groups that were studied in [14], as they are the most involved in the movement to be performed by the users (biceps, triceps brachii, the pectoralis and the rhomboids).

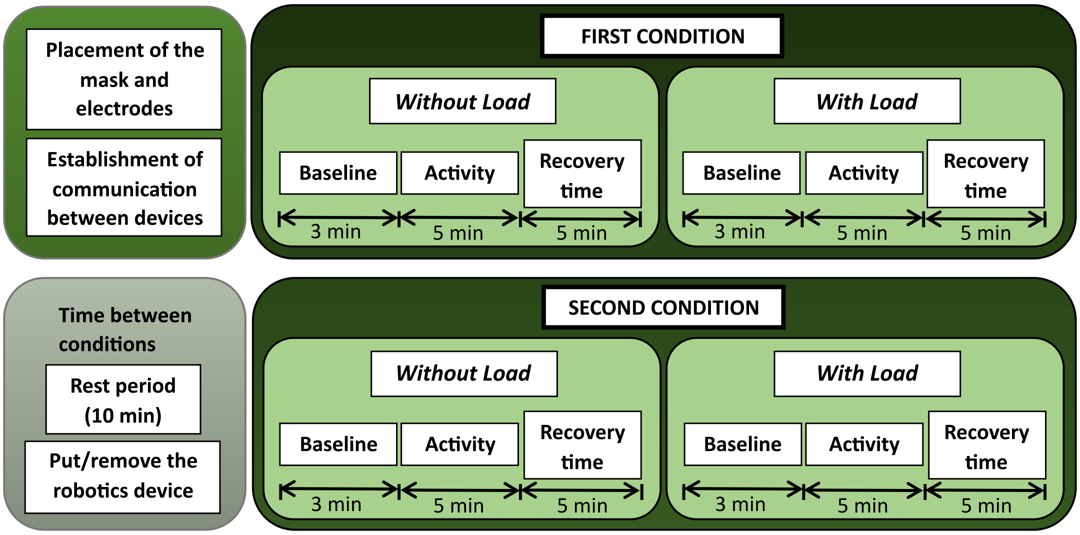


FIGURE 5. Study protocol. Both conditions are carried out consecutively, with a 10-minute break in between. NE and WE conditions are carried out randomly in order not to condition the experimentation.

EMG electrodes used in this study are circular adhesive pre-gelled Ag/AgCl electrodes with a diameter of 26 mm. The size of the electrodes is 7mm (standard SENIAM recommends a max. of 10mm) [23], [24]. For each muscle, the surface EMG electrodes were placed between the motor unit and the tendinous insertion of the muscle, along the longitudinal midline of the muscle. The longitudinal axis of the electrodes (which passes through both detecting surfaces) is parallel to the length of the muscle fibers. EMG references of the sensors were placed on an electrically neutral tissue. The reference of the sensor to measure the EMG activity of the biceps and triceps brachii was placed in the elbow, more specifically, in the Lateral epicondyle. And the reference of the sensor responsible for measuring the EMG activity of the pectoralis and the rhomboids was placed in the clavicle.

EMG signals were sampled at a sampling rate of 1 kHz. Measures has been processed following the SENIAM recommendations for surface EMG (band pass filter with cut-off frequency of 20 Hz and 500 Hz). Measures for each muscle in every subject have been normalized by the Maximum Voluntary Contraction (MVC).

2) CARDIORESPIRATORY RESPONSES

Heart rate (HR) and heart rate variability (HRV) are increasingly common measurements in sports environments to measure the intensity of the performed activity, as they are powerful biomarkers sensitive to physiological and psychological conditions [25]. Generally, a low HR value refers to a state of rest or moderate exercise, while higher values correspond to higher levels of exercise or exertion. On the other hand, higher HRV values (greater variability in the time interval between consecutive heartbeats) refer to lower intensity or stress values.

To measure the electrocardiogram (ECG) the Zephyr BioHarness^{TM} (Zephyr Technology Corporation) physiological monitoring telemetry device has been used. The BioHarness has a built-in signal-processing, so received signal is already clean. Only a 0.004Hz high pass filter has been applied to remove the DC component of the signal. HR has been extracted from the ECG signal, but also HRV has been study.

HRV is widely used to measure the mental workload and the stress level caused by some activity [26], [27]. Several studies use various HRV measures for detecting mental stress by using ultra short term HRV analysis [28]. For example, the Root mean square of successive RR interval differences (RMSSD) is considered a good measure of Autonomic Nervous System activity over the short-term [29], [30]. In addition, one of the most frequently reported factor associated with variation in HRV variables was low parasympathetic activity, which is characterized by a decrease in the High Frequency power (HF) [27]. Some studies indicate that HF are strongly correlated with RMSSD measurements [31].

In this study, HF has been computed in the last minute of each condition [31]. On the other hand, RMSSD has been obtained with the last 30 seconds of each condition [32].

In addition, data of oxygen consumption, respiratory frequency, tidal volume, and ventilation were obtained of each subject at the end of each of the conditions from the VO2 Master Pro mask. All of these measures are often used in indirect calorimetry to obtain an approximation of metabolic consumption in a non-invasive way [33]–[35].

The tidal volume is the volume of air that circulates between a normal inspiration and expiration without additional effort, that is, it is the volume of gas that is mobilized during one respiratory cycle.

On the other hand, the respiratory frequency is measured by counting the number of breaths per minute.

And finally, ventilation refers to the respiratory volume per minute, that is, it is the volume of gas inhaled or exhaled per minute, so it can be deduced from the tidal volume and the respiratory frequency.

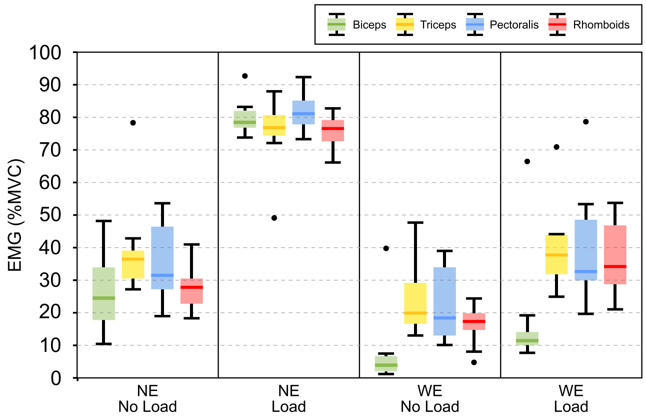


FIGURE 6. **Graphical representation of the results of the muscular activity. Boxplots comparison of the integral of the EMG signal of each muscle in every condition.**

F. STATISTICAL DATA ANALYSIS

In the statistical data analysis, a normality test was performed using the Shapiro-Wilk test. Results show evidence that parameters are not normally distributed. The Friedman test was employed to study differences between conditions. In the post-hoc analysis, pairwise comparisons has been studied by the Wilcoxon signed-rank test with the zero method proposed by Pratt [36], and the Holm-Bonferroni method was used to adjust for familywise error rate correction.

In the baseline recording periods, the values associated to the most relaxed state prior to the condition are taken. All physiological parameters (HR, HRV measures and measures of respiratory functions) have been normalized to the baseline value in every condition (Equation 1). This normalization method has already been used in other similar studies [37], [38]. In case of the EMG, measures have been normalized by the Maximum Voluntary Contraction (MVC). Statistical analysis was carried out with the normalized parameters.

$$x_{norm} = \frac{x - x_{baseline}}{x_{baseline}} \tag{1}$$

III. RESULTS

A. BIOMECHANICAL PARAMETERS

Fig. 6 shows the results of the muscle activity (EMG) for each of the muscle groups analyzed. EMG results show significant differences between conditions for all muscles (Friedman Test $p < 0.0001$).

Table 2 collects the results of the pairwise comparison. Paired comparisons show that all conditions are significantly different in all cases, except in the condition without either load or exoskeleton (NE-No Load) concerning to the condition using the exoskeleton with load (WE-Load) where we only observe a significant difference in the case of Rhomboids ($p = 0.024$).

In addition, all analyzed muscles (Biceps, Triceps, Pectoralis and Rhomboids) had a significant reduction in EMG activity in the two states (with/without load) wearing the exoskeleton compared to not wearing the exoskeleton. Specifically, reductions between wearing or not the exoskeleton with load (NE-Load vs WE-Load) were up to almost 64% for Biceps, 37% for Triceps, 38% for Pectoralis and 40% for Rhomboids.

TABLE 2. **Results of pairwise comparison between conditions for the EMG results of each muscle.**

Comparison		Biceps	Triceps	Pectoralis	Rhomboids
NE No Load	NE Load	0.003	0.008	0.003	0.003
NE No Load	WE No Load	0.004	0.042	0.054	0.005
NE No Load	WE Load	**0.054**	**0.83**	**0.7**	0.024
NE Load	WE Load	0.004	0.005	0.004	0.004
WE No Load	WE Load	0.004	0.008	0.004	0.004

Note. non-significant values are highlighted in **bold** ($p > 0.05$).

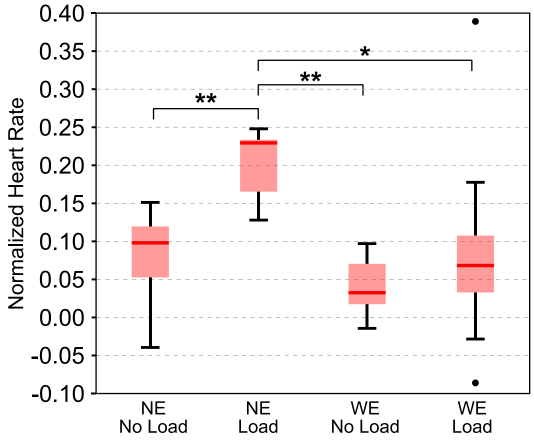


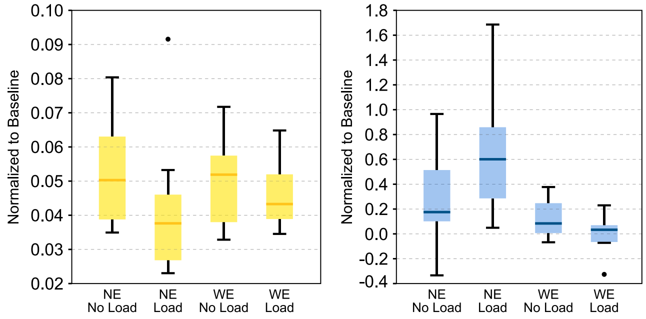
FIGURE 7. **Graphical representation of the results of heart rate (HR). Results have been normalized to the baseline value. Statistical differences are represented by * ($p <= 0.05$), ** ($p <= 0.01$) *** ($p <= 0.001$) and **** ($p <= 0.0001$).**

B. METABOLIC PARAMETERS

1) HEART RATE

The analysis shows significant differences between conditions in case of the HR (Friedman Test $p < 0.0001$) (Fig. 7). In the pairwise comparison, results indicate that without exoskeleton, the load causes a significant increase in HR (NE-No Load condition concerning NE-Load condition, $p = 0.003$) but when the exoskeleton is used, results suggest that there is no difference between the conditions with and without load (WE-No Load vs WE-Load, $p = 0.76$).

There is a significant heart rate reduction in the two states (with/without load) wearing the exoskeleton compared to not wearing the exoskeleton. In fact, the heart rate reductions between wearing or not wearing the exoskeleton with load (NE-Load vs WE-Load) were higher than 15%, and furthermore it can be observed that there is even a reduction in pulse of almost 2% when wearing the load with the exoskeleton to when performing the activity without the device and without load (NE-No Load vs WE-Load).



(a) (b)

FIGURE 8. Graphical representation of the results of heart rate variability (HRV). (a) Results of the Root Mean Square Successive Difference (RMSSD). (b) Results of the Power Spectra in High Frequency Range (HF). Results have been normalized to the baseline value.

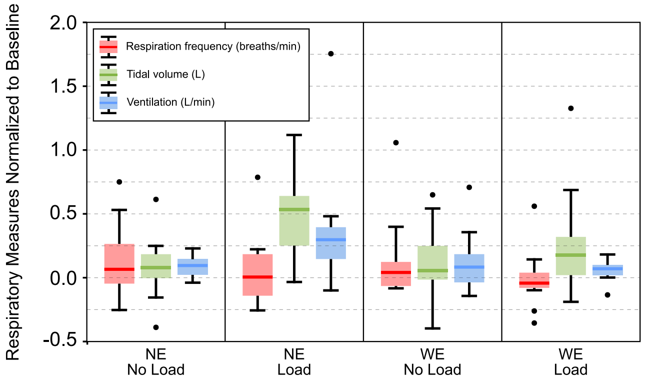


FIGURE 9. Graphical representation of the results of the ventilatory measures (respiratory frequency, tidal volume and ventilation). Results have been normalized to the baseline value.

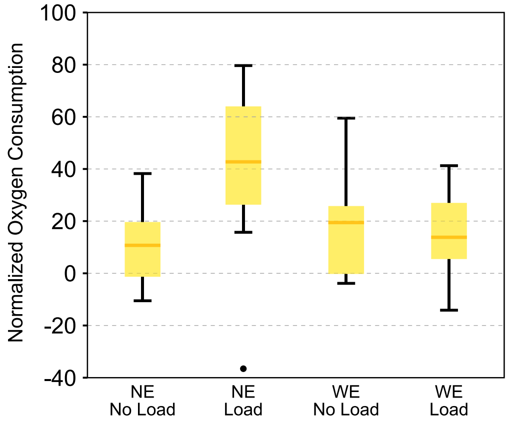


FIGURE 10. Graphical representation of the results of the oxygen consumption. Results have been normalized to the baseline value.

2) HEART RATE VARIABILITY

Regarding HRV measures results of the RMSSD show that differences between conditions are not statistically significant (Friedman Test $p = 0.068$) (see Fig. 8). However, the results suggest that the value obtained in the NE-Load condition is smaller, while the results obtained in the other conditions are very similar.

On the other hand, analysis of the HF shows significant differences between conditions (Friedman Test $p = 0.012$). However, in the pairwise comparison, results do not show significant differences between groups, but the results suggest that the measure obtained in condition with load but without exoskeleton (NE-Load) seems higher than using the exoskeleton with load.

3) RESPIRATORY RESPONSES

Fig. 9 shows a boxplot of the data concerning respiratory frequency, tidal volume, and ventilation. Analysis shows no significant differences between condition for respiratory frequency ($p = 0.7291$), or ventilation ($p = 0.1646$). However, although no significant difference is observed, tidal volume has a reliable trend toward significance ($p = 0.0576$).

4) OXYGEN CONSUMPTION

Fig. 10 shows a boxplot of the oxygen consumption data. Results show significant differences between conditions (Friedman Test $p = 0.004$).

In the pairwise comparison, in the conditions in which the exoskeleton is not used, the increment of the oxygen consumption introduced by the load narrowly eluded statistical significance (NE-No Load vs NE-Load, $p = 0.0557$). When wearing the exoskeleton, no differences were observed in the results between carrying the load or not ($p = 1.0$). In addition, although the results show a clear difference, in terms of oxygen consumption, we do not obtain a statistically significant reduction when wearing the exoskeleton with the load compared to not using it ($p = 0.17$). However, it should be noted that results of the oxygen consumption when wearing the exoskeleton with load (WE-Load) are similar to the result obtained in the condition without either load or exoskeleton (NE-No Load, $p = 1.0$). The reduction of oxygen consumption can be quantified at almost 25% between wearing or not the exoskeleton with load (NE-Load vs WE-Load).

IV. DISCUSSION

Analyzing the changes in muscle activity (EMG), in Fig. 6 it can be observed that the load significantly increases muscular activity in all muscle groups, as there is a significant difference between lifting the load without the exoskeleton (NE-Load) and the rest of conditions. Furthermore, it is worth noting the similar distribution of the data between the condition without either exoskeleton or load (NE-No load) and the condition with load and exoskeleton (WE-Load). Therefore, results suggest that the exoskeleton helps to reduce the muscular activity of the main muscles involved in the execution of the task, which translates into a reduction in the effort to perform the full exercise.

Quantifying the results, we can affirm that the proposed upper-limb exoskeleton reduces muscle activity by 36.76% in the muscle that has undergone the least changes during the study, the triceps, and the reduction increases to 63.5% in the case of the biceps (the muscle most assisted by the designed robotic system). These results are consistent with similar studies in the literature that reported a validation study to assess the functionality of a exoskeleton for the upper-limbs performing isometric and dynamic tasks. In *Tiseni et al. [39]*, the results show an average biceps brachii reduction of 45.5%, and *Kim et al. [40]* reported a muscular efforts reduction on biceps brachii by 23.4%.

Regarding heart rate (HR), Fig. 7 shows that the load tends to significantly increase the pulse when the drill is lifted and the task is carried out in free mode (NE-Load). However, this does not occur when subjects wear the exoskeleton. Furthermore, compared to the no exoskeleton load condition (NE-Load), a 17% reduction in heart rate is observed when performing the task with the exoskeleton without adding the load (WE-No Load), and more than 14% when moving the drill (WE-Load). Analyzing the rest of the conditions, it is observed that the distribution of data is very similar when the task is performed without load or exoskeleton and when it is performed with load and exoskeleton (NE-No Load vs WE-Load). As we observed in the EMG, these results also suggest that the proposed device offers support to the user, reducing the effort made by subjects to perform the activity.

These results are in line with works found in the literature presenting a similar study for the validation of an upper-limb exoskeleton by measuring cardiac responses. *Schmalz et al. [18]* reported two experimental tests of overhead work under laboratory conditions supported by the passive exoskeleton PAEXO, where the resuts show a 6% heart rate reduction between wearing or not the device. Other studies, [41], [42], reported a reduction of the pulse between 6% and 10%, depending on the level of assistance provided for the robotic system they pretend to evaluate.

On the other hand we have the HRV measures. RMSSD (Fig. 8a) does not show significant differences between conditions. However, there is an appreciable reduction when the task is performed without the exoskeleton and load (NE-Load). In case of the HF (Fig. 8b) analysis shows a reliable trend toward significance between NE-Load and the rest of conditions. In both HRV measures we observe a difference with respect to the others in the case of free mode with load (NE-Load). This is in line with the results we have previously observed, and therefore reinforces the hypothesis that the device helps to reduce the effort made by the subjects to perform the exercise.

Measures of respiratory function do not show significant differences between conditions (see Fig. 9). During exercise, as the activity progressed, users tended to hold their breath as they lift the load and keep it up. This could be explained by the anaerobic nature of the exercise (strength exercise). It therefore follows that this is the reason why a similar respiratory frequency was obtained for all conditions.

However, in the tidal volume a reliable trend toward significance is observed when subjects load the drill without the exoskeleton (NE-Load). This could indicate that, although the subjects hold their breath, they would take deeper breaths due to overexertion. The same is true for the ventilation data, where a slightly higher value can be observed when subjects load the drill without the exoskeleton (NE-Load) concerning the rest of the conditions. Although no significant difference is observed, the findings seem to indicate again subjects experience an increase the respiratory demand when the drill is raised without the exoskeleton (NE-Load).

A parameter directly related to respiratory function is oxygen consumption (Fig. 10). Results indicate that oxygen consumption increases when subjects have to lift the drill without using the exoskeleton (NE-Load), being this condition the condition that require a higher effort. Looking at the results shown in Fig. 10, we can affirm that the exoskeleton significantly reduces oxygen consumption when it is incorporated into the activity, since the results for both conditions (WE-No Load and WE-Load) are very similar to those obtained when the activity is carried out in free mode without weight (NE-No Load). In fact, when the exoskeleton is incorporated into the movement of the tool (WE-Load), we obtain a reduction in oxygen consumption of more than 24% compared to performing the task without the aid of the robotic device (NE-Load). These results are consistent with similar studies in the scientific literature, as in *Maurice et al. [41]* and *Schmalz et al. [18]*, where it is reported a reduction of oxygen consumption of 28% and 12%, respectively. As it was commented before, it's really hard to compare the results because of the differences in the experimental protocols and devices.

Oxygen consumption is directly related to metabolic consumption. The results suggest that the only condition that implies a higher metabolic consumption is the one in which the drill is lifted without using the exoskeleton (NE-Load). Therefore, the exoskeleton helps subjects to lift the load to perform the same task without making any effort so that not involve an increase in metabolic consumption.

Finally, it should be mentioned that all the results obtained in this study seem to indicate that the exoskeleton significantly reduces the effort required to perform the task, thus fulfilling the objective for which it has been designed.

V. CONCLUSION

The main objective of the study presented in this paper is to analyze whether the active upper-limb exoskeleton developed within the ExIF project reduces the metabolic parameters and the effort on the muscles of subjects when performing a given industrial task, requirements that must be met by exoskeleton-type robotic devices designed to be incorporated into the industry.

For this purpose, data have been collected regarding muscle activity (EMG), cardiac responses (HR and HRV) and respiratory activity (respiratory frequency, tidal volume, ventilation and oxygen consumption), as these are non-invasive measures and are a good way to approximate the intensity level of a task and the metabolic cost derived from performing it.

After analyzing the results obtained, it can be concluded that the proposed exoskeleton is an advantage in the performance of the analyzed task, since it reduces the muscular activity and heart rate of the users. This translates into a decrease in the level of intensity of the activity, which would imply a reduction in the possibility of suffering future musculoskeletal disorders if the system were to be incorporated into the industrial setting. In addition, the results show a decrease in the maximum oxygen consumption and in the volume of air required by the subjects to complete the activity when the task is performed with the assistance provided by the robotic exoskeleton. These reductions are directly related with the reduction of the worker's metabolic consumption in the workplace.

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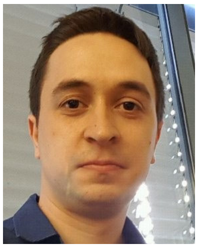

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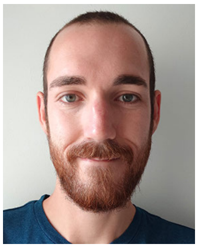

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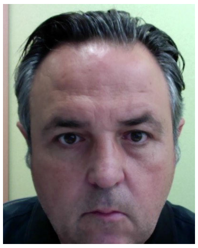

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