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Article

Assessment of a passive lumbar exoskeleton in material manual handling tasks under laboratory conditions

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Abstract: Manual material handling tasks in industry cause work-related musculoskeletal disorders. Exoskeletons are being introduced to reduce the risk of musculoskeletal injuries. This study investigated the effect of using a passive lumbar exoskeleton in terms of moderate ergonomic risk. Eight participants were monitored by electromyogram (EMG) and motion capture (MoCap) while performing tasks with and without the lumbar exoskeleton. The results showed a significant reduction in the root mean square (VRMS) for all muscles tracked: erector spinae (8%), semitendinosus (14%), gluteus (5%), and quadriceps (10.2%). The classic fatigue parameters showed a significant reduction in the case of the semitendinosus: 1.7% zero-crossing rate, 0.9% mean frequency, and 1.12% median frequency. In addition, the logarithm of the normalized Dimitrov's index showed reductions of 11.5, 8, and 14% in erector spinae, semitendinosus, and gluteus, respectively. The calculation of range of motion in the relevant joints demonstrated significant differences, but in almost all cases, the differences were smaller than 10. The findings of the study indicate that the passive exoskeleton reduces muscle activity and introduces a minor change of strategies for motion. Thus, EMG and MoCap appear to be appropriate measurements for designing an exoskeleton assessment procedure.

Keywords: exoskeleton; lumbar; EMG; motion-tracking; fatigue; manual material handling

1. Introduction

The health and comfort of industry workers are important issues, and making workstations safer is a priority. Musculoskeletal disorders (MSDs) continue to be the main cause of non-fatal injuries that require work leaves. Specifically, back injuries, including those of the spine and spinal cord, account for 39% of all injuries [1]. Reducing these numbers endorse the efforts to design more ergonomic workplaces. 39%

The desire to reduce such numbers encourages efforts to design more ergonomic workplaces. Many technological improvements have been implemented for industry workstations, such as those in warehouses, and the physical demand of certain tasks has been substantially reduced. Further, ergonomics specialists have contributed to reducing the incidence of workplace injuries and their consequences by implementing ergonomics criteria for workstations [2].

However, there are procedures that are still required to be done manually [3]. Many tasks in those kinds of workplaces require individuals to perform in poor working conditions to meet task demands, especially tasks that involve handling weights and pulling or pushing objects [4]. Repetitive back bending and twisting while handling weights can have a significant impact on postural stress [5]. Studies have reported that operators whose workplaces involve lifting, pulling, and pushing tasks are significantly more likely to suffer from lower back injuries compared to other kinds of workers without exposure to such handling tasks [6–9].

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In the last years, exoskeletons have emerged as support devices to help reduce the risk of MSDs at jobs where a better design of the workplace or automation of procedures is not possible. The different types of exoskeleton can be divided into active, which need power sources to work, and passive, which are based on a system of mechanisms and springs. Their design is focused on which body part they are intended to relieve while doing a particular kind of task. In this study, the exoskeletons of interest are those developed to protect the low back muscles in tasks that involve manual material handling [10,11].

There are many brands that are already commercializing this kind of support device, with designs that apply continuous torque to assist the lumbar joint, either by transferring part of the effort to the limbs [12,13], or by using an external power source [14,15].

The discussion regarding the objective effect of exoskeletons in terms of reducing the risk of MSDs is still on the table. Many researchers are conducting tests to quantify the benefits of devices worn on the body [16]. The most recent studies are attempting to quantify the differences in conditions with and without an exoskeleton while performing weight handling tasks. These studies include kinematics, joint moments, loads, and electromyography (EMG) [17,18]. Other studies are introducing measurements that may be related to metabolic cost, such as HR and oxygen consumption masks [19].

Kinematics is measured through motion capture in order to estimate the postural changes that the device might introduce that could have potential negative side effects, such as discomfort or a collateral risk of injury [17,20]. Joint moments and loads are measured in order to evaluate how joints effort varies under the two conditions.

EMG monitoring is the preferred measurement method in studies of exoskeleton assessment. In a recent study, a series of repetitive weight lifting tasks was designed and the activation of some of the muscles involved was measured [21]. In this study, the signals collected were differentiated by lifting or loading the weights; in the data analysis, they compared the values of mean activation when handling different weights. EMG measurement was used by other authors to estimate the changes in perceived weight when using the exoskeleton [22]. In other studies, researchers assessed their own designed exoskeleton, such as Lazzaroni *et al.* [23], who designed a control strategy to modulate the torque introduced by an exoskeleton, and Kim *et al.* [24], who designed an active back-support exoskeleton. Both studies assessed the effects of the devices by calculating the differences in amplitude of muscle activity. EMG gives information about muscle activity, and also about the process of muscle fatigue [25]. Studies have reported that muscle fatigue can be assessed by surface EMG, noting that electrophysiological fatigue, as assessed by EMG, precedes mechanical fatigue. Fatigue is reflected in the EMG signal as increased amplitude and a spectral shift to lower frequencies [26]. The EMG amplitude is increased due to the larger amount of cells recruited to maintain the force exerted. The displacement of spectral content toward low frequencies may be caused by an increase in the duration of the motor unit action potential and the consequent decrease in muscle fiber conduction velocity [27].

In this study, the objective was to gain a deeper understanding of the effects of a lumbar exoskeleton in a simulated pick-and-place workplace. In order to fulfil the main objective, a series of secondary objectives was proposed. First of all, to assess the exoskeleton in the appropriate physical demanding conditions, designing a series of tasks was fundamental. The criteria followed in the present work were based on the definition of ergonomic risk levels given by Waters *et al.* [28] [29]. These criteria use a group of factors, including weight, symmetry, distance, and frequency, of load handling to define a risk index, the composite index (CI), which is related to the probability of injury in the dorsolumbar area. With the designed tasks, posture and weight were controlled in both conditions, with and without exoskeleton, in order to gain a better understanding of the mechanical and physiological support that the exoskeleton provides to the worker. The secondary objective was to deeply investigate muscle activation in the two conditions. An analysis of muscular activation parameters, together with parameters associated with the fatigue process, was conducted. The parameters were obtained under controlled postures, and

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their evolution was calculated throughout the development of the tasks. This study adds to previous studies in the field, providing a deeper view of muscle behavior, on the one hand, by the extraction of parameters of time and frequency spectra that give information on the activity and the fatigue process, and, on the other hand, by the segmentation depending on the position of the weight handled. Lastly, to fulfil the main objective, motion was also captured. These data allowed not only estimations of the changes in positions and strategies of motion when wearing the exoskeleton, but also tracking of the body position over time with the objective of completing the EMG signal tagging and segmentation.

With the results of this study, it is possible to conclude that the evaluated lumbar exoskeleton has an effect on the user in terms of muscle activity and freedom of movement. Regarding muscle activity, the effect was beneficial in all cases and no damage was found. The benefits were seen in reduced muscle activity and the fatigue process. In the case of motion, constrictive changes were found, implying a relevant drawback. A second conclusion was that measuring and analyzing muscle activity and motion are appropriate in order to develop a protocol to assess the effect of exoskeletons.

2. Materials and Methods

The inclusion requirements were as follows: working age, 30 to 45 years old, IMC between 18.5 and 25.5, and in good physical shape; we also aimed to have a gender-balanced sample. The exclusion factors were the presence or history of musculoskeletal lesions or respiratory or cardiovascular pathologies. A total of 8 volunteers (4 women and 4 men) took part in the study. The participants came to the IBV facilities and provided written consent for the use and publication of their data for the purposes of this study. The average and standard deviation of the ages, weights, and heights of the participants were 35 ± 5 years, 67.9 ± 7.8 kg and, 175.6 ± 4.6 cm, respectively.

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A total of eight volunteers (four females and four males) took part in the study. The participants came to the IBV facilities and provided written consent to use and publish their data for the purposes of this study. The average and standard deviation of the ages, weights, and heights of the participants were 35 ± 5 years, 67.9 ± 7.8 kg and, 175.6 ± 4.6 cm, respectively.

2.1. Measurements protocol and setup design

The design tasks was carried out to emulate a common task in industry and warehouses, where the physical load for manual handling is usually very high, and to follow a series of ergonomics requirements. One of the main starting premises when designing the task was the level of risk. This is characterized by the composite index (CI) [28,29], which expresses risk associated with manual material handling with significant changes in handling conditions, and determines the probability of injury in the dorsolumbar region. For the purposes of this study, it should be moderate, which corresponds to a CI value between 1.0 and 1.6 for the general population [28]. To design tasks with such conditions, Ergo/IBV ergonomic risk assessment software was used [30,31]. This software calculates the CI of work stations by characterizing them using a list of factors. The basic design of the tasks, which were the starting point, consisted of a set of repetitions of multiple-load manual handling (with significant changes in some of the variables associated with weight handling). Using the Ergo/IBV, the tasks were planned to consist of three series of depalletizing pallets with 4 rows of 4 boxes of 7, 8, and 9 kg in each series (Figure 1). The series covered moderate CI values in a wide range, from close to 1 to very close to 1.6.

The variables introduced in the Ergo/IBV in order to achieve such CI values are as follows:

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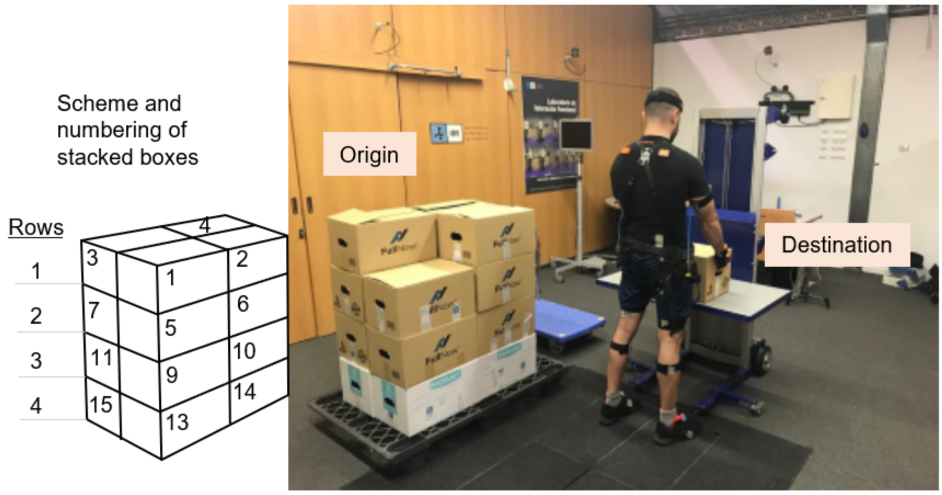

Figure 1. Right: Picture of test set up. Structure of the pallet of 16 boxes and participant fully instrumented with exoskeleton, EMG sensors and MoCap inertials. Origin: where boxes on pallet are picked up. Destination: table where user places boxes. Left: Illustration of setup scheme. Numbers represent the order boxes are picked up.

- Duration of the task: Short, less than 1 hour of manipulation, fulfilling the recovery period of 1.2 times the work period.
- Frequency: An average frequency of 10 boxes lifted per minute was established, which means a lift every 6 seconds.
- Horizontal location: Position at the destination remains constant (25 cm), whereas, position at the origin varies according to the configuration of the boxes in the pallet (30 to 62 cm).
- Vertical location: As in the case of horizontal position, position at the destination remained constant (75 cm) and at the origin varied (29 to 104 cm).
- Coupling: The grip is considered to be good. The user holds the box with both hands, the grip is comfortable, the boxes have handles, and there are no improper hand/wrist postures when handling the boxes.
- Angle of asymmetry: An asymmetry angle of 45° is set when the user takes the boxes from the pallet (origin) and there is no asymmetry when the boxes are placed on the table (destination).

The user takes the boxes from the pallet following a previously established pattern, to ensure that all users perform the task in the same way. The 16 boxes are numbered following the order illustrated in Figure 1 (left):

- First row (top), boxes 1-4.
- Second row, boxes 5-8.
- Third row, boxes 9-12.
- Fourth row (bottom), boxes 13-16.

Also, the technician indicates the rhythm (frequency of manipulation) to the subject by using a metronome.

2.2. Equipment

EMG data were measured using a Noraxon wireless electromyography system (Ultium™ EMG) with 4 channels monitoring the myoelectric activity of 4 muscles: erector spinae, gluteus medius, quadriceps femoris, and semitendinosus. The sampled frequency was 2000 Hz and was previewed and exported using the Noraxon myoMUSCLE™ software. The bipolar electrodes were located according to the SENIAM guidelines [32].

The Xsens™ MVN Analyze system in whole-body configuration was used for motion capture; 17 inertial sensors were distributed over the head, torso, arms, hands, legs, and

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Figure 2. Assessed lumbar Laevo^{TM} V2 exoskeleton.

feet. The angles for each coordinate were recorded at 100 Hz frequency using the Xsens own software.

The tested device was the commercial passive lumbar Laevo^{TM} V2 exoskeleton (Figure 2) [33]. Its objective is relief of back pressure, by helping the user while working in bending, forward, or lifting posture, supporting part of the user's body weight, reducing stress on the back, and improving the user's awareness of their posture. According to the manufacturer's instructions, the size of the exoskeleton was adapted to the anatomy of each participant, and they all were given help putting on the exoskeleton. The weight of the exoskeleton used in the tests is 2.8 kg.

The experiment was led by a technician, who was in charge of instrumenting the inertial sensors and guiding the volunteers in the task development, signal acquisition, and surveillance of the test. A clinical evaluator was also present to carry out EMG sensor placement.

2.3. Data analysis

2.3.1. Assessment of muscle activation and fatigue

Muscle activation and fatigue were analyzed by using EMG signals in four chosen muscles. After the EMG signals were acquired, pre-processing was carried out with a zero-phase bandpass Butterworth filter of order 10. The cut-off frequencies were 20 and 200 Hz to remove movement artefacts and limit the study bandwidth. Muscle activation and fatigue were assessed by calculating certain EMG signal parameters. The first step was to divide the signals to define 16 segments corresponding to the lifting task of each box. The Figure 3 shows 4 acquired signals during the last 4 movements of a complete exercise (subject 4, exercise with boxes 13-16, without exoskeleton). The marks at the beginning and end of each movement correspond to the fragment where the participant is lifting the box. Marks were located exactly for each case using the MoCap simultaneously recorded by visual inspection. However, these marks only indicate the beginning and end of each movement, not the beginning and end of the myoelectrical activation of the muscle that precedes the mechanical activation [34,35]. For this reason, marks were relocated one second before, as shown in Figure 3. Then, a posterior visual check with slight manual correction was carried out.

Six parameters were calculated for each of the 16 segments (movements):

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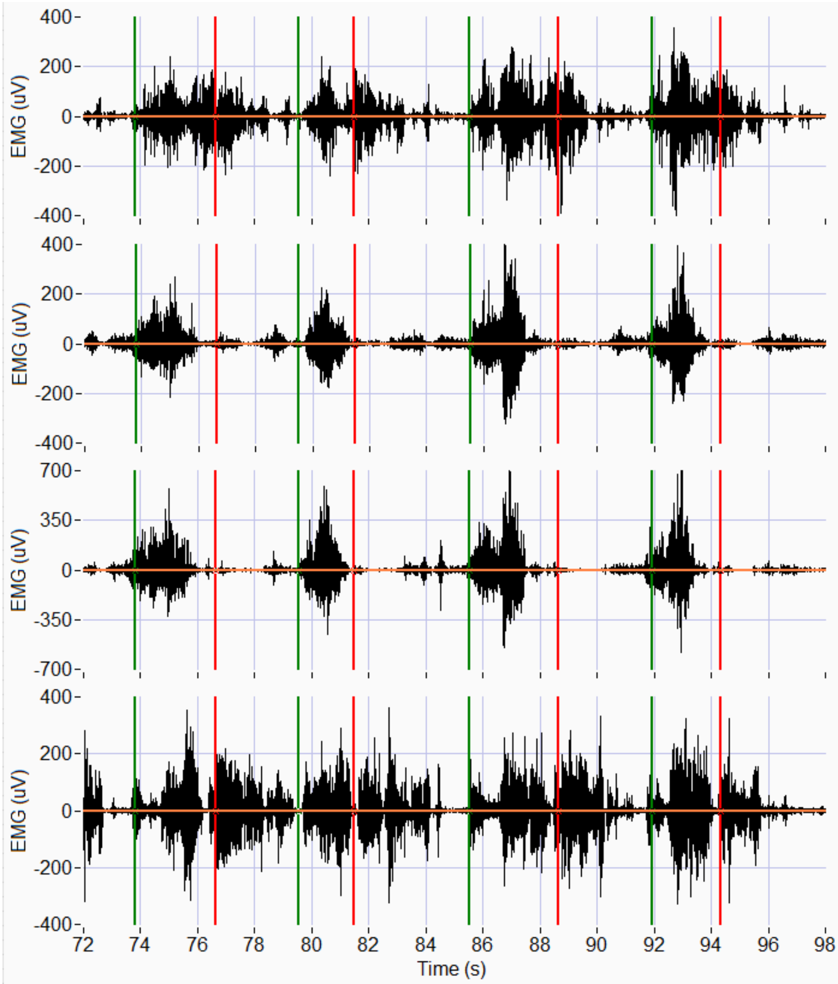

Figure 3. Surface EMG signals acquired simultaneously from four muscles. From top to bottom: erector spinae, gluteus medius, quadriceps femoris, semitendinosus. Time window corresponds to last 4 movements of exercise by subject 4 without exoskeleton. Vertical marks indicate beginning (green) and end (red) of myoelectrical activation, before visual check carried out to catch the boxes.

- Root mean square of the segment (VRMS) (μV).

$$VRMS = \sqrt{\frac{1}{N}\Sigma_{i=1}^{N}(x[i])^2}, \tag{1}$$

Where $x[i]$ from $i = 1$ to N is the signal segment being analyzed.

- Zero-crossing rate (TZC, %), relative to the total amount of data in the segment, which provides indirect information of the signal frequency.

$$TZC = \frac{\Sigma_{i=1}^{N}|sgn(x[i]) - sgn(x[i-1])|}{N} \cdot 100, \tag{2}$$

Where $sgn(x[i])$ from $i = 1$ to N is the sign of the signal being analyzed.
The following frequency parameters are obtained from spectrograms (0.5 seconds time steps). If $SP[j,k]$ is the spectrogram time frequency distribution, where j is the time index (from $j = 1$ to L, depending of the window length) and k is the frequency index (from $k = 1$ to M; $M = 2048$ corresponding to 1kHz). Then:

- Mean frequency (FMN, Hz), calculated as the average of the mean power frequency from the spectrogram (0.5 second time steps):

$$FMN = \frac{\Sigma_{j=1}^{L} FMN_j}{N}, \tag{3}$$

Where FMN_j is the mean power frequency calculated from each time step of the spectrogram ($SP_j[k] = SP[j,k]$), that is:

$$FMN_j = \frac{\Sigma_{k=1}^{M} k \cdot SP_j[k]}{\Sigma_{k=1}^{M} SP_j[k]} \cdot \frac{f_m}{M}, \tag{4}$$

- Median frequency (FMD, Hz) calculated as the average of the median power frequency from the spectrogram (0.5 second time steps):

$$FMD = \frac{\Sigma_{j=1}^{L} FMD_j}{N}, \tag{5}$$

Where FMD_j is the median power frequency calculated from each time step of the spectrogram ($SP_j[k] = SP[j,k]$), that is:

$$FMD_j = D \cdot \frac{f_m}{N} \xrightarrow{\text{which fulfills}} \sum_{k=1}^{D} SP_j[k] = \sum_{k=D}^{M} SP_j[k], \tag{6}$$

- Logarithm of the Dimitrov index ($log(FI_n)$) normalized by the minimum value of each exercise and participant, obtained from the spectral marginal of the spectrogram ($PSD[k]$):

$$PSD[k] = \sum_{j=1}^{L} SP[j,k], \tag{7}$$

The Dimitrov index [25,36] is calculated in the band frequency from 20 Hz ($k = 41$) to 200 Hz ($k = 410$):

$$FI = \frac{\Sigma_{k=41}^{410} k^{-1} \cdot PSD[k]}{\Sigma_{k=41}^{410} k^{5} \cdot PSD[k]} \cdot \left(\frac{f_m}{M}\right)^{-6} \tag{8}$$

The logarithm is calculated after normalization by the minimum value of each exercise and participant (FI_{min}):

$$log(FI_n) = log\left(\frac{FI}{FI_{min}}\right) \tag{9}$$

The objective of the statistical analysis was to find the relationship between the use of the exoskeleton and the calculated variables related to muscular effort and fatigue throughout each task. The factors defining each fragment of signal are the user, the monitored muscle, the position of the box-moving activity, and the weight of the box.
Taking these into account, the model was built as follows:

$$y(var, muscle) \sim exo * box + weight + (1|user) \tag{10}$$

where *exo* refers to the condition with or without exoskeleton, *box* to the position of the box from one to 16, *weight* to the box's weight of 7, 8, or 9kg, and *user* appears as the random effect. The model was performed for each variable (*var*): VRMS, TZC, FMN, FMD, and $log(FI_n)$ and each muscle: lumbar, gluteus, quadriceps, and semitendinosus. A post-hot analysis was carried out to evaluate the marginal averages and observe the differences between the conditions exo and no exo, and the same for the box position.
All calculations were done with R, using the pwr package[37] for the normality test, lme4 [38] for ANOVA, and phia [39] for the post hoc analysis.

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The results are shown in the next section; only the variables showing significant differences are included. The results are given as percentage of reduction with respect to the condition without the exoskeleton, as follows:

$$\%_{var} = \frac{Mean_{var,exo} - Mean_{var,noexo}}{Mean_{var,noexo}} \tag{11}$$

A negative value of this percentage for a certain parameter means a reduction with respect to the condition without exoskeleton, and a positive value means an increase.

2.3.2. Assessment of posture

TThe influence of the exoskeleton on posture was evaluated with the use of a motion capture (MoCap) system. The five percentiles (P_5, P_{25}, P_{50}, P_{75}, and P_{95}) of the trunk and hip were obtained from the MoCap.
The range of motion was calculated as the difference between extreme percentiles:

$$P_{RoM} = P_{95} - P_5 \tag{12}$$

A t-test was performed in R to find significant differences ($p - value < 0.05$) between the two conditions.

3. Results

3.1. EMG

3.1.1. Muscle Activation (VRMS)

Significant differences were found for this variable for all four muscles, and in all cases the difference meant reduced VRMS when wearing the exoskeleton (Table 1).
In the case of the erector spinae, the reduction was 8%. The VRMS graph shows a positive slope (Figure 4 a). This trend indicates that the muscular activity is increasing in a quite constant proportion throughout the exercise.
This trend indicates that muscular activity increased at a quite constant proportion throughout the exercise. Experimentally, in terms of average VRMS for all boxes, the quadriceps shows a decrease of 10.2% in the exoskeleton condition (Table 1). Figure 4 c shows there is a positive overall trend for both curves (exo and no exo). The values in both conditions overlap for some box handling, but are clearly higher with the exoskeleton for, e.g., box 14, located at the floor level; however, this effect is not observed in the rest of the boxes.
As shown in Table 1, the VRMS for gluteus shows a 5% reduction when wearing the exoskeleton. It can be observed in Figure 4 b that while the trend is positive, similar to the trend for the erector spinae, the biggest difference between the exoskeleton and no exoskeleton condition is found with the last boxes. These are the boxes located closest to the floor, thus demand the maximum effort for this muscle; also, the effective value, represented by VRMS, is higher.

Table 1. Percentage of variation in EMG variables caused by exoskeleton, showing values with significant differences, with p-values below 0.05. -: $p > 0.05$, *: $p \leq 0.05$,
**: $p \leq 0.01$, ***: $p \leq 0.001$, ****: $p \leq 0.0001$

Muscle	VRMS(%)		TZC(%)		FMN(%)		FMD(%)		log(FIn)(%)	
Erector Spinae	-8	****	-		-		-		-11.5	**
Semitendinosus	-14	****	1.7	***	0.9	*	1.12	*	-8	*
Gluteus	-5	**	-		-		-		-14	**
Quadriceps	-10.2	*	-		-		-		-	

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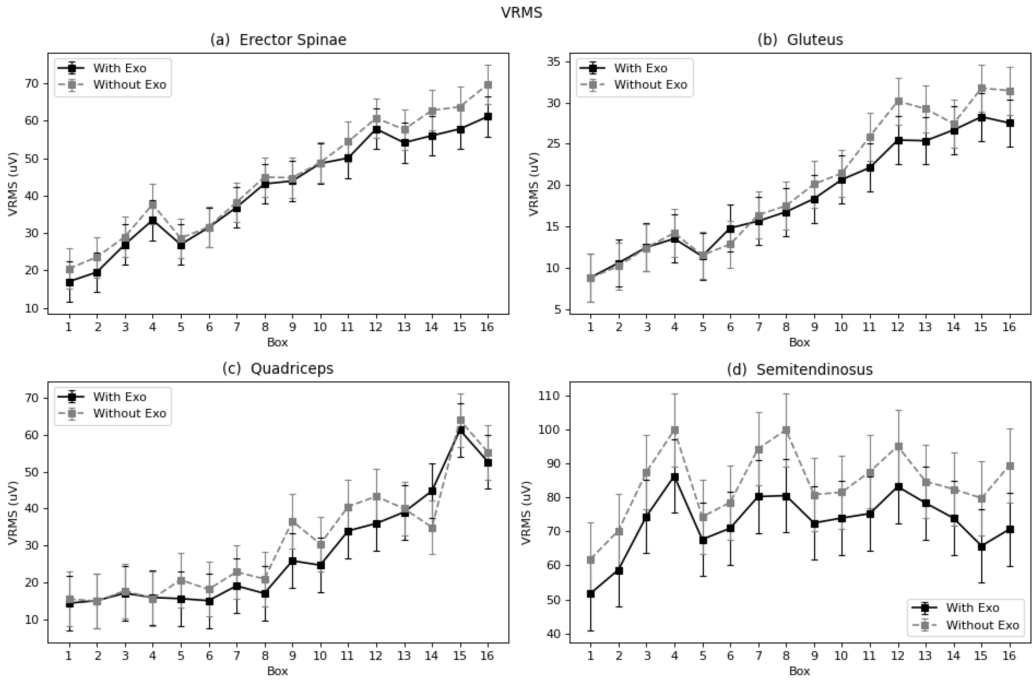

Figure 4. Marginal mean curves over the ergo-areas of VRMS parameter for all four muscles: (**a**) Erector Spinae, (**b**) Gluteus, (**c**) Quadriceps, and (**d**) Semitendinosus.

The 14% VRMS reduction for the semitendinosus muscle (Table 1) shows that this muscle received the most benefit from the exoskeleton. As shown in Figure 4 d, this release is approximately constant throughout the exercise, along with the VRMS trend during the series, which is not have positive, but flattened, with soft peaks for every fourth box of each row (4, 8, 12, and 16).

3.1.2. Lineal fatigue parameters: TZC, FMN, and FMD

An increase in the values of TZC, FMN, and FMD, showing a positive percentage, implies a decrease in fatigue with the exoskeleton. So, contrary to the VRMS results, a positive percentage, or an increase, means a reduction in fatigue. The only muscle showing a significant increase in TZC, FMN, and FMD is the semitendinosus, with 1.7, 0.9, and 1.12%, respectively. As described in the previous subsection, the semitendinosus was observed to have the most reduced muscle activity (VRMS). As the numbers show, this also indicates a decrease in fatigue (Table 1).

In the case of erector spinae and gluteus, the trend of the curves of each parameter and muscle follows a similar negative pattern in almost all cases (Figure 5, 6, and 7 (a) and (b)).This proves that these muscles suffered increased fatigue as the subject continued to carry the series of boxes. Nevertheless, no differences were observed in the process of fatigue between the two conditions (with and without exoskeleton), nor was a different trend observed. The semitendinosus, however, does show differences, as seen in the results in Table 1 and Figures 5, 6, and 7 d. In all three cases, the curves for the exoskeleton condition have a smaller slope, meaning a slowdown in the process of fatigue. In the case of the quadriceps, the muscle that is not assisted by the device, the curve is not constant; there is no clear trend (Figures 5, 6, and 7 c). The behavior and motions observed with the last four boxes showed decreased fatigue when wearing the exoskeleton.

3.1.3. Non-linear fatigue parameters: Log(FImin)

With regard to the normalized Dimitrov's index, for the muscles that potentially benefit from the exoskeleton (erector spinae, gluteus, and semitendinosus) significant differences

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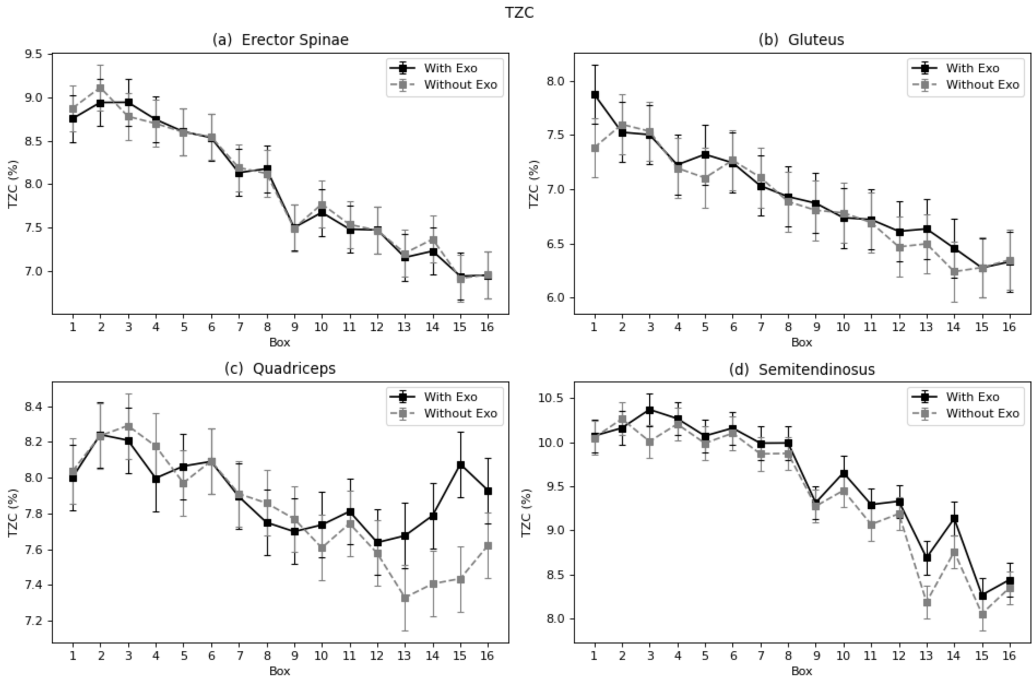

Figure 5. Marginal mean curves over the ergo-areas of TZC parameter for all four muscles: (**a**) Erector Spinae, (**b**) Gluteus, (**c**) Quadriceps, and (**d**) Semitendinosus.

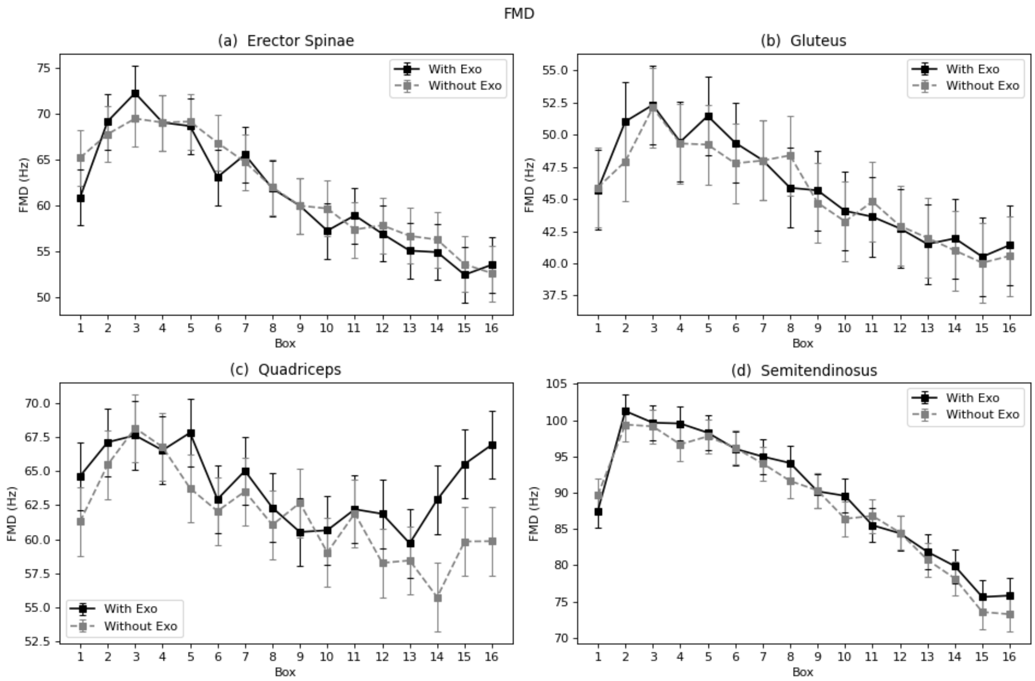

Figure 6. Marginal mean curves over the ergo-areas of FMD parameter for all four muscles: (**a**) Erector Spinae, (**b**) Gluteus, (**c**) Quadriceps, and (**d**) Semitendinosus.

were found (Table 1). These differences correspond to -11.5% for the erector spinae, -14% for the gluteus, and -8% for the semitendinosus. For this parameter, a decreased percentage implies a decrease in fatigue (unlike the previous parameters). These reductions imply that all three mentioned muscles show reduced fatigue with the use of the exoskeleton.

The trend observed is positive, meaning the muscles suffer increased fatigue as the subject continued carrying the series of boxes, which agrees with the rest of the fatigue parameters

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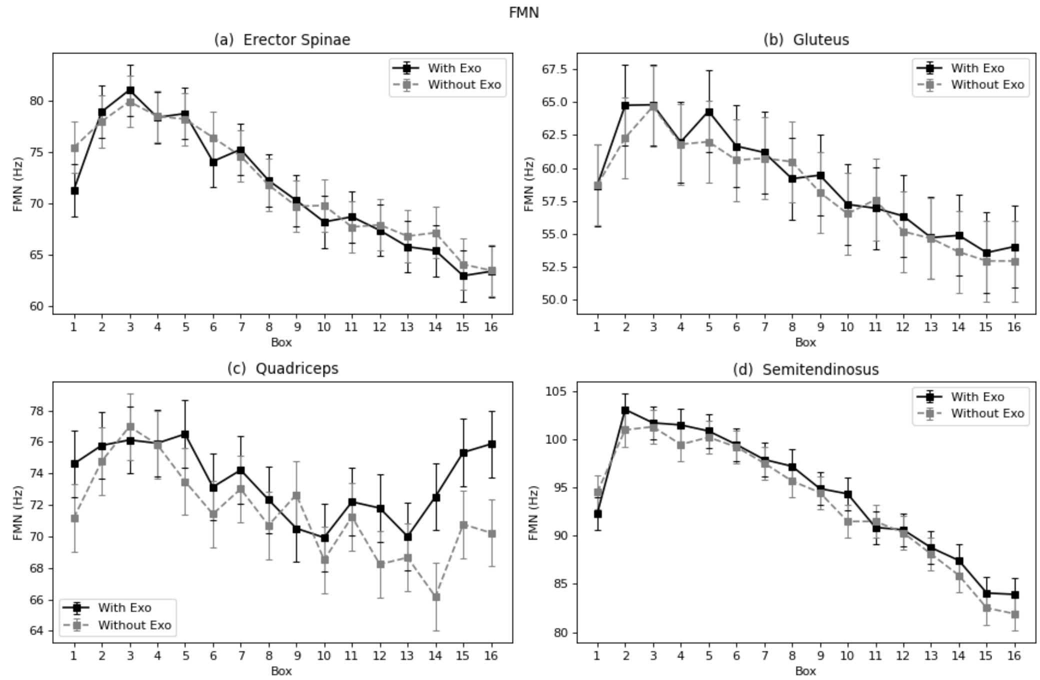

Figure 7. Marginal mean curves over the ergo-areas of FMN parameter for all four muscles: (**a**) Erector Spinae, (**b**) Gluteus, (**c**) Quadriceps, and (**d**) Semitendinosus.

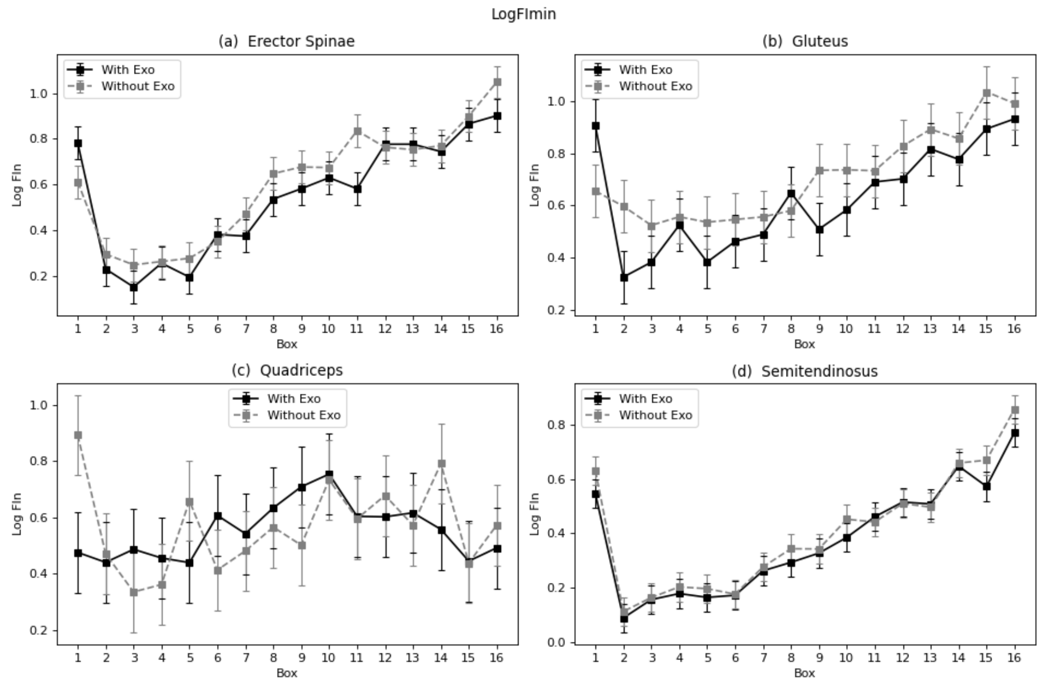

Figure 8. Marginal mean curves over the ergo-areas of Log(FImin) parameter for all four muscles: (**a**) Erector Spinae, (**b**) Gluteus, (**c**) Quadriceps, and (**d**) Semitendinosus.

(Figure 8 a, b, d).). In all cases, the curve related to the condition with the exoskeleton is above the curve for the condition without, implying a diminution in fatigue when wearing the assistance device. In the case of the quadriceps, the trend is irregular and the effect of the device on the fatigue process is uneven (Figure 8 (c)).

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3.2. Motion Capture

The results of the motion analysis in the present study demonstrate significant differences in some of the joint coordinate ranges and percentiles (Table 2). In almost all the cases, the differences were smaller than 10. In the case of the lower back range of motion, in extension and rotation, we could observe reductions of 3 (p-value = 0.001), and 39 (p-value = 0.01), respectively. No other differences in range of motion were found; the P_5 showed an 8% reduction in right hip rotation and a 5% reduction in right knee flexion.

Table 2. Percentage reduction in joint percentiles and range caused by the exoskeleton. The table shows the figures where the p-values are below 0.05.

Lumbar		Right Hip		Right Knee	
P_{RoM} Flexion - Extension	- 3%	P_5 Rotation	-8%	P_5 Flexion Extension	-5%
P_{RoM} Rotation	-39%				

4. Discussion

The lumbar muscles are, a priori, the main beneficiaries of the exoskeleton. The results show a decrease in muscle activity and a decrease in fatigue expressed in terms of Log(FImin). When comparing our results obtained with those of studies mentioned in the Introduction, agreement is found with the outcomes obtained by Antwi-Afari *et al.* [21] and Di Natali *et al.* [22], who also observed reduced lumbar muscle activity when monitoring people performing load-lifting tasks. These are examples of the many studies that measured the back muscles and observed reductions [23,24] when assessing their own or a third-party designed exoskeleton. In the designed task of the present study, muscular activity increased in a quite constant proportion throughout the exercise. The exoskeleton had a more evident effect in moments when the demand of muscle activity was higher. The quadriceps was chosen as the potentially prejudiced muscle, for compensating the reduced activity of lumbar muscles. It participates in flexion of the hip, and the exoskeleton is designed to discharge the erector spinae to charge it on this muscle. Like the rest of the muscles, on balance, this muscle also showed reduced activity, although with the smallest significance (*). Contrary to the other muscles, no significant change in terms of fatigue was observed. Hence, the hypothesis that there would be a negative effect on the quadriceps was not supported.Glinski *et al.* [40] assessed a lumbar exoskeleton with comparable performance to the Laevo, with leg pads located over the quadriceps area. In that study, they observed an increase in right quadriceps activation, and a decrease in left quadriceps activation. In the present work, the left leg was analyzed leg, because of the asymmetrical configuration of the task, which had a bigger demand on this side. In this case, the result agrees with the cited work when comparing left quadriceps outcomes, but no conclusions can be drawn for the right quadriceps. The gluteus and semitendinosus function by supporting the extension of the hip joint, and theoretically, by using the exoskeleton, which facilitates this motion, they should manifest relief. Both the gluteus and semitendinosus presented reduced activity with the exoskeleton. In terms of fatigue, both muscles showed a reduction as expressed by the Log(FImin), and the semitendinosus by TZC, FMD, and FMN. However, studies including the semitendinosus and gluteus focused on walk-assisted exoskeletons [41–43], and no comparisons were made. These were considered relevant in this study because passive systems (and in general systems that are not anchored to the ground) can only work by modifying the load conditions between different body segments. Since the lumbar exoskeleton basically covers the lumbar, sacral, and hip joints, it can modify the loading conditions between these segments, and thus modify the activation of muscle groups that control these joints. The gluteus and semitendinosus, together with the 359 quadriceps, are the most powerful muscle groups that are involved, although not solely, in the 360 control of the hip joint. The results of the gluteus and semitendinosus are consistent with the 361 theoretical expectation of

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exoskeleton performance. The results of motion analysis in the present study show reductions the movement of the back joints as a consequence of slight restriction imposed by the exoskeleton. While the differences were small, they reveal a minor change in strategy for the tasks as a result of using the device. This observation is in agreement with the review of Pesenti *et al.* [16].
This work analyzed the use of a passive lumbar exoskeleton in laboratory conditions. The experimental results show that the use of an exoskeleton led to a significant reduction in the effective value of muscular activity in all analyzed muscles. In addition, a decrease in fatigue was observed in the erector spinae, semitendinosus, and gluteus muscles, as indicated by a series of parameters. No differences were found in the fatigue process of quadriceps, the muscle considered to be potentially adversely affected. The curves plotted for each muscle throughout the exercise with the boxes clearly showed a tendency of increased effective value and fatigue as the exercise proceeded. Despite the risk of the exoskeleton constraining natural movement, in this study, only very small percentage reductions in range of motion were found in the lumbar joint, and minor modifications in the participants' mobility patterns were observed. Some other coordinates, such as in the right hip and knee, showed a reduction in the 5th percentile of range of movement. This may be associated with the change in motion strategy of participants when handling the weights while wearing the exoskeleton.

5. Conclusions

The results suggest that the use of a lumbar exoskeleton provides a benefit to the worker, taking into account the muscles that can potentially benefit, but also those for which are expected. Despite the observed advantages of an exoskeleton, there is still plenty of room for improvement. It must be borne in mind that the study scope was the objective evaluation of tasks with limited duration; for further evaluation of acceptance and long-term effects, a longitudinal study should be carried out as the next step. Companies must take into account that the use of this equipment may be a possible solution in cases where other technical or organizational measures are not feasible or effective for reducing the physical load in the workplace. An ergonomic evaluation and a redesign of the job considering the results of such evaluation should always be the first way to improve a job, considering other measures such as the use of exoskeletons when efforts are exhausted and the expected improvement has not been achieved.

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