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**Abstract**

This study aimed at determining the effect of a passive exoskeleton on local perceived discom- fort, perceived effort and low back muscles' activity. Thirteen volunteers performed two simulated working tasks with and without the exoskeleton. In the static task, the exoskeleton decreased the lumbar perceived discomfort, the perceived effort and the level of low back muscles' activity (~10%) while increasing discomfort in the chest and feet. The percent decrease in EMG amplitude was correlated with the percent increase in perceived effort with exoskeleton. For the dynamic task, the exoskeleton increased the discomfort in the chest and decreased the level of back muscle activity (~5%). Current findings suggest exoskeleton is effective in reducing the back load while increasing the perceived discomfort at non-targeted body regions in both working tasks. The concurrent increase of discomfort in non-targeted areas probably led to a higher perceived effort despite the reduction of low back muscle activity.

**Practitioner summary:** This study provided insights into exoskeleton effects on local discom- fort, perceived effort and muscle activity. Overall, the potential benefits of passive exoskeleton should be considered alongside its adverse effects on the non-targeted body regions that can lead to an increase of perceived effort despite the reduction of back muscle activity.

**Abbreviations: EMG:** surface electromyogram; ISO/TR: international organization for standardization/technical report; RMS: root mean square; SD: standard deviation; WMSDs: work-related musculoskeletal disorders

## 1. Introduction

Work-related musculoskeletal disorders (WMSDs) are a significant safety problem within the European Union, affecting about 40 million European workers and becoming the most common work-related injury in the European Union (de Kok et al. 2019; Roquelaure 2018). WMSDs can be caused by common work demands, such as repetitive and sustained tasks, incongruous postures, localised muscular loadings, and fatigue (Anagha and Xavier 2020; Bao, Howard, and Lin 2020; Buckle and Jason Devereux 2002; Griffith et al. 2012; Wickström and Pentti 1998). Epidemiological studies have shown that workers usually report excessive discomfort and pain in the low back region during occupational activities (Elders, Heinrich, and Burdorf 2003; Rizzello, Ntani, and Coggon 2019; Wickström and Pentti 1998). Given the prevalence of WMSDs, preventive approaches to reduce the workload have been a crucial issue in ergonomics.

Several preventive measures have been investigated and implemented over the years through the optimisation of processes, tools, and work environments according to the classic ergonomics principles (McCauley 2012; Pheasant and Haslegrave 2006). In the industrial context, the advent of the new Industry 4.0 paradigm has led to the development and promotion of innovative solutions, such as exoskeletons (Ranavolo et al. 2018). Briefly, these wearable and external mechanical structures are generally classified

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depending on: (a) the part of the body they aim to support (upper limbs, trunk, lower limbs or whole-body); (b) the actuation mechanism, which divides exoskeleton into active, when the actuator requires an external power source, and passive, when no external power source is required (Bogue 2018; de Looze et al. 2016; Lee et al. 2012; Wang et al. 2017). Several researchers have evaluated the effects of passive exoskeletons on body regions where workers commonly report discomfort and pain (e.g. in the low back area) through the application of objective and subjective measures (de Looze, Krause, and O'Sullivan 2017; Voilqué et al. 2019).

Effective biomechanical assistance using passive exoskeleton for back support has been commonly observed from the assessment of muscle activity with classical bipolar surface electromyography. Briefly, this technique provides information about the level or the timing of muscle activity by positioning a pair of closely spaced surface electrodes over a small portion of muscle (Cavalcanti Garcia and Vieira 2011). In general, prior studies using bipolar detection systems have observed that passive trunk exoskeletons lead to a reduction ranging from 13% to 57% of the level of erector spinae muscles' activity during sustained tasks (Abdoli-Eramaki, Agnew, and Stevenson 2006; Alemi et al. 2019; Baltrusch et al. 2019; Barret and Fathallah 2001; Bosch et al. 2016; Graham, Agnew, and Stevenson 2009; Koopman et al. 2019; Lotz et al. 2009; Ulrey and Fathallah 2013; Whitfield et al. 2014). However, the reduction of low back muscles' activity using passive exoskeletons (e.g. the Laevo one) reported in literature is highly variable (Baltrusch et al. 2019; Bosch et al. 2016; Koopman et al. 2019). Many factors, such as differences in the experimental design and conditions (for example lifting style and lifting height) can influence the results. Moreover, one methodological aspect related to the detection of surface electromyogram (EMG) could also play an important role. The local sampling of surface EMG using bipolar electrodes might also contribute to explain the inconsistency observed in the literature. EMGs with different amplitudes have been observed in multiple regions of low back muscles during sustained lumbar flexion (Tucker et al. 2009) and repetitive lifting tasks (cf. Figure 8 in Falla et al. 2014), indicating a redistribution of muscle activity with the progression of the task. Methodologically, these findings suggest that the sampling of surface EMG from a small muscle region may provide a biased indication of the level of low back muscles' activity during working activities. The high-density surface electromyography has been indicated to overcome such limits of the bipolar electromyography because it allows the assessment of muscle activity from a representative muscle region (Farina 2006; Gazzoni 2010). Consequently, the high-density surface electromyography can be an important tool for the evaluation of exoskeleton effectiveness on muscle demand, revealing whether the exoskeleton-related differences in muscle activity are greater or not than previously appreciated.

Subjective measures have also been applied to investigate subject discomfort and effort perception while using passive trunk exoskeletons. The reduction of the rates of local perceived discomfort and perceived effort has been observed when using Laevo passive exoskeleton for back support during assembly tasks (Bosch et al. 2016; Madinei et al. 2020), and static or dynamic activities (Baltrusch et al. 2018; Hensel and Keil 2019). Nevertheless, collateral effects seem to emerge with the use of passive devices, such as an increase of perceived discomfort in non-targeted body regions (e.g. legs, chest and shoulders; Baltrusch et al. 2018; Bosch et al. 2016; Fox et al. 2019; Hensel and Keil 2019; Ulrey and Fathallah 2013). Owing to the possible undesired effects, there is still a need to assess whether the passive exoskeleton effects generalises to different body regions during simulated working tasks. Moreover, to our knowledge, there are no exoskeleton-related studies systematically correlating subjective and objective measures based on biological signals. The correlation between a quantitative measure of muscle effort (e.g. EMG amplitude) and qualitative measures may reveal whether and how strongly the perceived benefit detected locally or globally may be explained by reductions in the level of muscle effort at the low back when using passive trunk exoskeletons. Overall, this scenario lays the foundation for proceeding with the investigation of passive exoskeleton effects considering both subjective and objective measures.

The purpose of this research was to assess the effect of Laevo passive exoskeleton on the low back muscles' activity, the local perceived discomfort and the perceived physical effort in two working tasks, usually performed in the real automotive work environment. Local perceived discomfort and perceived effort were assessed through the application of validated ergonomic subjective research tools (Borg 1990; Corlett 1990; Corlett and Bishop 1976). The level of muscle activity at the low back was assessed bilaterally from a detection system for the sampling of surface electromyograms from multiple regions of a single muscle (high-density surface EMG; Gazzoni

2010). We additionally correlated the level of low back muscles' activity, quantified from the spatial distribution of surface EMGs, with both the local perceived discomfort at low back (region of interest) and the perceived effort. To our knowledge, this is the first study that used the abovementioned measures and techniques altogether and correlated objective and subjective measures when using a passive exoskeleton. According to previous evidence related to Laevo exoskeleton, we expected this passive system would lead to a reduction of the low back load (Bosch et al. 2016; Koopman et al. 2019; Madinei et al. 2020) while increasing the perceived discomfort at non-targeted regions during the working tasks (Baltrusch et al. 2018; Bosch et al. 2016).

## 2. Material and methods

### 2.1. Participants

Thirteen male volunteers without prior experience in working with exoskeletons, participated in the study (mean ± SD; age: 28 ± 2.8 years; body mass: 74.5 ± 7.5 kg; height: 178 ± 6 cm). We included subjects with a stature within limits prescribed by the exoskeleton' manufacturers (164–188 cm; Laevo 2019) and were representative of the 5th, 50th and 95th percentile of the Italian population stature according to ISO/TR 7250-2 (2010) data. Participants had an average body mass index of 24 (SD ± 2.00) kg/m$^2$, which means a normal weight nutritional status according to World Health Organization (WHO 2000). All the participants did not report any muscular or neurological disorders in the last two years. Each subject provided written informed consent, including image publication, before participating in the study. This work was approved by the Regional Ethics Committee (Commissione di Vigilanza, Servizio Sanitario Nazionale—Regione Piemonte—ASL 1—Torino, Italy) and it was carried out in accordance with the *Declaration of Helsinki*.

### 2.2. Passive exoskeleton

The passive exoskeleton Laevo V2.5 (Laevo B.V., Delft, Netherlands) was used in this study. The operating system of this exoskeleton consists of two gas springs positioned at hip level, which provide support when the trunk is bent, and the level of support depends on the trunk bending angle, e.g. during static forward bending postures maintenance and manual load lifting (Laevo 2019). More specifically, the device transfers the forces from the user's pad on the chest (bypassing the lumbar zone) to the pads on the user's thighs, connected to the springs through two circular rods (Laevo 2019).

### 2.3. Experimental procedures

Participants were asked to perform two different tasks, a static and a dynamic one, with and without wearing the passive exoskeleton. The tasks were adapted from usual tasks performed in the real automotive work environment to the testing needs of laboratory conditions (see below). Before the beginning of the test, each participant was familiarised with the passive exoskeleton. The trial order was randomised, and after each trial, recovery time was provided to participants to avoid cumulative fatigue. The experimental procedures were performed in one visit, lasting around 90 minutes.

#### 2.3.1. Task A – static forward bending

This task consisted of maintaining a static 45 degrees trunk flexion posture (Figure 1(a)). A standard goniometer was used to roughly measure the trunk flexion angle, defined as the angle between the line passing through the trochanter and the edge of the acromion, and the vertical plane (Tiple et al. 2009). The visual feedback of the right hip joint angle was provided to volunteers to assist them in keeping the static forward bending (see Section 2.4.2.; Tucker et al. 2009). More specifically, from the visual feedback, subjects were instructed to maintain constant the hip joint angle with a tolerance of ±5% of the initial value (first 10s of the task). Participants were asked to keep their upper limbs relaxed, their feet in a parallel position and slightly apart during the whole condition. Slight knee flexion was allowed to avoid excessive stress at the posterior part of lower limbs, as recommended by the manufacturer (Laevo 2019). Trials were stopped by the experimenter when the participant claimed he was not able to continue due to fatigue or discomfort.

#### 2.3.2. Task B – dynamic lifting and lowering

The dynamic task was intentionally designed as critical from a biomechanical point of view, according to the reference standard for the manual handling evaluation (ISO 11228-1 2003). In this task, participants were instructed to repetitively lift and lower a box (mass: 10 kg) between two surfaces located roughly at knee height (box handles from the ground level: 50 cm; Figure 1(b), left panel) and at hip height (box handles from the ground level: 100 cm; Figure 1(b), right panel). The horizontal distance between the mid-point of the ankles and the hands when participants rested

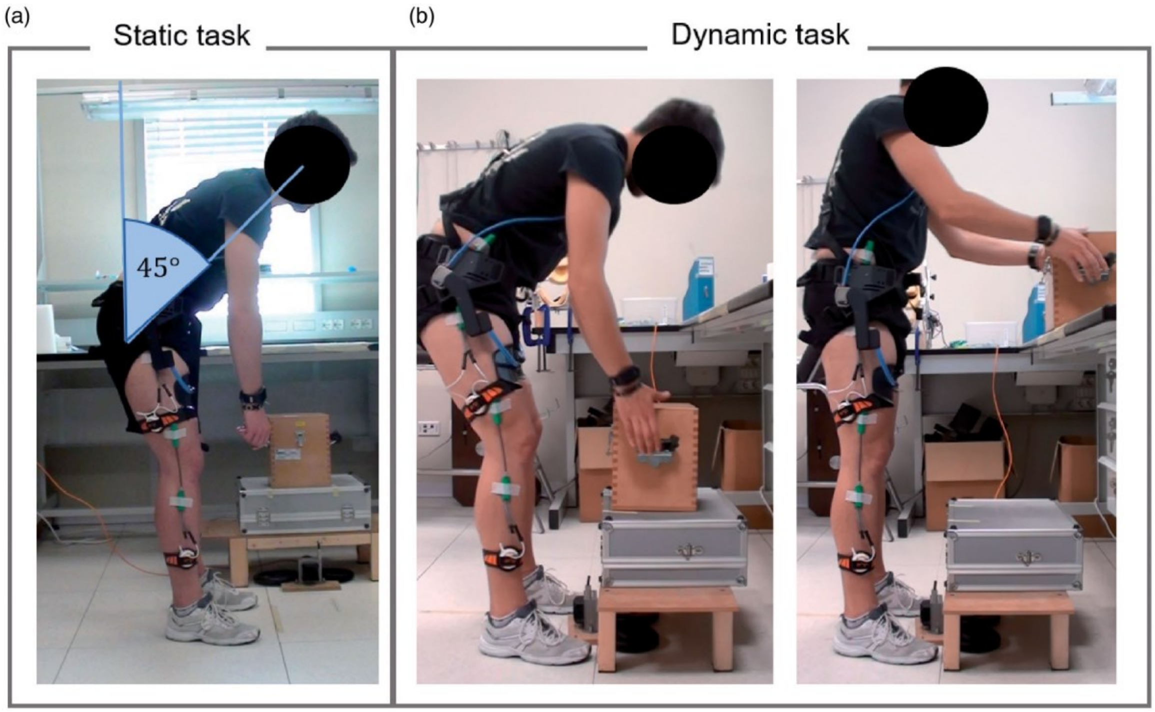


Figure 1. Participant wearing the passive exoskeleton and performing the simulated working tasks: the static forward bending (a) and the repetitive lifting and lowering task (b).

the box on the upper surface was 60 cm, and the subject's feet remained at the same position throughout the experimental condition. Participants were asked to move the box using the squat technique. The timing was provided by a digital metronome (15 bpm): at each beep, the participant had to perform one single action (lifting or lowering). The entire duration of the task was 10 minutes.

## 2.4. Measurements

### 2.4.1. Perceived localised discomfort, perceived effort and endurance time

The local perceived discomfort and perceived effort were assessed at the end of each trial. Discomfort, expressed as sensations of stiffness, pain and local fatigue (Nakata, Hagner, and Jonsson 1992), was measured through the adapted Corlett and Bishop Scale (Corlett 1990; Corlett and Bishop 1976). This scale uses a diagram of the body divided into twenty-eight regions, allowing subjects to indicate the location of discomfort in different body parts. Participants rated their intensity of discomfort for each region using a 0–5 point scale, where level 0 means no discomfort and level 5 means extreme discomfort. The subjective perception of effort was investigated using the 10 points Borg Scale (Borg 1990), where participants rated their perceived intensity of physical effort at the end of each trial. Specifically, for the static task, endurance time was also registered at the end of each trial.

### 2.4.2. Electromyography

Monopolar surface EMGs were sampled from the low back muscles with two electrode grids (8 × 4 of electrodes, inter-electrode distance: 10 mm; Figure 2(a)) placed serially on each trunk side to cover most of the lumbar, erector spinae. A modular, smart, and wearable system was used for high-density surface EMG detection (10–500 Hz bandwidth, LISIN, Politecnico di Torino, Turin, Italy; (Cerone, Botter, and Gazzoni 2019 and Figure 2(a)). The grids were positioned with the lower edge roughly at L5 level and ~2 cm laterally from the lumbar spinous process midpoint (Falla et al. 2014). The reference electrode of each electrode grid was placed over the thoracic vertebrae. Before the application of grids, the skin region over the low back muscles was prepared by gentle abrasion using abrasive paste and cleaned with water.

The level of lumbar muscles' activity for each trial was estimated from the average root mean square (RMS) amplitude, identified from the multiple surface EMGs collected with the grids of electrodes. First, single-differential EMGs were obtained as the algebraic difference between the band-pass filtered monopolar EMGs (fourth order Butterworth filter, 20–450 Hz cut-off; zero lag, bidirectional filter) in the longitudinal direction. Afterwards, the single-differential EMGs were

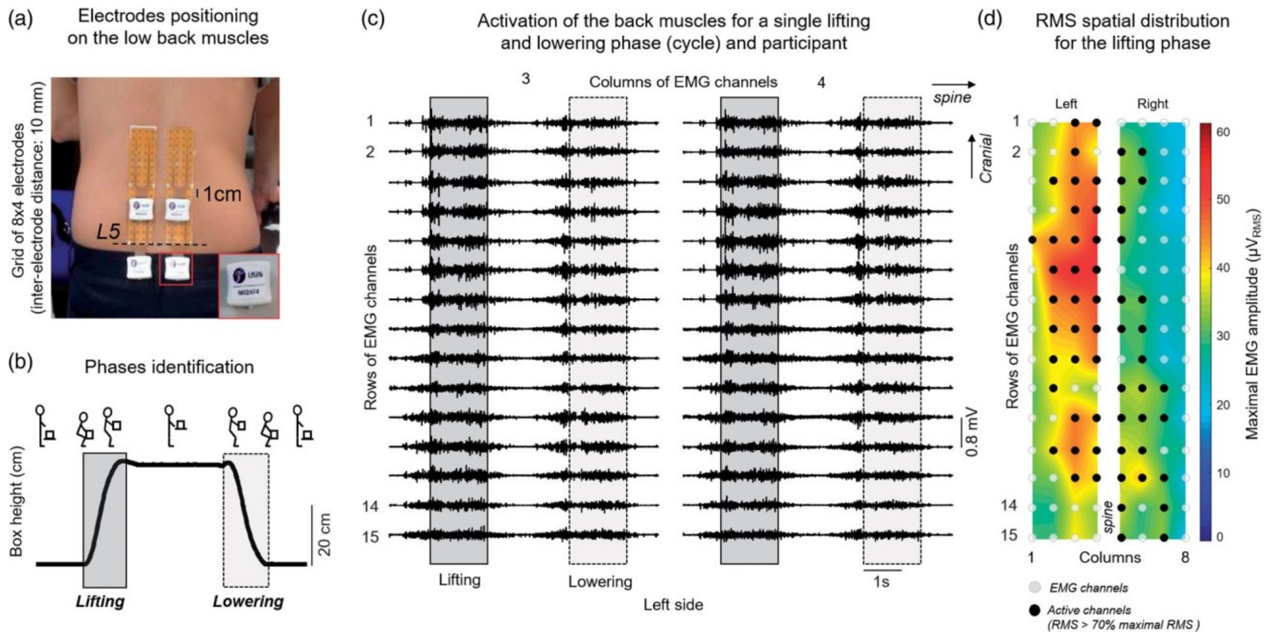


Figure 2. Electrode positioning, segmentation of surface EMGs and computation of average RMS map. Panel (a) shows the positioning of the grid of surface electrodes on the low back muscles bilaterally. Two electrode grids (8x4 of electrodes, inter-electrode distance: 10 mm) were placed serially on each body side to cover most part of the lumbar, erector spinae muscle. Panel (b) indicates an example of variations in the height of box during one cycle (one lifting and lowering phase) of the dynamic task. Dark and light grey rectangles indicate respectively the period corresponding to the lifting and lowering phases. Panel (c) shows single-differential surface EMGs sampled from the third and fourth columns of the two grids of electrodes positioned on the left side and the periods corresponding to the lifting and lowering phases (dark and light grey rectangles respectively) while a representative subject using the passive exoskeleton. Note that EMGs with relatively low amplitude coincide with the period of standing position. Panel (d) shows the average RMS map (interpolation by a factor 8) computed for the lifting phase while the same participant wearing the passive exoskeleton. White and black circles respectively indicate the channels with RMS amplitude smaller and higher (i.e., active channels) than the 70% of the maximal RMS in the map. The colour bar shows the range of intensity values of the RMS map. Note RMS channels with high amplitude in the third and fourth columns of the RMS map (left) correspond to the EMGs with high amplitude in (c) during the lifting phase.

then visually inspected to control their quality. In case of differential EMGs with contact problems (e.g. high skin-electrode impedance), such signals were interpolated from the spatial average of the adjacent channels in the grid. We observed the presence of low quality EMGs for 3 out of the 13 subjects tested during the simulated, working tasks. The EMG signals of these subjects were disregarded, and thus, EMG data from 10 subjects were used for statistical analysis.

After controlling for signal quality, the RMS amplitude was computed over the whole task duration for each EMG channel in the grid for the static task, obtaining one RMS map for each body side. For the dynamic task, firstly, individual lifting and lowering phases were respectively identified from the first derivative of the variations in the height of box with a custom written Matlab script (The MathWorks Inc., Natick, Massachusetts, USA; Figure 2(b)). From the close inspection of panel c in Figure 2, the periods corresponding to the lifting and lowering phases show relatively high EMG activity, though bursts of EMG activity were also observed before the onset of lifting (more distally) and lowering phases. EMGs with high amplitude before the onset of each phase movement can likely be related to the trunk extension before the shift of box. For each EMG channel in the grid, the RMS amplitude was calculated on EMG samples corresponding to the lifting and lowering phases (Figure 2(c)), providing a total of 75 RMS values per phase. Then, for each phase of movement and trunk side, one average RMS map was obtained by averaging the RMS values identified for each EMG channel (Figure 2(d)). Finally, regardless of working task (static or dynamic), a global index of activity was defined by averaging the channels showing an RMS value greater than the 70% of the maximal RMS in the map (see black circles in Figure 2(d)). The 70% amplitude threshold was selected to provide a robust identification of the actual region of muscle activity, as shown by Vieira, Merletti, and Mesin (2010). For each working task, the average RMS amplitude values obtained without and with exoskeleton were both normalised by the highest RMS amplitude value found between conditions.

In order to provide the visual feedback of hip position in the static task, an electrogoniometer (Twin-Axis Electrogoniometer SG150, Biometrics Ltd., Newport, United Kingdom) was positioned on the right hip of each participant. For the dynamic task, a linear encoder (Draw wire sensor, series SX80, WayCon Positionsmesstechnik GmbH, Taufkirchen, Germany) was used to record variations in the height of the box and to discriminate the lifting and lowering phases throughout the repetitive task. All signals were sampled synchronously during the working tasks at 2,048Hz using a 16-bit A/D converter.

### *2.5. Statistical analysis*

Inferential statistics were applied using SPSS Software V25 (IBM SPSS Statistics). First, data exploration and Shapiro-Wilk's *W*-test indicated data distribution for both perceived discomfort and perceived effort were not normally distributed ($p < 0.05$ in all cases). The discomfort and effort scores obtained after the two conditions (with and without exoskeleton), were compared through the non-parametric Wilcoxon signed-rank test. Data distribution for time endurance and the amplitude of surface EMGs were considered Gaussian (Shapiro–Wilk test, $p > 0.05$ in all cases). The differences in the endurance time between conditions were assessed from the t-test for paired samples. For muscle activity and the static task, the two-way analysis of variance (ANOVA) for repeated measures was applied to evaluate the effect of two independent variables, Device (2 levels: with vs without exoskeleton) and Side (2 levels: left vs right), on the average RMS amplitude of surface EMGs. For the dynamic task, the three-way ANOVA for repeated measures was applied to evaluate the effect of Phase (2 levels: lifting vs lowering) as well as Device and Side on the average amplitude of surface EMGs. Regardless of working task, whenever any significant interaction was highlighted by ANOVA, paired comparisons were assessed with the Tukey-HSD post-hoc test. Finally, in case of significant changes in the objective and subjective measures between conditions during the working tasks, Pearson's correlation coefficient was performed to test whether the degree of low back muscles' activity (percent change in RMS amplitude; *with – without* exoskeleton) was correlated with the level of perceived discomfort in the lumbar zone and perceived effort separately (percent change in score value, normalised by the highest score of scale). In case of observation with Cook's distance larger than three times the mean Cook's distance (Lewis et al., 2012), such value was considered as an outlier and removed for the correlation analysis. The level of statistical significance was set at 5%, and the electromyographic results were reported using parametric and descriptive statistics.

## 3. Results

### *3.1. Perceived discomfort, effort and endurance time*

#### *3.1.1. Perceived localised discomfort*

Regarding the static task and the trunk body regions of Corlett and Bishop Scale, significantly lower rates of discomfort in the lumbar region [*(with – without)/with exoskeleton:* -30%] were observed when participants performed the task with the exoskeleton than without ($p$ ¼ 0.008, $Z$ ¼ —2.653; Figure 3(a)). Conversely, the use of the exoskeleton leads to a significant increase of discomfort in the chest region (þ100%; $p$ ¼ 0.007; Z ¼ 2.699; Figure 3(a)). Concerning the lower limbs body regions, discomfort ratings were significantly higher in the left (þ70%) and right (þ50%) foot with exoskeleton when compared to the condition without exoskeleton ($p$ ¼ 0.170, $Z$ ¼ —2.379 and $p$ ¼ 0.031, $Z$ ¼ —2.154 respectively; Figure 3(b)). Regarding the upper limb regions, no significant differences in the discomfort perceived scores were found between conditions (Figure 3(c)).

Regarding the dynamic task, the chest region was the only one among the trunk body regions in which differences in discomfort ratings were significantly higher with the exoskeleton (þ100%; $p$ ¼ 0.004, $Z$ ¼ —2.877; Figure 4(a)). Concerning upper and lower limb regions, no significant differences in the discomfort perceived scores were found between conditions ($p > 0.050$; Figure 4(b,c)).

#### *3.1.2. Perceived effort*

Concerning the perceived effort investigated with Borg Scale, participants expressed significantly lower scores when they used the exoskeleton performing the static task ($p$ ¼ 0.40, $Z$ ¼ —2.058; left panel of Figure 5). In case of the dynamic task, paired comparisons revealed the absence of statistically significant differences between the two conditions ($p$ ¼ 0.265, $Z$ ¼ —1,115; right panel of Figure 5).

#### *3.1.3. Endurance*

Regarding the static task, endurance time resulted significantly higher when participants performed the task with the exoskeleton (mean

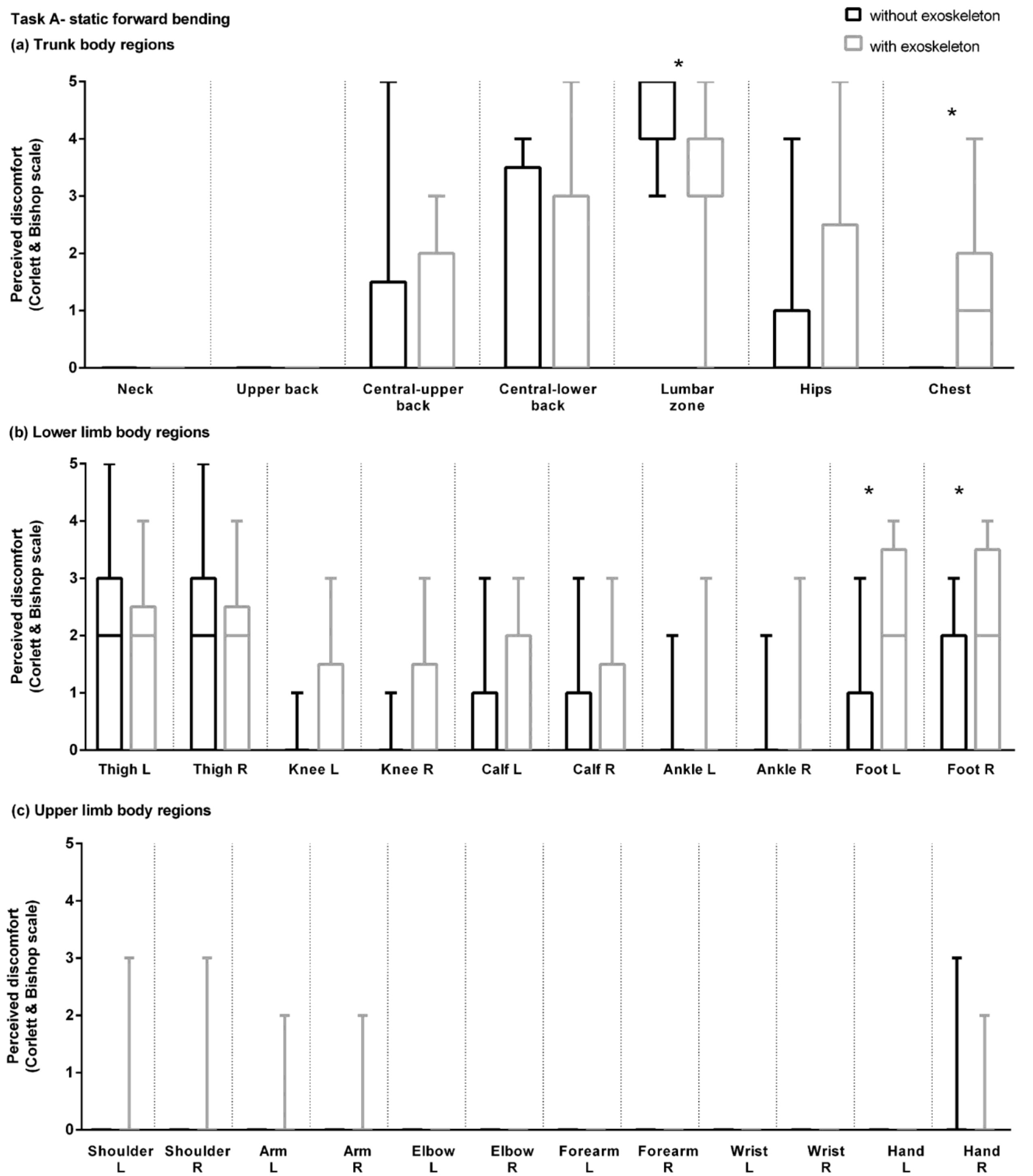


Figure 3. Boxplots of the perceived discomfort scores using Corlett and Bishop scale (0¼no perceived discomfort, 5¼extreme perceived discomfort) assigned for trunk body regions (a), lower limb regions (b) and upper limb regions (c) at the end of the static task (Task A) without (black boxes) and with (grey boxes) exoskeleton. Asterisks (ω) indicate the statistically significant differences ($p < 0.05$).

and SD: 648.38 ± 194.75 s) compared to without (384.46 ± 130.52 s; $t(12)$¼7.461, $p < 0.001$).

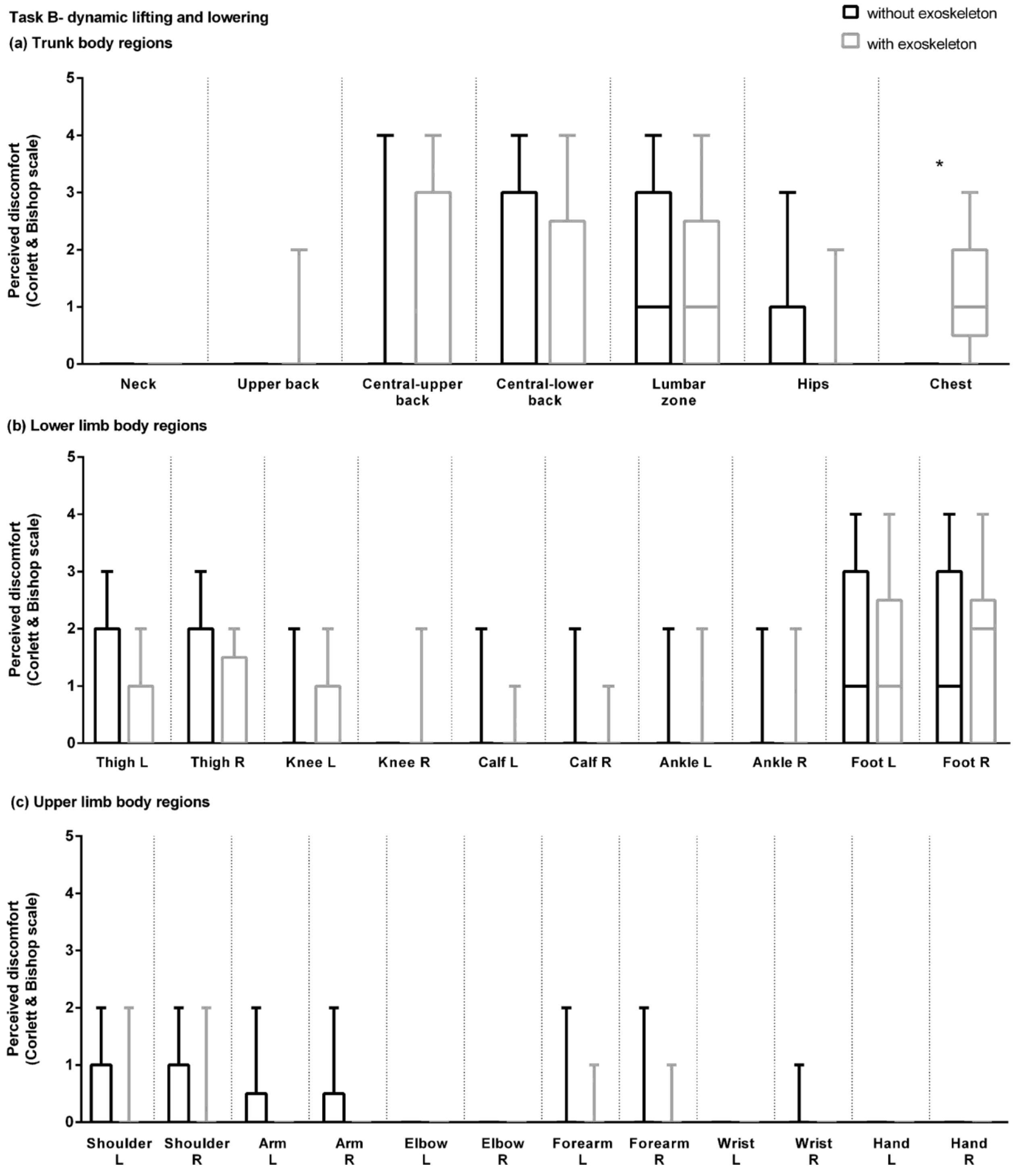


Figure 4. Boxplots of the perceived discomfort scores using Corlett and Bishop scale (0 ¼ no perceived discomfort, 5 ¼ extreme perceived discomfort) assigned for trunk body regions (a), lower limb regions (b) and upper limb regions (c) at the end of the dynamic task (Task B) without (black boxes) and with (grey boxes) exoskeleton. Asterisks (ω) indicate statistically significant differences ($p < 0.05$).

### 3.2. Muscle activity

The use of passive exoskeleton reduced the degree of muscle activity in both working tasks significantly. First, for the static task, the two-way ANOVA revealed a main Device effect ($F$ ¼ 9.582, $p$ ¼ 0.007) while no main Side effect ($F$ ¼ 0.152, $p$ ¼ 0.701) and interaction between Device and Side ($F$ ¼ 0.004, $p$ ¼ 0.951) were found for the RMS amplitude of surface EMGs (Figure 6). When pooling data across body sides, EMGs with lower amplitude (8%) were detected while subjects wearing the passive exoskeleton than without exoskeleton (left panel in Figure 6). Concerning the dynamic condition, a main effect of Device ($F$ ¼ 11.280, $p$ ¼ 0.001) was also found for the average RMS amplitude, with lower values (4.5%) for the condition with the exoskeleton than without

(Figure 6). As ANOVA did not show Side and Phase effects for each trial (with and without exoskeleton), the normalised RMS amplitude was pooled across sides for the static task, while for the dynamic task, it was pooled across sides and phases for further correlation analysis.

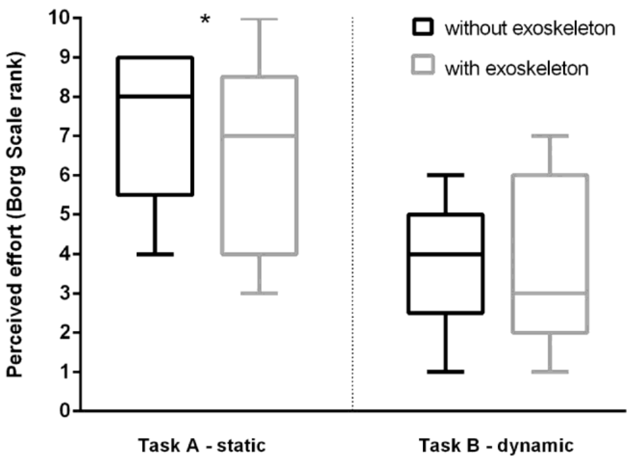


Figure 5. Boxplots of perceived effort scores using 10-Borg Scale (0 ¼ no perceived effort, 10 ¼ strong perceived effort) assigned for Task A (static) and Task B (dynamic), without (black) and with (grey) exoskeleton. Asterisks (ω) indicate statistically significant differences ($p < 0.05$).

### 3.3. Correlation between EMG amplitude and subjective scales

Correlations between the amplitude of surface EMGs and subjective measures were dependent on the type of scale. Concerning the static task, there was a significant and negative correlation between the percent change in RMS amplitude and percent change in perceived effort (*r* ¼ —0,850; *p* ¼ 0,003; *N* ¼ 9, 1 out of 10 subjects was considered as an outlier; Figure 7) while no statistically significant association was found between percent change in RMS and percent change in local perceived discomfort (*r* ¼ —0,294; *p* ¼ 0,441; *N* ¼ 10). This means that a lower perceived physical effort is correlated with a higher level of muscle activity at the low back when using the passive system (Figure 7). Given no significant changes in the low back perceived discomfort and in the perceived effort were observed between conditions during the dynamic task (see results in Figures 4 and 5), the correlation was not applied for this task.

## 4. Discussion

Passive exoskeletons are currently arousing strong interest both in the industrial sector and among researchers because of their potential to reduce the biomechanical overload in body areas where workers report excessive discomfort and pain during occupational activities. This study aimed at assessing the effect of a passive trunk exoskeleton during two

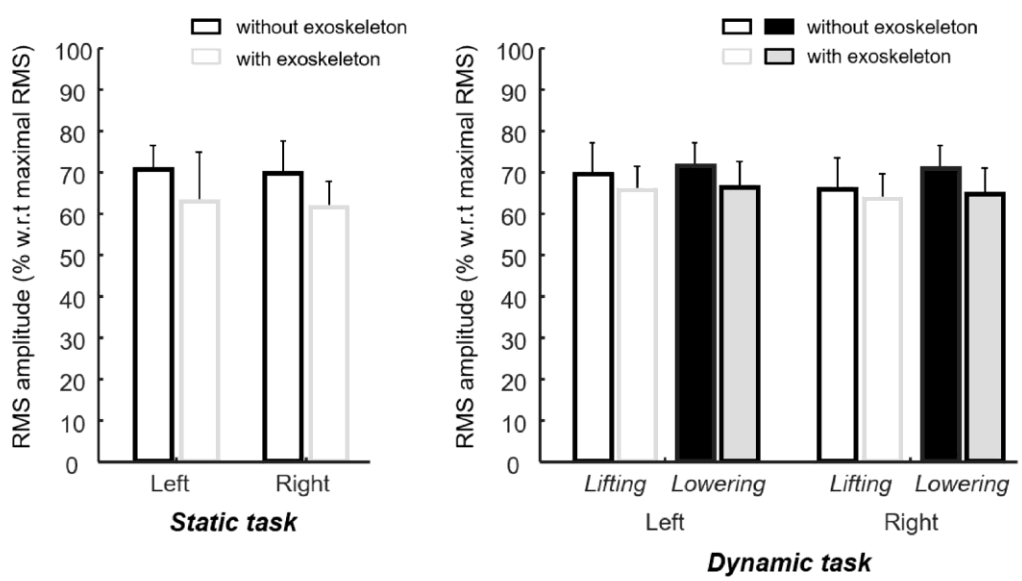


Figure 6. Normalised, RMS amplitude (mean ± SD) obtained for the static (left) and dynamic (right) tasks. A significant Device main effect was revealed in both working tasks ($p < 0.008$ in all cases), with lower values for the condition with (With exo) than without exoskeleton (Without exo).

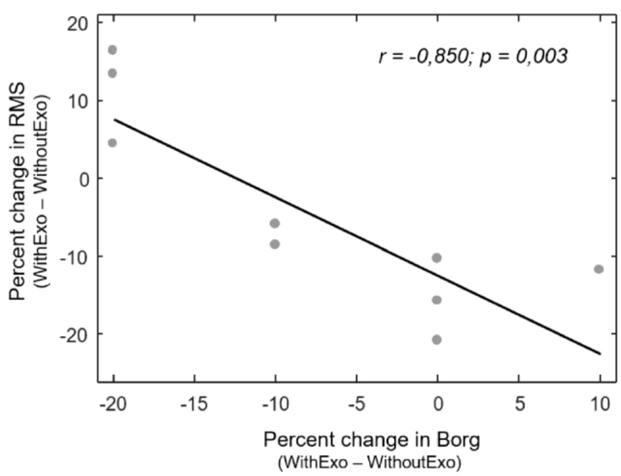


Figure 7. Relationship between percent change in RMS amplitude and percent change in Borg scale for the static task ($r$¼ −0.8502; $p$¼0.0037). Negative relative differences mean a lower effort with than without exoskeleton. Regression (black) line was drawn for clarity.

typical working tasks from subjective and objective measures to clarify the impact of using this device on the prevention of WMSDs. Local perceived discomfort and perceived effort were assessed (Borg 1990; Corlett 1990; Corlett and Bishop 1976), and bilateral low back muscles' activity was quantified from the spatial distribution of surface EMGs. Additionally, subjective ratings and EMG data were correlated for the first time to understand whether exoskeleton-related differences in the low back activity may explain the perception of discomfort in the low back and the perception of effort while using the passive exoskeleton.

### *4.1. Effect of exoskeleton on local discomfort, perceived effort and muscle activity*

Differences in the local perceived discomfort between conditions with and without exoskeleton were task-dependent. The use of the passive device led to a significant reduction of the local perceived discomfort in the low back region while increasing discomfort in the chest and feet during the static forward bending (Figure 3(a)). These results are in line with previous studies demonstrating individuals wearing the Laevo exoskeleton have the perception of less discomfort in the back at the cost of increased discomfort in the chest (Baltrusch et al. 2018; Bosch et al. 2016; Hensel and Keil 2019). Moreover, similar findings were observed with a personal lift-assist device during a static forward bending task (Graham, Agnew, and Stevenson 2009), indicating such effects are reported for different passive trunk systems. Different perceptions may underlie different discomfort scores across body regions. Lower discomfort in the back might result from the perception of less muscle effort (see Figure 6), while higher discomfort in the chest or legs might be related to the contact pressure between the exoskeleton and the body (Bosch et al. 2016; Hensel and Keil 2019). In this study, we also assessed the effect of the Laevo exoskeleton on the perceived discomfort in the feet, which is not as studied as the regions where the exoskeleton interacts with the human body (e.g. thigh and chest regions). Especially for the static task, we found an increased perceived discomfort in the feet with the use of Laevo exoskeleton. Possible exoskeleton-related differences in the postural control during the prolonged forward bending might play a role in the increase of perceived discomfort in the feet. The use of exoskeleton may further challenge the postural control (i.e., increase the size of postural sways) in a prolonged leaning posture while keeping both feet completely on the ground (Duarte and Zatsiorsky 2002), contributing likely to the discomfort in the feet. However, in absence of direct measures of balance performance, such interpretations require further investigations. Our results are not in line with Hensel and Keil (2019) who did not find a change in the perceived discomfort in the feet with the use of Laevo exoskeleton. A possible explanation might be related to differences in the working task and the study design. In our study, participants kept the same feet position throughout the entire task while in the study of Hensel and Keil (2019), the exoskeleton was tested during real static working tasks without providing indications about the feet position. Notwithstanding the potential factors accounting for the discomfort scores across body regions when using the passive system, our results seem to support the assumption that the reduction of perceived discomfort at lumbar level obtained with the Laevo exoskeleton is compensated at non-targeted body areas.

Exoskeleton-related differences in the perceived discomfort at the targeted region were not as clear as for the dynamic condition. No differences in the perceived discomfort at the low back were observed between conditions for the dynamic task (lumbar zone in Figure 4). Similarly, Hensel and Keil (2019) showed that the use of the Laevo exoskeleton did not lead to a decrease in the perceived discomfort in the back during dynamic situations. A possible explanation is likely found in the reduced potential of the passive system to change the level of low back muscles' activity during a lifting task. According to our results, significant reductions in the degree of muscle activity when using this passive system were lower in the lifting (~5%) than in the sustained task (~10%; Figure 6), likely explaining the non-significant differences in the perceived discomfort at the low back. In addition, subjects reported a higher perceived discomfort in the chest region with than without the use of the Laevo exoskeleton during the lifting task. This result corroborates previous evidence on the perceived discomfort in the chest when using this passive device, regardless of the type of working task (Baltrusch et al. 2018; Bosch et al. 2016; Hensel and Keil 2019). Therefore, our findings indicate further developments need to focus on the adaptations of Laevo exoskeleton system to increase its potential in reducing muscle effort in the low back and perceived discomfort across body regions for various work-related tasks (e.g. dynamic situations), with implications on the user acceptance of Laevo exoskeleton.

Changes in the global perceived effort with the use of exoskeleton also depends on the simulated working task. A significant lower physical perceived effort was observed when participants performed the static forward bending task with than without the exoskeleton (Figure 5). This result is consistent with Baltrusch et al. (2018) who tested the effect of Laevo exoskeleton on the perceived discomfort during a static task and found lower scores of discomfort with the use of this device. When considering other passive trunk exoskeletons, previous evidence reported lower scores of perceived effort, measured by Borg Scale, while using a personal lift-assist device during a static forward bending task (Graham, Agnew, and Stevenson 2009). However, differences in global perceived effort between conditions were not observed for the dynamic task (Task B in Figure 5). Different factors could have accounted for non-significant differences in the global perceived effort between conditions during the dynamic task. First, a possible explanation could be that the proportional effect of the Laevo exoskeleton on muscle activity is lower in dynamic lifting compared to static bending (Figure 6). A second issue to consider is the duration of the rest period within and between work cycles used in our study during the lifting task. More specifically, the 1:1 work-to-rest ratio in the repetitive task could explain the low ratings of perceived effort in both conditions, with and without Laevo exoskeleton (Graham, Agnew, and Stevenson 2009). Based on these data, subjects seem to perceive that the passive device reduces physical effort globally and especially during the static task.

When considering muscle activity, differences in the degree of low back muscles' activity emerged in both simulated working conditions. First, for the static task, the degree of low back muscles' activity was on average lower (~10%) with than without exoskeleton (Figure 6). This percentage of amplitude reduction was comparable with those previously detected when using the Laevo exoskeleton during static bending, ranging from 10% to 38% (Bosch et al. 2016; Koopman et al. 2019). Furthermore, endurance time was roughly two times longer with than without exoskeleton, corroborating previous evidence (Bosch et al. 2016). For the dynamic task, we also found a lower level of low back muscles' activity (~5%) with than without the use of Laevo exoskeleton (Figure 6). This result is in accordance with previous literature; however, the overall exoskeleton-related reductions in the low back activity during a lifting task observed in literature did not reach significance (Baltrusch et al. 2019). A possible explanation may lie in the local sampling of surface EMGs; since an uneven distribution of activity was observed during a lifting task in the low back muscles (Falla et al. 2014), the estimated level of muscle activity depends on where the bipolar EMG signal is collected and could be underestimated. Hence, the high-density surface EMG used here can be an important tool to reveal the exoskeleton effectiveness on muscle demand during dynamic situations. Finally, when comparing the Laevo exoskeleton effects on muscle activity between static bending and repetitive lifting, a larger effect was observed for the static task. In accordance with prior evidence, such exoskeleton-related differences between working tasks might be explained by the continuous support provided the Laevo exoskeleton during the forward bending (Baltrusch et al. 2019). Collectively, our current results suggest exoskeleton differences in muscle activity, as estimated from a wide region in the low back, were revealed during different working tasks, with implications on the prevention of WMSDs.

### *4.2. Correlation between muscle activity and subjective scales*

To assess whether possible reductions in both the low back perceived discomfort and the perceived effort can be explained by the reduction in the degree of low back muscles' activity when using the Laevo exoskeleton, correlation analyses were conducted. Our results demonstrated that the percent change in RMS amplitude was negatively associated with the percent change in the perceived effort during the static task (Figure 7). The individuals who relax more the lumbar muscles are therefore expected to report a higher perceived effort while wearing the Laevo exoskeleton.

The increase of perceived effort, as muscle activity decreases, could be explained by the concurrent increase of discomfort scores in the exoskeleton non-targeted body areas, as suggested by the Corlett and Bishop scale's results (Figure 3). According to our results, 3 out of 10 participants increase muscle activity with the use of exoskeleton, showing an inter-individual variability in muscle activity when using this passive system. Different sources could have masked the exoskeleton effects on muscle activity, though not on perceived effort, during static bending. As recently reported by Koopman et al. (2019), the flexion-relaxation phenomenon or subtle posture variations in the lumbar flexion might prevent further reduction or even contribute to an increase in the low back activity when using the Laevo exoskeleton during this working task. However, even in the presence of such factors on muscle activity, the Laevo exoskeleton is expected to reduce spine compression during forward bending (Koopman et al. 2019). This could contribute to the perception of less perceived effort while increasing muscle activity in the low back with the use of this passive device. In addition, though differences in the perceived rates of lumbar discomfort between conditions were statistically significant (Figure 3(a)), there was no correlation between the percent change in RMS and the percent change in local perceived discomfort. Very low rates variability between individuals for the discomfort in the low back with the exoskeleton (most subjects with a percent decrease of 20%) accounts for the absence of association between percent changes. Current findings suggest the exoskeleton-related differences in muscle activity are not supposed to influence the perceived discomfort in the back, investigated by Corlett and Bishop scale, when using the Laevo exoskeleton during static bending.

## 5. Conclusions

In summary, our findings showed that the Laevo exoskeleton effects on local discomfort, perceived effort, and spatial distribution of back muscles activity depend on the working task. For the static task, a reduction in both the back load (in terms of perceived discomfort and muscle activity) and the perception of effort was observed with the device. Moreover, our correlation results indicate that the reduction in the low back muscle activity might be associated with an increase of perceived effort when using the Laevo exoskeleton. For the repetitive task, though a reduction in the degree of low back muscles' activity was observed with the use of the exoskeleton, no significant differences in the perceived discomfort at the low back and in the perception of effort were observed between conditions. Owing to its ability in reducing the back muscle effort during the sustained and repetitive tasks tested here, the Laevo passive exoskeleton can be considered a promising tool to prevent WMSDs. However, product improvements should concentrate on the potential of Laevo exoskeleton in reducing muscle effort, especially during dynamic situations, to increase its impact on the prevention of WMSDs. Moreover, collateral effects were revealed in both the work-related tasks thanks to the application of subjective perception analysis measures, i.e. the increase of perceived discomfort in the exoskeleton non-targeted body regions. In this view, while testing exoskeletons, the application of both the objective and subjective measures should be considered as a useful approach in future works to assist in the investigation of exoskeleton effects, optimising its design and user acceptance.

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