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Back-Support Exoskeleton Control Strategy for Pulling Activities: Design and Preliminary Evaluation

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Abstract: The execution of manual material handling activities in the workplace exposes workers to large lumbar loads that increase the risk of musculoskeletal disorders and low back pain. In particular, the redesign of the workplace is making the execution of pulling activities more common, as an alternative to lifting and carrying tasks. The biomechanical analysis of the task revealed a substantial activation of the spinal muscles. This suggests that the user may benefit from the assistance of a back-support exoskeleton that reduces the spinal muscle activity and their contribution to lumbar compression. This work addresses this challenge by exploiting the versatility of an active back-support exoskeleton. A control strategy was specifically designed for assisting pulling that modulates the assistive torques using the forearm muscle activity. These torques are expected to adapt to the user's assistance needs and the pulled object mass, as forearm muscle activity is considered an indicator of grip strength. We devised laboratory experiments to assess the feasibility and effectiveness of the proposed strategy. We found that, for the majority of the subjects, back muscle activity reductions were associated with the exoskeleton use. Furthermore, subjective measurements reveal advantages in terms of perceived support, comfort, ease of use, and intuitiveness.

Keywords: low back pain; exoskeleton; back-support; manual material handling; pulling task

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1. Introduction

Pulling and pushing tasks are becoming more common in industrial settings with the redesign of the workspaces and the introduction of assistance equipment, such as carts or trucks that facilitate manual material handling (MMH) activities [1]. In many industrial sectors, almost half of all working processes currently involves pulling and pushing tasks on a regular and repetitive basis [2,3]. The aim is to replace lifting and carrying activities that are generally assumed to cause low back pain (LBP) and musculoskeletal disorders (MSDs) at the low back [4,5]. However, several epidemiological studies have identified strong evidence for the causal association between occupational pulling and pushing exposure and increased incidence of MSDs [6–8]. In particular, a review of epidemiological studies showed that between 9 and 18% of low back injuries were associated with pulling and pushing activities. [9,10].

Occupational back-support exoskeletons are a possible novel solution that can be introduced in the workplace to reduce the incidence of occupational LBP and the risk of developing MSDs, by limiting workers' lumbar load during the execution of MMH activities [11,12]. They provide to users assistive torques in the sagittal plane, approximately aligned with the lumbar joint. These torques generate an extension moment in the same direction as the extension moment generated by the erector spinae muscles. By reducing the activation of these muscles, a back-support exoskeleton can reduce the muscle contribution to lumbar compression, as documented by recent studies [13–16], and thus mitigate the risk of injury. In the literature, back-support exoskeletons have been introduced and employed mainly for assisting static forward bending and symmetric lifting and lowering tasks [11,12]. As a matter of fact, for the execution of other activities, which workers may perform in the same workplace, the use of a back-support exoskeleton has not been considered extensively.

This work presents a first attempt at providing assistance for a pulling task using a back-support exoskeleton to mitigate the risks associated with pulling activities performed in the workplace. To achieve this, an active exoskeleton was employed that allows the modulation of the assistive torques using actuators and irrespective of the user's posture. Passive exoskeletons, by contrast, cannot modulate the assistance or inject external power, as they use purely mechanical components (e.g., springs and dumpers). The assistance requirement is established at the design stage and depends on the physical characteristics of the elastic elements that just store and dissipate the energy extracted from the user's movements [12]. For back-support usage, the energy is stored when the user bends forward and then used to support the trunk extension during the lifting phase. As examples, the VT-Lowe's [17] prototype employs carbon fiber beams, while commercial devices as the Laevo V2 [18] and the BackX [19] use gas springs; soft devices, such as the Apex [20], are made with elastic bands. Carbon fiber beams, gas springs, and elastic bands flex to store energy during the lowering phase and return it to support the lifting phase. However, for activities other than lifting or static bending, different passive prototypes have been found to restrict or interfere with the user movement [18,21]. Conversely, due to the possibility of modulating the assistance, active exoskeletons are generally considered more versatile and can be exploited to assist the workers in different occupational tasks, including tasks executed in an upright posture. As an example, the XoTrunk active exoskeleton was proved to be suitable and potentially effective for assisting carrying [22]. Moreover, active exoskeletons can implement multiple strategies in the same device and interchangeably use them to assist with the current task a user is performing [23]. As a result, the versatility of active exoskeletons allows for providing assistance in a wider range of applications.

In the following, we first present the biomechanics of the pulling task, as analyzed by previous literature (Section 1.1), and then show the reasons why we expect that the assistance provided by a back-support exoskeleton can benefit a user performing pulling (Section 1.2). Section 2 reports the design of the control strategy implemented for assisting with the pulling task (Section 2.1) and the details of the experimental evaluation (Section 2.2), indicating the experimental design adopted and the metrics analyzed. The results are presented in Section 3 and discussed in Section 4. Finally, Section 5 concludes this work.

1.1. Biomechanics of Pulling

Comparing pulling with pushing activities, a higher mechanical load was found to be associated with the pulling task [24–28]. Two factors may explain these results. Firstly, the lever arm of the trunk flexor muscles (activated during pushing) is larger than the lever arm of the trunk extensor muscles (activated during pulling). Consequently, the compression force generated by flexor muscles on the lumbo-sacral disc (L5-S1) is smaller [9]. Secondly, the absolute torque at the L5-S1 joint is generally higher in pulling activities [24,27]. In pulling tasks, the reaction forces at the hands generate a flexion moment at L5-S1 that increases the lumbar load and needs to be counteracted by the back extensor muscles [28]. In contrast, during pushing, the reaction forces at the hands create an extension moment that can be partially counterbalanced by bending the torso (causing a flexion moment about L5-S1).

Analyzing pulling tasks, different studies have found that the lumbar compression exceeded the safety limit of 3400 N [26–30], established by NIOSH [31]. These excessive values were found for heavier pulled weights, as expected, and for lower handle heights (about waist level) [26–29]. Pulling at shoulder height seems to favorably affect the mechanical loading on the spine, probably because the trunk flexion is reduced [24]. The compression force is at its maximum at the beginning of pulling, while, during the continuous activity, the compression force is nearly constant, except for small step-induced changes [25,29]. Moreover, as expected, the maximum compression force increases with statistical significance if the execution speed increases [26]. As regards anterior/posterior shear forces, in some studies, the peak exceeded the safety limit of 500 N (suggested by McGill [32]) for pulling at waist and shoulder heights, increasing with the pulled object weight [25,27,28,30]. Overall, the lumbar moment and compression values found during pulling weights ranging between 20 and 60 kg are comparable with the values obtained when lifting a load weighing 10 kg [33,34].

Assessing the activation of different muscles during the execution of pulling, a high activation was observed for the erector spinae muscles [30,35–37] that increases with the weight [30] and the floor inclination [36]. In particular, the activity was above all previously determined recommended levels [35] and above the 5 and 8% maximum voluntary contraction (MVC), recommended by Sjogaard and Jonsson, and by Rohmert [38–40] respectively for exertions lasting over 1 h.

However, the results were not consistent between all the different studies. These discrepancies may arise because the researchers employed different experimental designs and imposed different restrictions (e.g., participant posture or cart characteristics) on how to execute the tasks. Moreover, the lumbar load varies substantially also between subjects due to individual technique and posture. Pulling a 60 Kg trolley on a 5-degree inclined surface results in peak compression forces that range between 2000 N and 5500 N for the different subjects of the same study [29]. Experience was also found to have a positive contribution in reducing compression forces, meaning that the technique does influence the individual lumbar load [30].

1.2. Rationale for Assisting Pulling

Back-support exoskeletons have been documented to be effective for assisting static forward bending and lifting and lowering tasks [11–13]. The compression forces on the L5-S1 disc are reduced because the exoskeleton assistive torques are able to partially relieve the erector spinae muscles. The extension moment generated by the exoskeleton torques, in fact, is in the same direction as the extension moment generated by the erector spinae muscles. As a consequence, occupational LBP and back-related MSDs incidence associated with the execution of these tasks is expected to decrease.

As regards pulling tasks, in the previous section, evidence was discussed that shows that the lower back is considered a high-risk area during pulling, due to the high mechanical load generated on the lumbar joint. Therefore, using a back-support exoskeleton to assist the pulling task may help to mitigate the risk associated with its execution. In particular, the level of activation observed for the erector spinae muscles suggests that they contribute significantly to generating excessive levels of lumbar load [2,41]. Consequently, the use of a back-support exoskeleton that is able to reduce the activity of the erector spinae muscles for static bending and lifting tasks may benefit the users also during the execution of pulling. However, it should be noted that, compared with lifting, pulling tasks do not necessarily involve substantial trunk bending. As a consequence, passive exoskeletons assistance, which is provided based on absolute or relative trunk inclination, cannot be adapted to assist pulling. Active exoskeletons, on the contrary, can modulate the assistance by means of specifically designed control strategies, regardless of the position of the wearer. With the proper assistance of an active exoskeleton, lumbar compression during pulling is expected to decrease.

The aim is to design a control strategy that can effectively assist users during the execution of pulling tasks, by providing them with assistive torques that reduce the activation of their spinal muscles.

2. Materials and Methods

We implemented the strategy on the XoTrunk device [42], displayed in Figure 1.

Figure 1. The XoTrunk exoskeleton prototype (see [42] for more details).

The XoTrunk is an active back-support exoskeleton with two electric actuators, aligned with the hip joint axes of flexion–extension that generate assistive torques in the sagittal plane to support hip and back extension. The control system is structured in three levels: the high level classifies the task the user is performing; the mid level modulates the assistance with control strategies specifically designed for different target tasks; the low level regulates the output torques of the two actuators. More details are available in [14,33].

2.1. Control Strategy

In order to design a proper control strategy to assist with pulling, we need to define when the activity starts and how the assistance has to be modulated. To address the first issue, the assistance is triggered once a button is pressed. The modulation of the torque throughout the duration of the task is achieved thanks to a Myo armband (Myo gesture control armband10, Thalmic Labs Inc., Kitchener, ON, Canada). This device has already been tried and tested in different experiments with the XoTrunk exoskeleton [14,33] to define the *hybrid* control strategy, which assists lifting tasks. The Myo armband integrates eight pairs of dry electrodes that record via surface electromyography (sEMG) the activity of the forearm muscles, which are active during a pulling task. The sEMG signals are preprocessed (filtered and rectified) on the Myo armband itself. Then, for control purposes, the exoskeleton on-board computer sums the eight signals to calculate the overall activity of the forearm muscles; this procedure is particularly convenient for actual use as it eliminates the need for precise electrode placement and calibration. The on-board computer further filters the overall signal with a low-pass filter with a cut-off frequency of 3 Hz. This processed signal is considered an indication of grip strength and therefore connected to the mass of the pulled object. Consequently, the *pulling strategy* modulates the torque according to this signal, normalized to a maximum value acquired before task execution:

$$\tau = K_{pull} \frac{EMG_{forearm}}{EMG^{MAX}_{forearm}} \tag{1}$$

where K_{pull} is the *pulling strategy* assistance gain (defined in Section 2.2.1). This torque, as stated before, is provided continuously to the user only when the assistance button is pressed.

2.2. Experimental Design and Metrics

An experimental protocol is defined to evaluate the effects of the exoskeleton *pulling strategy* on assisting the execution of the task. The experiment tests two hypotheses:

Hypothesis 1 (**H1**)**.** *The control strategy designed to assist with the pulling task reduces the mechanical load at the user's back, as assessed by muscle activity measurements.*

Hypothesis 2 (**H2**)**.** *The assistance provided by the exoskeleton for assisting the task is positively experienced by users, evaluated with subjective measurements.*

2.2.1. Experimental Design

Ten male healthy subjects (age: 29.8 ± 4.3 years, weight: 74.4 ± 7.7 kg, height: 177.8 ± 6.1 cm) with no history of LBP participate in the experiments, approved by the Ethics Committee of Liguria (protocol reference number: CER Liguria 001/2019). We devise an experimental set-up with a pull cable routed through a pulley and attached on one side to a box and on the other side to a bar, as displayed in Figure 2.

Figure 2. The experimental setup with the pull cable attached on one side to the box and on the other side to a bar, which is pulled by the subject. The figure displays pulling at waist level (**left**) and shoulder level (**right**) in the *exo* assistance mode.

Both the box weight and the pulley height from the ground can be adjusted. In particular, we test two payloads (10 and 20 kg) and two heights, namely the pulley is set at the same level of the waist and of the shoulder of the subject performing the task. The weight of 20 kg was chosen based on the recommended psychophysical studies of Snook and Ciriello [43]. The task, defined as double-handed pulling, consists of three repetitions of static pulling of the bar balancing the box weight. The duration of each repetition is of 5 s, followed by 5 s of rest. No instructions on the techniques for executing the pulling movement are given. The task is executed in two different conditions:

- without the exoskeleton: *no-exo*;
- with the exoskeleton controlled with the *pulling strategy* defined in Equation (1), which will be referred to as *exo*.

To allow comparison between subjects, we empirically select the values for the gain K_{pull}, as defined in Equation (1), instead of adjusting it to each subject's individual preference and body characteristics or task features (e.g., the weight of the pulled box). With $EMG_{forearm} / EMG_{forearm}^{MAX}$ ranging between 0 and 1, the value of the gain K_{pull} is set equal to 20, in order to have a maximum assistive torque of 40 Nm (i.e., 20 Nm from each actuator). The maximum value of 40 Nm was selected based on the authors' previous experience and the intended assistance objective. Previous studies have proved the effectiveness of this amount of assistance in reducing both the EMG activation and the weight experienced by the users during the execution of MMH tasks [14,22,44]. Moreover, an assistive torque equal to 40 Nm is in line with the goal of providing around one-third of the torque required to perform the target task (previous studies indicated L5-S1 moment values range between 50 and 180 Nm for double-handed pulling tasks [24,30]). The assistance is manually triggered by the experimenter using the button. Each subject performs eight double-handled pull tasks (i.e., each combination of the three independent variables: assistance mode, box weight, and height: $2 \times 2 \times 2$). The order of the assistance mode (*no-exo* and *exo*), box weight (10 and 20 kg), and height (waist and shoulder height) is randomized. Before data collection, participants are familiarized with the exoskeleton.

2.2.2. Metrics

The metrics analyzed to test the hypotheses and evaluate the control strategy are: the mean and peak activation of the spinal muscles (Hypothesis 1) and subjective measurements acquired via questionnaires (Hypothesis 2).

The EMG of spinal muscles (Iliocostalis Lumborum (IL) and Longissimus Lumborum (LL)) are recorded bilaterally (right and left) with pairs of sEMG electrodes (BTS FREEEMG, BTS Bioengineering, Italy), placed following SENIAM guidelines [45]. EMG data are bandpass filtered (10–400 Hz) with a zero-phase forward–backward 2nd order Butterworth digital IIR filter, filtered to remove the electrical noise at 50 Hz (forward-backward 2nd order Butterworth band-stop filter) and the electrocardiography (ECG) signal (high-pass filter to remove heart rate artifacts [46]). The signals, then, are rectified and low-pass filtered with a cut-off frequency of 2.5 Hz (forward 2nd order Butterworth digital IIR filter) to obtain the envelope [47]. To compare muscle activity levels between muscles, tasks, and individuals, EMG signals are normalized to the MVC [48], measured prior to task execution. To obtain the spinal muscle MVC, subjects perform a maximum exertion task, repeated three times [49,50]; the subjects lie in a prone position, with the torso hanging over the edge of a test bench, and are asked to extend the trunk upward against manual resistance applied by the experimenters.

From the normalized EMG signals, two metrics are extracted to estimate the mean and the peak activation of the back muscles: the root mean square (RMS) and the 90th percentile values. The RMS value of the EMG signal allows for evaluating the effect of the exoskeleton use in reducing the average muscle activation throughout the whole execution of a task and to assess the cumulative loads on the low back. The 90th percentile (chosen instead of the peak value because it is more robust to outliers [51]) captures the exoskeleton ability to reduce the maximum muscle activation and, thus, the peak low back loads. Evaluating these two metrics provides a complete insight into the changes in spinal muscles activation induced by the exoskeleton assistance. From the risk perspective, mean activation is associated with cumulative fatigue, which increases musculoskeletal injury probability [52], while peak activation is associated with traumatic damages in the vertebral discs, which can lead to spinal degeneration and pain [53].

The RMS and the 90th percentile muscle activities (i.e., the dependent variables) are statistically tested using three-way repeated measures ANOVA to study the effects of the multiple factors (i.e., the independent variables): assistance mode (*no-exo* and *exo*), pulling height (waist and shoulder), box weight (10 and 20 kg), and their interactions. To perform ANOVA analysis, the normality of the distributions of the dependent variables was tested with the Kolmogorov–Smirnov test (at the 5% significance level). Moreover, because of the large inter-subject variability we expect from the EMG signals, we decide to focus on the analysis of intra-subject variability [22]. The ratios ρ_i between the test and the control assistance modes (i.e., *exo* against *no-exo*) are calculated separately for each subject i and then compared with the results obtained for the other subjects. The vector ρ is the population of the ratios and is the vector collecting each ρ_i for subject $i = 1, 2, ..., N$. For the two EMG metrics and for the subject i, ρ_i is calculated as:

$$\rho_i = \frac{EMG_i^{exo}}{EMG_i^{no-exo}} \tag{2}$$

A value of $\rho_i < 1$ implies that, for subject i, the exoskeleton produces a $(1 - \rho_i)\%$ reduction of the analyzed metric with respect to the *no-exo* assistance mode. In contrast, $\rho_i > 1$ indicates an increase of $(\rho_i - 1)\%$ with respect to the *no-exo* assistance mode. The number of subjects for which $\rho_i < 1$ is indicated as γ^-, while the number of subjects for which $\rho_i > 1$ is γ^+.

Subjective measures are assessed with a user's impression questionnaire using a visual-analog scale (VAS), as it is considered to reduce the confounding effect of variation between subjects' interpretations of numerical rating scales [54]. After the execution of all the tasks in the *exo* assistance mode, the participant is asked to indicate the perceived physical and mental load. Questions q1–q4 concern the physical load, while questions q5 and q6 the mental load:

- (q1) The level of assistance is too high.
- (q2) I had to work against the assistance to accomplish my task.
- (q3) I feel the exoskeleton helps me to perform the task.
- (q4) I feel that the exoskeleton assistance is comfortable during the execution of the task.
- (q5) I find it easy and intuitive to operate the exoskeleton.
- (q6) I feel that my work performance is lower when using the exoskeleton (e.g., I work slower).

This questionnaire is presented on paper and the participants score each question placing a cross on the VAS scale, rating from "strongly disagree" to "strongly agree".

Furthermore, the NASA-TLX (Task Load Index) questionnaire [55] for assessing the work load is presented to participants after the end of each assistance mode, i.e., *no-exo* and *exo*. This questionnaire, which assesses the mental, physical, and temporal demands, performance, effort, and frustration associated with the execution of the task, also employs a non-numerical rating scale. A paired *t*-test is performed to test if the means of the two normally distributed variables (i.e., the two observations per subject) differ from one another because of the independent variable (i.e., the assistance mode: *no-exo* and *exo*).

3. Results

3.1. Muscle Activity

Three-way repeated measures ANOVA test reports no significant results for both the RMS and the 90th percentile back muscle activity. The reason for the lack of statistical significance is probably due to the large inter-subject variability of EMG signals (even after MVC normalization). As an example, 90th percentile muscle activity values for pulling the 20 kg box at shoulder level without the exoskeleton are 40% and 7% MVC for subjects 1 and 6, respectively.

Therefore, the following analysis focuses on intra-subject variability, by computing the ratio between *exo* and *no-exo* values of the selected metric for each subject (as defined in Equation (2)), and then comparing with the ratios obtained for the other subjects. The population distribution of the ratios ρ for RMS and 90th percentile spinal muscle activity are displayed in Figure 3, represented via boxplots. On each box (one box for each combination of pulling height and box weight), the central line is the median value, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points considered to be not outliers, and the outliers are plotted individually. Statistically significant differences between ratios ρ and distribution of ones were found only for some conditions (indicated with # in Figure 3). In Tables 1 and 2, the numbers of γ^- and γ^+ (i.e., number of subjects γ^- for which the exoskeleton use results in reduced muscle activity ($\rho_i < 1$) and number of subjects γ^+ for which the exoskeleton use results in increased muscle activity ($\rho_i > 1$)) are reported for the two metrics separately and for each combination of pulling height and box weight. Back muscle activity reductions associated with the exoskeleton use were found for the majority of the subjects, as observable in Figure 3 and Tables 1 and 2. Overall, using the exoskeleton leads to reductions of RMS and 90th percentile activity in the range of 25–38% and 21–37%, respectively (Figure 3). These reductions appear more limited for the task executed at shoulder height with the 20 kg box.

As regards the number of subjects for which the exoskeleton use results in reduced muscle activity, pulling the 10 kg box at both waist and shoulder heights with the *exo* assistance results in reductions of RMS back muscle activity for 9 subjects out of 10, and in reductions of 90th percentile muscle activity for 8 subjects. The exoskeleton use reduces RMS and 90th percentile muscle activity for eight and seven subjects, respectively, when executing the pulling task of the 20 kg box at waist height. As previously observed in Figure 3, also Tables 1 and 2 report for the pulling task executed at shoulder height with the 20 kg box the lower muscle activity reductions, which are obtained for 6 subjects out of 10.

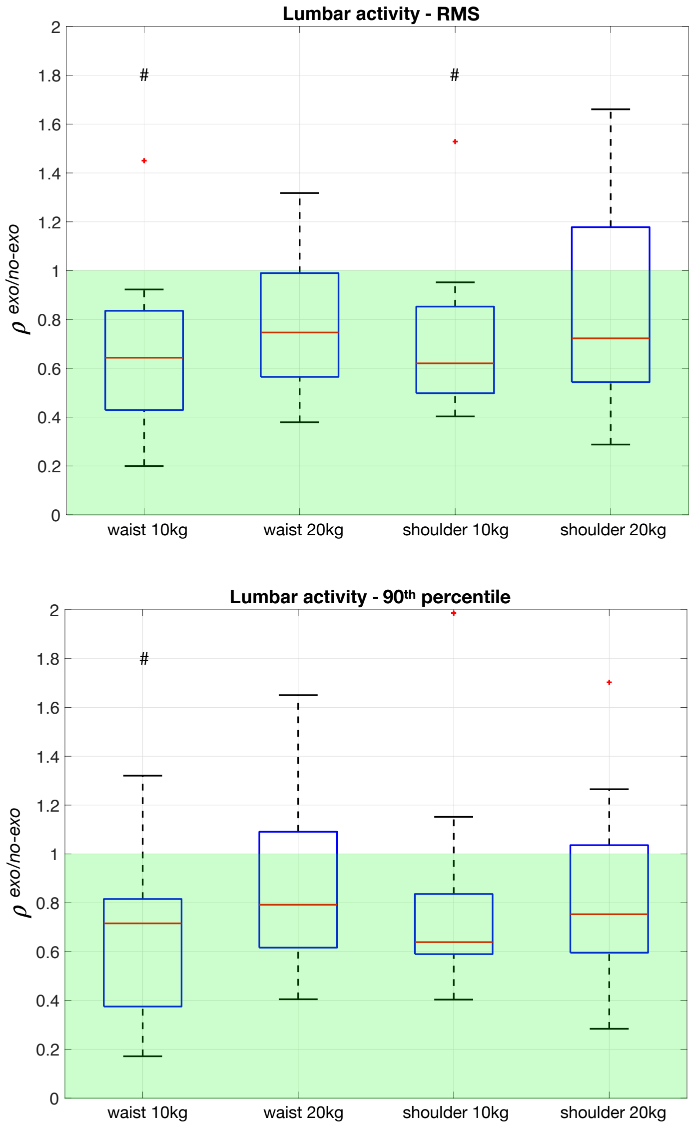

Figure 3. The population distribution of the ratios ρ for RMS and 90th percentile spinal muscle activity are represented via boxplots. On each boxplot (one box for each combination of pulling height and box weight), the central line is the median value, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points considered to be not outliers, and the outliers are plotted individually. The green areas indicate the regions where $\rho < 1$ (i.e., *exo* assistance results in a $(1 - \rho_i)\%$ reduction of the muscle activity with respect to the *no-exo* assistance mode). # indicates a statistically significant difference with a distribution of ones.

As regards the assistance provided by the exoskeleton, the maximum torque values averaged between participants (with standard deviation) are 24 ($\pm$7), 27 ($\pm$5), 24 ($\pm$6), and 26 ($\pm$5) Nm, respectively, for the four conditions, i.e., pulling at waist height 10 kg, waist height 20 kg, shoulder height 10 kg, and shoulder height 20 kg. In these four conditions, the mean torques averaged between participants are 16 (±5), 20 (±4), 16 (±4), and 19 (±4) Nm, respectively.

Table 1. Number of subjects γ^- for which the exoskeleton use results in a reduced RMS muscle activation ($\rho_i < 1$) and number of subjects γ^+ for which the exoskeleton use results in an increased mean muscle activation ($\rho_i > 1$), for each combination of pulling height (waist and shoulder) and box weight (10 and 20 kg).

	Waist 10 kg	**Waist 20 kg**	**Shoulder 10 kg**	**Shoulder 20 kg**
γ^-	9	8	9	6
γ^+	1	2	1	4

Table 2. Number of subjects γ^- for which the exoskeleton use results in a reduced 90th percentile muscle activation ($\rho_i < 1$) and number of subjects γ^+ for which the exoskeleton use results in an increased peak muscle activation ($\rho_i > 1$), for each combination of pulling height (waist and shoulder) and box weight (10 and 20 kg).

	Waist 10 kg	**Waist 20 kg**	**Shoulder 10 kg**	**Shoulder 20 kg**
γ^-	8	7	8	6
γ^+	2	3	2	4

3.2. Subjective Measurements

The results of the subjective measures are presented in Figures 4 and 5.

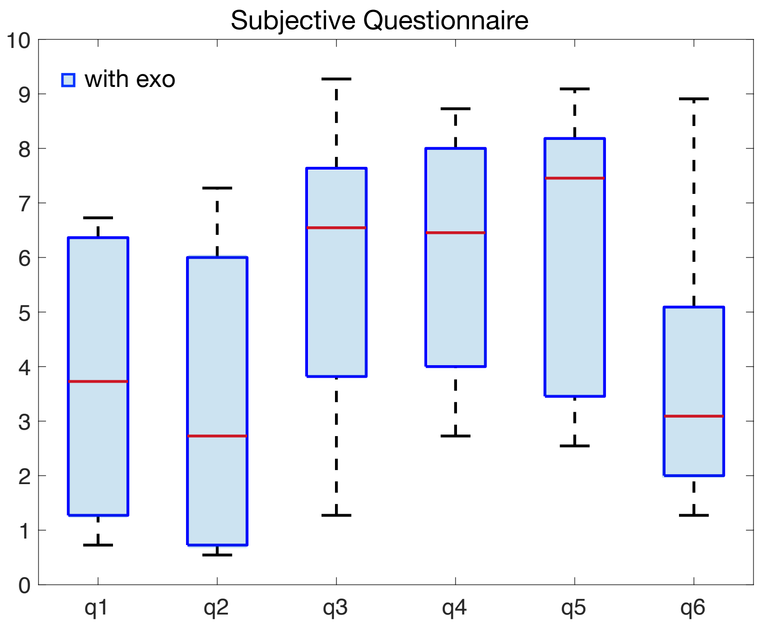

Figure 4. Boxplots of the user's impression questionnaire regarding the physical and mental load perceived by participants when executing the task in the *exo* assistance mode. The red lines represent the sample median, the distances between the tops and bottoms are the interquartile ranges. Whiskers show the min and max values. 0 = strongly disagree, 10 = strongly agree.

Subjective measures assessed with the user's impression questionnaire using the VAS scale are reported in Figure 4. The questions asked participants about their physical and mental load when using the exoskeleton. The results reported in Figure 4 are resized on a scale ranging from 0 (strongly disagree) to 10 (strongly agree). The assistance provided by the exoskeleton, addressed by q1–q4, is rated as not too high (q1) or opposed to their movement (q2) by most of the subjects. Moreover, using the exoskeleton is perceived by users as helpful for performing the task (q3) and comfortable in use (q4). Overall, participants found the use of the exoskeleton with the designed assistance to be easy and intuitive (q5). Finally, slight evidence of a slowdown (reduced working speed) associated with the exoskeleton use is observed (q6).

The results of the NASA-TLX questionnaire are reported in Figure 5. A paired *t*-test is performed to test if the means of the two normally distributed variables (i.e., the two observations per subject) differ from one another because of the independent variable (i.e., *no-exo* and *exo*). A statistical significance between the observations was not found. The results of the NASA-TLX test report normally distributed scores that appear to be quite similar between the *no-exo* and *exo* assistance (Figure 5). In particular, the mean of the physical demand decreases with the exoskeleton, although this difference is low and is not significant. On the contrary, the mental and temporal demands, as well as the performance, effort, and frustration do not appear to be affected by the exoskeleton use.

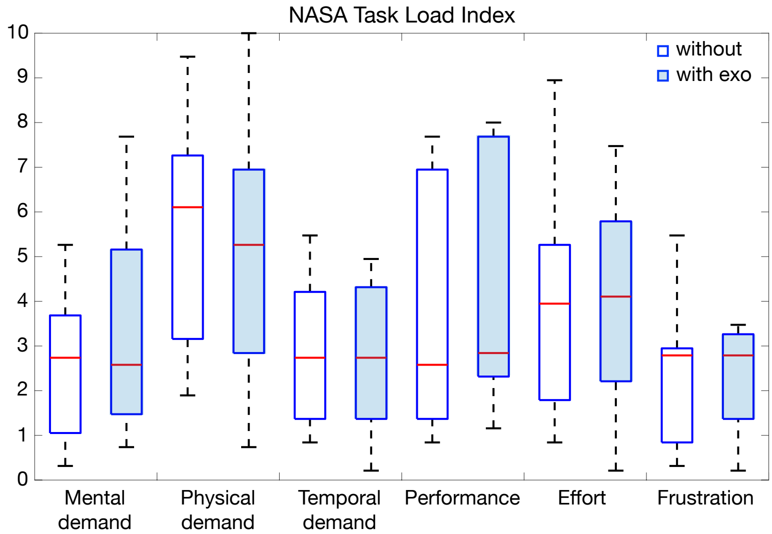

Figure 5. Boxplots of the work load assessed with the NASA-TLX questionnaire for the *no-exo* and *exo* assistance modes. The red lines represent the sample median, the distances between the tops and bottoms are the interquartile ranges. Whiskers show the min and max values. 0 = very low, 10 = very high. For the performance index, 0 = perfect, 10 = failure.

4. Discussion

A back-support exoskeleton control strategy designed to assist pulling aims at reducing the activity of erector spinae muscles to decrease their contribution to lumbar compression, as occurs when assisting static bending and lifting and lowering tasks. In this work, a *pulling strategy*, implemented on the XoTrunk exoskeleton, is evaluated focusing on the effects of the exoskeleton assistance on the users' back muscle activity. Furthermore, subjective measurements are collected, to include in the evaluation the users' perceived comfort and their impressions about the assistance. To the authors' knowledge, in fact, this work represents the first attempt at assessing the effects of assistance provided during pulling tasks while using a back-support exoskeleton. At this stage of the control design process, we believe that outcomes of the subjective assessment may be particularly helpful to guide the next steps.

4.1. Effects of the Assistance on Muscle Activity and Subjective Measurements

As regards muscle activity, the choice of analyzing the ratios between *exo* and *no-exo* values of the two metrics was made because of the large variability of the EMG signals between subjects, even after MVC normalization. Different sources may have contributed to introducing the large variability observed between subjects, as the task execution technique or participants' ability to generate the maximum muscle contraction during isometric exertion tasks (MVC acquisition). Analyzing RMS and 90th percentile ratios of the EMG means that the effects of the assistance are evaluated on each subject separately and then compared with the results of the other subjects. The overall outcomes result in reductions of the RMS and the 90th percentile muscle activity ranging between 21% and 38%. These reductions, however, vary between subjects, and for some participants are negative (i.e., $\rho > 1$ which means that for γ^+ subjects the use of the exoskeleton results in an increase of the back muscle activity).

Differences in the reductions are visible between the two different payloads, specifically greater reductions occur for tasks executed with the 10 kg box. In fact, for the lighter load, reductions of the median values ranging between 28% and 38% are associated with the exoskeleton use, while, for the heavier load, these reductions range between 21% and 28% (median values of the boxplots displayed in Figure 3). Likewise, the number of subjects γ^- for which the exoskeleton use has a beneficial effect on muscle activity ($\rho_i < 1$) is higher for the lighter load than for the heavier one (γ^- for both waist and shoulder height, as indicated in Tables 1 and 2). For the payloads, the weight of 20 kg was chosen based on the recommended psychophysical studies of Snook and Ciriello [43], while 10 kg was chosen to investigate below this limit [30]. As found in previous studies [30,35], increasing the load results in increased muscle activation. However, the statistical test of the RMS and the 90th percentile EMG did not find a significant effect of the weight, probably because of the large variability of muscle activity between subjects.

In this preliminary evaluation study, the second hypothesis tested is whether the assistance provided by the exoskeleton for assisting the task is positively experienced by users. To test this hypothesis, subjective measures are assessed with an ad-hoc user's impression questionnaire, which tests the physical and mental loads associated with the exoskeleton use, and the NASA-TLX questionnaire, which compares the work load with and without the exoskeleton. Overall, the use of the exoskeleton does not significantly modify the physical and mental workloads experienced by the participants. Indeed, to obtain statistically significant results of subjective measures, a larger number of participants is required. In this respect, this study was devised as a formative evaluation for judging the validity of the questionnaires proposed. As the distributions of the answers are normally distributed (Kolmogorov–Smirnov test), these questionnaires can be considered to be valid for this evaluation study and should be further investigated involving more participants. Future works will also involve the assessment of any negative side effect that the use of the exoskeleton may produce in this specific case (e.g., increased leg-muscle activity).

4.2. Practical Implications

The main advantage of the present work is that the designed assistance has beneficial effects on users performing a simplified double-handed pulling task in a laboratory setting. Indeed, as already said, the execution of pulling tasks is becoming increasingly common in the workplace, and it is associated with a high risk of developing MSDs and LBP, like other MMH tasks as lifting, static bending, or carrying [10].

Furthermore, the designed assistance was implemented on an active exoskeleton that has the possibility to implement and interchangeably use multiple control strategies. As a result, the same device can assist the different MMH tasks that workers may perform every day during their work shift. Previous studies have shown the beneficial effects of this exoskeleton on assisting lifting and lowering tasks [14,33], as well as carrying [22]. By adding this new control strategy (mid-level control) and taking advantage of the ability to recognize which MMH activity the user is performing (high-level control), the exoskeleton will be able to support the execution of complex tasks performed in the workplace. Indeed, as an example, load picking in a warehouse may require walking, lifting, carrying of boxes, and pulling or pushing of carts. For each of these activities, specific control strategies should be designed. The strategy proposed in this work for assisting pulling contributes to enhancing the versatility of active back-support exoskeletons as it can be implemented on similar (active) devices such as the commercial systems HAL [56], Cray X [57], and

H-WEX [58]. The Myo armband, needed for implementing the strategy, is an inexpensive and easy to use device that is particularly convenient for actual use in the workplace: it is powered by built-in batteries, uses wireless communication to send out data, is not invasive or uncomfortable to wear, and uses dry electrodes, which require no skin preparation nor pre-gelled disposable electrodes.

Finally, assisting the users while they are performing pulling tasks is required to mitigate the risk associated with its execution in the workplace. Indeed, compared to lifting, no guidelines have been rigorously and specifically defined to mitigate the biomechanical load (and thus the risk) for the execution of pulling. For lifting, the NIOSH lifting equation [59] is used to calculate a recommended weight limit (RWL), according to the task execution conditions (e.g., the horizontal and vertical location of the object relative to the body, the vertical distance, the frequency and the duration of the activity). The RWL is the maximum acceptable weight that nearly all healthy employees could lift over the course of an 8-hour shift without increasing the risk of developing MSDs at the back. The lifting equation is based on the limits of 3400 N for the compression force, and the computation of a RWL is possible because, for lifting, we have a straightforward relation between the weight and position of the lifted object and the associated compression force on the low back [3]. By contrast, in pulling exertions, this calculation cannot be used because it is impossible to assess the size and direction of the external forces even if the weight of the handled object is known [3]. As a result, the recommendations defined for pulling are based on psychophysically determined limits [43] that may not correspond to the biomechanical tolerance of the lumbar spine. In fact, prior literature has shown little association between spinal loads and psychophysically determined maximum acceptable forces [28,60,61]. Recently, new recommended limits have been suggested by Weston [28], based on the low back loads, which are more conservative than the prior psychophysical limits established by Snook and Ciriello [43]. However, these limits also consider measures that are generally not acquired in the workplace (i.e., hand forces) and are difficult to translate into practical safe task conditions (e.g., weight limits, subject's posture during the pulling exertion). Considering this, the possibility to assist workers during the execution of pulling tasks with an exoskeleton that can reduce the related lumbar load is central, even if a higher risk is still associated with the execution of lifting activities [10]. As stated before, in real scenarios, it is more difficult to mitigate the biomechanical risk correlated to pulling compared with lifting, for which strict guidelines and restrictions have been introduced in the workplaces.

4.3. Limitations

Considering its implementation, the main limitation of the *pulling strategy* is that the assistance should be manually triggered by an external button. In this preliminary evaluation, we decide to give to the experimenter the responsibility to trigger the assistance. However, for real scenario applications, users should have direct access to the trigger command. Therefore, the button should be easily accessible to the user; as an example, it could be embedded into the tool the user uses for pulling or into ad-hoc gloves. Otherwise, a more efficient way to trigger the assistance could be obtained by implementing into the high-level control of the exoskeleton the ability to recognize when the user is executing a pulling task.

Moreover, for this preliminary evaluation, we kept fixed the value of the gain K_{pull} for all the subjects. However, personalized and thus more effective assistance may be obtained with subject-specific gains. In particular, the gain can be selected to adjust the assistance to subjects' individual preferences (e.g., comfort and perceived pressure), body characteristics, and task conditions (e.g., the weight of the pulled object). Additional assistance may also be required to support users because of the adopted posture. For instance, the trunk motion during the execution of pulling tasks while wearing the exoskeleton can be further characterized to modulate the assistance accordingly [62].

A further limitation is the magnitude of the torque provided by the exoskeleton controlled with the *pulling strategy*, as defined in Equation (1). In particular, the modulation of the torque is obtained based on the activation of the user's forearm muscles, which is considered to be an indication of grip strength. As a consequence, an increase in the torque commanded by the control strategy is expected according to an increase in the pulled weight. However, the increase of the assistive torque with the weight is limited (maximum torque from 24 ($\pm$7) to 27 ($\pm$5) Nm, and from 24 ($\pm$6) to 26 ($\pm$5) Nm, respectively, for waist height 10 kg and 20 kg, and shoulder height 10 kg and 20 kg). Moreover, the maximum torques provided to the participants were in all cases below the maximum possible torque (40 Nm) that the exoskeleton can provide. Increasing the torque provided might be particularly useful for the 20 kg pulls.

5. Conclusions

It emerges from the biomechanical analysis that the execution of pulling activities exposes workers to large lumbar loads that increase the risk of LBP and back-related MSDs. This work represents a first attempt at assisting pulling tasks with a versatile back-support exoskeleton: an active device, originally designed for assisting lifting and lowering tasks that, thanks to its electrical actuators, can design control strategies for each different task. Therefore, we introduced a new control strategy that modulates the assistive torques according to the users' forearm muscle activity, which is considered to be an indication of grip strength; this assistance is triggered once a button is pressed.

The control strategy was experimentally evaluated in a laboratory environment. Ten healthy male subjects performed a total of eight double-handled pull tasks, for each combination of box weights (10 and 20 kg) and heights (waist and shoulder), and in two conditions: one without the exoskeleton and one with the exoskeleton controlled with the *pulling strategy*. We measured the activity of the spinal muscles and, after task execution, the user's subjective impression and perceived effort were assessed through questionnaires.

Reductions of the muscle activity associated with the exoskeleton use range between 21% and 38% with respect to *no-exo* condition. Moreover, while for some participants the exoskeleton use results in an increased muscle activation, the number of subjects for which the exoskeleton has a beneficial effect is much higher in all the conditions. In particular, the assistance appears more effective for the tasks executed with the lighter load, probably because the assistive torques were less helpful for the heavier mass. Overall, objective measurements, in terms of users' back muscle activity reductions, prove the promising benefit of the designed assistance and indicate where improvements are needed for future works. Subjective measurements, assessed with questionnaires, show that the assistance was positively experienced by users, with advantages in terms of support for performing the task, comfort, ease of use, and intuitiveness.

The main contribution of the present work is that it enhances active back-support exoskeletons versatility to the new area of object pushing/pulling. This can be achieved thanks to the ability to modulate the assistance by means of control strategies. This work provides a first attempt at assisting pulling tasks that has an important impact in the workplace in terms of the number of pulling activities workers perform every day and related risk of injury.

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