

Changes in the distribution of muscle activity when using a passive trunk exoskeleton depend on the type of working task: A high-density surface EMG study

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1 **Title**

2 Changes in the distribution of muscle activity when using a passive trunk exoskeleton depend on the  
3 type of working task: a high-density surface EMG study

4

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26

27

28

29 **Abstract**

30 Exoskeleton effectiveness in reducing muscle efforts has been usually assessed from surface  
31 electromyograms (EMGs) collected locally. It has been demonstrated, however, that muscle activity,  
32 redistribute within the low back muscles during static and dynamic contractions, suggesting the need  
33 of detecting surface EMGs from a large muscle region to reliably investigate changes in global muscle  
34 activation. This study used high density surface EMG to assess the effects of a passive trunk  
35 exoskeleton on the distribution of low back muscles' activity during different working tasks. Ten, male  
36 volunteers performed a static and a dynamic task with and without the exoskeleton. Multiple EMGs  
37 were sampled bilaterally from the lumbar erector spinae muscles while the hip and knee angles were  
38 measured unilaterally. Key results revealed for the static task exoskeleton led to a decrease in the  
39 average root mean square (RMS) amplitude (~10%) concomitantly with a stable mean frequency and  
40 a redistribution of muscle activity (~0.5 cm) in the caudal direction toward the end of the task. For the  
41 dynamic task, the exoskeleton reduced the RMS amplitude (~5%) at the beginning of the task and  
42 the variability in the muscle activity distribution during the task. Moreover, a reduced range of motion  
43 in the lower limb was observed when using the exoskeleton during the dynamic task. Current results  
44 support the notion the passive exoskeleton has the potential to alleviate muscular loading at low back  
45 level especially for the static task.

46  
47 **Keywords:** ergonomics, exoskeleton, surface electromyography

## 48 **1. Introduction**

49 Work-related musculoskeletal disorders (WMSDs), mainly interesting the neck-shoulder and low back  
50 regions, rank among the most serious health problems in the occupational sector (Amell and Kumar,  
51 2001; Roquelaure, 2018). WMSDs have a multifactorial origin (Buckle and Jason Devereux, 2002;  
52 Hartvigsen et al., 2018); different factors may account for WMSDs, such as repetitive or sustained  
53 activity and incorrect postures during work activities (Elders et al., 2003; Punnett et al., 1991;  
54 Wickström and Pentti, 1998). The prevention of WMSDs is therefore of crucial interest in the industry  
55 sector.

56

57 Different approaches have been proposed to reduce the risk of WMSDs. Examples of preventive  
58 measures involve modification and/or reorganization of workstations and equipment, the automation  
59 of factories, practice of physical activity, postural and muscle activity re-education using biofeedback  
60 (Carayon et al., 1999; Falla et al., 2007; Holtermann et al., 2008; Neumann et al., 2002; Zare et al.,  
61 2015). More recently, industrial exoskeletons have been proposed to support workers in sustained or  
62 repetitive tasks. Briefly, these body-worn assistive devices are generally classified according to a) the  
63 targeted region to be supported (e.g., upper limbs, trunk, lower limbs, or whole-body) and b) the  
64 actuation mechanism: active (requiring an external power source) or passive (De Looze et al., 2016).  
65 While passive exoskeletons are being adopted by manufacturing companies, active exoskeletons are  
66 mainly in a development stage due to their challenging design (e.g., the weight of the device; De  
67 Looze et al., 2016; Graham et al., 2009).

68

69 Electromyography has been extensively used to assess the effectiveness of passive exoskeletons in  
70 muscle effort reduction. The standard bipolar technique is usually applied to estimate the level of  
71 muscle activity (Abdoli-Eramaki et al., 2006; Bosch et al., 2016; Graham et al., 2009). However,  
72 because of local sampling, bipolar electromyogram (EMG) could be not fully representative of the  
73 whole muscle activity (Merletti et al., 2003). For instance, it has been demonstrated the distribution of  
74 EMG activity obtained from the lumbar muscles significantly changes during a fatiguing task and  
75 cannot be tracked using a standard bipolar detection (Falla et al., 2014; Tucker et al., 2009). This  
76 poses some methodological challenges in the assessment of lumbar exoskeleton which likely explain

77 the wide range of percentage attenuation of low back muscles' activity using passive exoskeletons  
78 across studies (from 10 to 60%; De Looze et al., 2016; Koopman et al., 2019) and contradictory results  
79 between static and dynamic tasks (Baltrusch et al., 2019; Bosch et al., 2016). The detection of muscle  
80 activity from a representative muscle region seems therefore essential to assess differences induced  
81 by the use of exoskeletons in low back muscles' activity.

82

83 This study aimed at investigating the spatial distribution of low back muscles' activity when using a  
84 passive trunk exoskeleton during different working conditions. In virtue of the attenuation effect of  
85 passive exoskeletons on the level of low back muscles' loading (Abdoli-E et al., 2006; Bosch et al.,  
86 2016; Graham et al., 2009) and changes in the EMG distribution over lumbar muscles during  
87 simulated working conditions (Falla et al., 2014; Tucker et al., 2009), we expected to observe changes  
88 in muscle activity level dependent on the detection site.

89

## 90 **2. Material and methods**

### 91 2.1 Participants and experimental procedures

92 Ten male volunteers were recruited (mean  $\pm$  SD; age:  $28 \pm 2.8$  years; body mass:  $74.5 \pm 7.5$  kg;  
93 height:  $178 \pm 0.6$  cm) and provided written informed consent before the study. The experimental  
94 procedures were conducted following the *Declaration of Helsinki* and approved by the Regional Ethics  
95 Committee (Commissione di Vigilanza, Servizio Sanitario Nazionale—Regione Piemonte— ASL 1—  
96 Torino, Italy). Subjects were instructed to perform two simulated working activities (one static and one  
97 dynamic) with and without a passive trunk exoskeleton (Laevo v2.57, Delft, The Netherlands). The  
98 order of the four trials was randomized for each subject and a rest time of 30 minutes was observed  
99 between two consecutive trials.

100

### 101 2.2 Working conditions

102 In the static task, subjects were instructed to maintain a posture with the trunk flexed at 45 degrees  
103 with the knees slightly bent and upper arms hanging down vertically (Figure 1A). Participants were  
104 provided with visual feedback of the right hip flexion angle on a monitor screen (see. 2.3.2 Joint  
105 angles) to keep it within a range of 10% ( $\pm 5\%$ ) of its initial value (Tucker et al., 2009). The trial was

106 stopped by the experimenter when the participant was not able to maintain the required posture  
107 (endurance time).

108

109 In the dynamic task, subjects were asked to repetitively move, with squat technique, a wooden box  
110 (10 kg; Falla et al., 2014; Baltrusch et al., 2019) between two surfaces placed at 50 cm and 100 cm  
111 from the floor. The contour of the box was marked on both surfaces to ensure participants would place  
112 the box in the same position during the task (Abdoli-E et al., 2006). The repositioning task (one lifting  
113 and one lowering) was performed at a cadence of 1task/8s for 10 minutes (right panel in Figure 1A),  
114 provided by a metronome. Before starting the task, subjects were familiarized with it for approximately  
115 one minute.

116

## 117 2.3 Data acquisition

### 118 2.3.1 Surface EMG

119 Monopolar EMGs were sampled from back muscles bilaterally with two electrode grids positioned  
120 serially (16x4 of electrodes, inter-electrode distance: 10 mm; Figure 1B) to cover most of the lumbar  
121 erector spinae and multifidus muscles (Falla et al., 2014). Before the application of electrode grids,  
122 the skin was cleaned with abrasive paste. A reference electrode was placed over T5. EMGs were  
123 recorded with a wearable system for high-density surface EMG (Figure 1B; 10-500 Hz bandwidth,  
124 LISIN, Politecnico di Torino, Turin, Italy; Cerone et al., 2019).

125

### 126 2.3.2 Joint angles

127 To investigate the effects of exoskeleton on the postural strategy, right hip and knee joint angles were  
128 collected (Twin-Axis Electrogoniometer SG150, Biometrics Ltd., Newport, United Kingdom).  
129 Goniometers were positioned as shown in Figure 1A. A linear encoder (Draw wire sensor, series  
130 SX80, WayCon Positionsmesstechnik GmbH, Taufkirchen, Germany) was used to acquire the vertical  
131 box movement to discriminate the lifting and lowering phases throughout the repetitive task. All signals  
132 were sampled synchronously during the working tasks at 2,048 Hz using a 16-bit A/D converter.

133

## 134 2.4 Electromyographic and kinematic analysis

135 Monopolar surface EMGs were first visually inspected. Whenever any electrode presented contact  
136 problems, the corresponding signal was interpolated by averaging the signals from the adjacent  
137 electrodes. Single-differential EMGs (SD EMGs) were calculated along the muscle's longitudinal axis  
138 and band-pass filtered (20 – 450 Hz, anti-causal fourth-order Butterworth). Since the endurance time  
139 was different for the static task between conditions, the shorter endurance time was considered to  
140 define the duration of the contraction for both. The maps of the root mean square (RMS) and mean  
141 power spectral frequency (MNF) of SD EMGs were computed over the first (0-10%), middle (40-50%),  
142 and last (90-100%) decile of the task duration to study muscle fatigue (Cifrek et al., 2009). For the  
143 dynamic task, the lifting and lowering phases were identified respectively as the intervals  
144 corresponding to the positive and negative values of the first derivative of the height of the box (Figure  
145 2A). For each movement phase, RMS and MNF maps were calculated for the first, middle, and last  
146 minute of the task by averaging the EMG variables across the cycles within the considered minute  
147 (Figures 2B and 2C).

148

149 The average RMS, the average MNF, and the coordinates of the centroid of the RMS distribution  
150 were calculated as global descriptors of each EMG map considering only the channels with RMS  
151 higher than 70% of the maximum value in the map (Figure 3; Vieira et al., 2010). The average RMS  
152 and MNF were normalized for the highest value across their respective maps, considering both  
153 exoskeleton conditions.

154

155 Hip and knee joint angles were low-pass filtered (10 Hz, anti-causal 2<sup>nd</sup>-order Butterworth filter). The  
156 average angular position for the static task and the maximum and minimum joint angles for the  
157 dynamic task were computed for the three considered periods of the task. The average duration of  
158 lifting and lowering phases across cycles was computed to test whether participants keep a constant  
159 lifting and lowering pace with the exoskeleton.

160

## 161 2.5 Statistical analysis

162 Normal distribution of data was verified in both static and dynamic tasks (Kolmogorov-Smirnov,  $p >$   
163 0.05 in all cases). A three-way repeated-measures ANOVA was used to evaluate the effect of Time

164 (3 levels: start, middle, end), Exoskeleton (with and without), and Side (left and right; between factor)  
165 on the global descriptors of EMG maps. Furthermore, a three-way repeated-measures ANOVA was  
166 applied to compare the maximum and minimum angles between dynamic conditions with Time and  
167 Exoskeleton as repeated measures and, Cycle phase, as between factor. A two-way repeated-  
168 measures ANOVA was used to compare the average joint angles during the static tasks, with  
169 Exoskeleton as between factor. Whenever any significant difference was revealed by ANOVA, paired  
170 comparisons were assessed with the Tukey-HSD post hoc test. Finally, a Student *t*-test for paired  
171 samples was applied to test for differences in i) the endurance time and ii) the average duration of  
172 lifting and lowering phases between with and without the exoskeleton. The level of statistical  
173 significance was set at 5%.

174

### 175 **3. Results**

176 The visual analysis of the signals commonly revealed good signal quality (Figures 2-4). The average  
177 number of interpolated signals was 10 out of 128 channels per subject, considering all tested  
178 conditions.

179

#### 180 **3.1 Static task**

181 Figure 4 shows raw signals and RMS maps for a representative participant. RMS maps showed lower  
182 amplitude with than without the exoskeleton during the whole static task, regardless of the trunk side  
183 (Figures 4C-D). In both conditions, RMS distribution shifted in caudal direction over time (Figures 4C-  
184 D).

185

186 ANOVA revealed significant effects of Exoskeleton ( $F=10.611$ ,  $p=0.004$ ) and Time ( $F=6.339$ ,  $p=0.004$ )  
187 on the RMS amplitude. On average, a significant RMS reduction (~10%) was found with exoskeleton  
188 ( $p<0.005$ ) and between the beginning and end of the task (~5%;  $p=0.001$ ; Figure 5A). MNF was  
189 dependent on the interaction between Time and Exoskeleton ( $F=5.044$ ,  $p<0.011$ ); MNF reduced at  
190 the end of the task without the exoskeleton ( $p<0.001$ ; Figure 5B). A significant Time main effect for  
191 the y-coordinate of the centroid ( $F=4.119$ ,  $p=0.024$ ) was observed, with muscle activity shifting more  
192 distally (~0.5 cm) toward the end of the task in both conditions (Figure 5C;  $F>3.730$ ,  $p=0.042$ ).



193

194 For the knee angle, a main effect of Time was identified ( $F=4.119$ ,  $p=0.027$ ) with higher values at the  
195 end ( $14.22 \pm 13.34$  degrees) than at the beginning of the task ( $9.34 \pm 11.62$  degrees;  $p=0.021$ ) while  
196 there was a trend to higher hip angle values toward the end of the static task ( $F=2.881$ ,  $p=0.069$ ). The  
197 endurance time was about two times longer with ( $10.037 \pm 3.40$  min) than without exoskeleton ( $6.107$   
198  $\pm 2.13$  min;  $p<0.01$ ).

199

### 200 3.2 Dynamic task

201 The RMS distribution differed between exoskeleton conditions. For the representative subject, a  
202 stable distribution was observed over time with the exoskeleton while a redistribution arose markedly  
203 toward the end of the task without the exoskeleton (Figure 6). Surface EMGs with relatively lower  
204 amplitude were detected with than without exoskeleton mainly at the beginning of the task (Figure 6).

205

206 For the lifting phase, RMS was dependent on the interaction between Time and Exoskeleton  
207 ( $F=5.011$ ,  $p<0.012$ ), with lower EMG amplitude ( $\sim 5\%$ ) with than without exoskeleton at the beginning  
208 of the task (Figure 7A). For MNF, there was a Time main effect ( $F=3.286$ ,  $p=0.048$ ), with lower values  
209 toward the end of the task (Figure 7B;  $p<0.001$ ). For the centroid in the cranial-caudal direction,  
210 ANOVA revealed a trend toward an interaction between Time and Exoskeleton ( $F=2.816$ ,  $p=0.073$ ).  
211 By pooling data, muscle activity tended to shift more distally at the end of the task without than with  
212 the exoskeleton ( $\sim 0.5$  cm; Figure 7C).

213

214 For the lowering phase, RMS was dependent on the interaction between Time and Exoskeleton  
215 ( $F=4.783$ ,  $p=0.014$ ). A significant lower RMS ( $\sim 5\%$ ) was found at the beginning of the task with than  
216 without the exoskeleton ( $p<0.05$ ; Figure 8A). For MNF, ANOVA revealed significant effects of Time  
217 ( $F=11.274$ ,  $p<0.001$ ) and Exoskeleton ( $F=4.813$ ,  $p=0.041$ ), showing an increase in MNF from the  
218 beginning to the end of the task for both conditions ( $\sim 5\%$ ;  $p<0.05$ ), but with lower values with than  
219 without exoskeleton (Figure 8B).

220

221 ANOVA revealed a Time effect on the hip joint for both cycle phases ( $F > 4.949$ ,  $p < 0.012$ ), with a  
222 decrease of maximum ( $\Delta: \sim 8.0$  degrees;  $p = 0.018$ ) and minimum ( $\Delta: \sim 3.0$  degrees;  $p = 0.020$ ) angles,  
223 regardless of the device condition (Figure 9A). A significant main effect of Exoskeleton was revealed  
224 for the knee maximum angle ( $F = 8.729$ ,  $p = 0.008$ ), with a lower angle ( $\sim 6.5$  degrees) with than without  
225 exoskeleton, regardless of the cycle phase (Figure 9B). For the knee minimum angle, a significant  
226 interaction between Time and Exoskeleton was revealed ( $F = 3.675$ ,  $p < 0.035$ ), indicating a more flexed  
227 knee position with than without the exoskeleton at the beginning of the task ( $p = 0.003$ ).

228

229 No differences in the duration of movement phases were observed between conditions without (lifting:  
230  $1.328 \pm 0.05$  s; lowering:  $1.463 \pm 0.054$  s) and with exoskeleton (lifting:  $1.341 \pm 0.06$  s; lowering:  $1.446$   
231  $\pm 0.065$  s;  $p > 0.357$  in both cases).

232

## 233 4. Discussion

### 234 4.1 Static task

#### 235 4.1.1 Global EMG amplitude and frequency

236 The average RMS was about 10% lower with than without the exoskeleton throughout the static task  
237 (Figure 5A). These findings are in agreement with previous works on Laevo (Bosch et al., 2016; De  
238 Looze et al., 2016; Koopman et al., 2019) and other trunk exoskeletons (Graham et al., 2009).  
239 Additionally, we observed a decrease in RMS in both conditions and a decrease in MNF without the  
240 exoskeleton over time (Figure 5B). The decrement in EMG MNF and RMS in time could be related to  
241 changes in subject posture because of unconscious knee and hip flexion during static bending. It was  
242 reported the load sharing between lumbar active and passive tissues in maintaining a flexed trunk  
243 posture is influenced by lumbar flexion; less lumbar muscle activation is needed when lumbar flexion  
244 increases (Alessa and Ning, 2018; Arjmand and Shirazi-Adl, 2005; McGill, 2002). In any case, the  
245 kinematic changes in time should not affect the observed effect of Exoskeleton on muscle activation  
246 since they were not different between conditions, suggesting eventual changes in back muscle length  
247 over the exertion (and then in the EMG pick up area) should be equal between conditions. The  
248 marginal decrement in RMS during both conditions could originate, alternatively, from another factor  
249 unrelated to muscle activity, i.e., sweat accumulation. We observed few instances of low-quality

250 EMGs in the grid possibly because of subjects' sweating. EMG amplitude may be more sensitive to  
251 the sweat accumulation underneath the electrodes when compared to MNF (Abdoli-Eramaki et al.,  
252 2012). In this case, we could consider the possibility that the decrease of MNF without the exoskeleton  
253 can be an indication of higher muscle fatigue (Figure 5; Cifrek et al., 2009). Thus, our findings seem  
254 to suggest the passive exoskeleton Laevo decreases muscle intensity and delays muscle fatigue at  
255 low back during the static task. The observed exoskeleton reductions in muscle activity (~10%) were  
256 however relatively low when compared to previous studies (Bosch et al., 2016; Koopman et al., 2019),  
257 thus caution should be taken in its effectiveness on the prevention of musculoskeletal disorders.

258

#### 259 4.1.2 The distribution of EMG amplitude

260 Muscle activity shifted more distally (~0.5 cm) with time in both the exoskeleton conditions (Figure  
261 5C). This corroborates a previous study (Tucker et al., 2009) showing a redistribution of muscle  
262 activity during a similar static task with a shift toward the caudal direction. Since lower level of muscle  
263 activity (RMS) was detected with than without exoskeleton (Figure 5A), EMG redistribution maybe not  
264 necessarily associated with muscle intensity when using the exoskeleton but for how long the lumbar  
265 muscles are activated. This is consistent with the notion that the nervous system may rely on the  
266 redistribution of muscle activity to maintain motor output when muscles are exposed to sustained  
267 activation (Farina et al., 2008; Tucker et al., 2009). Extending the observation of Bosh et al. (2016),  
268 current results suggest increases in endurance time (maintenance of the required posture) with the  
269 Laevo exoskeleton depends both on the amplitude and the amplitude redistribution of surface EMGs.  
270 Moreover, methodologically, these results indicate different changes in EMG could be observed  
271 depending on the portion of muscle the EMG is sampled from. It is likely the use of a single pair of  
272 electrodes is among the factors contributing to the highly variable reduction of EMG activity with  
273 exoskeleton reported in literature (from 10 to 60%; Bosch et al., 2016; De Looze et al., 2016; Koopman  
274 et al., 2019). In general, our results seem to show the use of a passive exoskeleton allows the  
275 redistribution of muscle activity with a lower degree of muscle activation during the static task.

276

#### 277 4.2 Dynamic task

##### 278 4.2.1 Global EMG amplitude and frequency

279 Exoskeleton-related differences in muscle activity for the dynamic task were not as clear as for the  
280 static task. A RMS reduction (~5%) was observed with the exoskeleton only at the beginning of lifting  
281 repetitions (upper panel in Figure 7A), corroborating previous findings on marginal Laevo effect on  
282 muscle activity during this task (Baltrush et al., 2019). Such differences in muscle activity however  
283 could be additionally influenced by geometrical factors due to kinematic differences between  
284 conditions (knee angle, Figure 9B; Farina et al., 2006). Nevertheless, the absence of between-  
285 conditions differences in the hip angle (Figure 9A), often associated with the trunk angle during lifting  
286 (Bonato et al., 2002; Falla et al., 2014), suggests exoskeleton-related differences in muscle activity  
287 are the likely explanation for these results. Moreover, MNF did not differ between conditions, though  
288 it changed over time (Figure 7B). The MNF decrease with a concomitant RMS increase observed with  
289 the exoskeleton supports the hypothesis of muscle fatigue, which may be due to the focal overload of  
290 the same muscle region during the whole task (Figure 7C), as discussed below. Similarly, reduced  
291 RMS was observed at the beginning of lowering repetitions with than without the exoskeleton (Figure  
292 8A). From the middle to the end of the task, however, muscle activity seems to increase with the  
293 exoskeleton. These results may derive from the coactivation strategy at the trunk level to overcome  
294 the resistance of the exoskeleton during trunk flexion in the lowering phase. Baltrusch et al. (2019),  
295 for example, observed a significant increase in the activation of abdominal muscles, especially when  
296 lowering with the Laevo exoskeleton. On the contrary, without the exoskeleton, the constant average  
297 EMG amplitude disregards this hypothesis. Thus, our results suggest participants overall did not show  
298 a decrease of low back muscles' activity but, rather, a likely increase in muscle effort with the use of  
299 passive exoskeleton during the whole repetitive task. Here, however, we investigated static and  
300 dynamic tasks performed in a sagittally symmetric posture. Whether current findings generalize to  
301 modern work, where asymmetric postures and trunk rotation are common, require future  
302 investigations.

303

#### 304 4.2.2 The distribution of EMG amplitude

305 Muscle activity tended to redistribute toward lower back regions during the lifting task without the  
306 exoskeleton whereas no changes were observed with the exoskeleton (Figure 7C). This result  
307 corroborates previous work showing caudal EMGs' redistribution following repetitive lifting without any

308 back support (Falla et al., 2014). With the exoskeleton, our findings revealed a constant RMS  
309 distribution over time (Figure 7C). No change in the distribution of muscle activity is often related to  
310 the overload of a specific muscle region, contributing likely to muscle fatigue (Farina et al., 2008; Falla  
311 et al., 2014). Indeed, the RMS increase and concomitant MNF decrease over time (Figure 7), can be  
312 indicative of fatigue of initially recruited motor units (Cifrek et al., 2009). Without the use of the  
313 exoskeleton, the overload of the same muscle region did not occur probably because muscle activity  
314 redistributes across the muscle regions during the task (Figures 6 and 7C). In this case, the influence  
315 of fatigue-induced changes in the trend of EMG variables during the repetitive work (e.g., de-  
316 recruitment of fatigued motor units) may explain the reduction in both RMS and MNF from the middle  
317 of the task (see white circles in Figures 7A-B). Current findings suggest therefore the physiological  
318 adaptation in the neuromuscular system to the repetitive effort (i.e., the redistribution of muscle  
319 activity) did not occur with the exoskeleton, which might be one of the concerns when using this  
320 device.

321

#### 322 4.2.3 Kinematics

323 Another issue regards the movement strategy with the exoskeleton. When considering the knee joint,  
324 a lower knee maximum angle was revealed with than without the exoskeleton (Figure 9B). This is in  
325 line with Baltrush et al. (2019), who observed a trend towards reduced range of knee motion with the  
326 same exoskeleton, probably due to its resistance to movement. Despite a loss of range of knee motion  
327 with the exoskeleton, participants were able to keep a consistent lifting and lowering pace in both  
328 conditions. Thus, since exoskeleton led to kinematics changes, future investigations should focus on  
329 the exoskeleton design to optimize movement strategies.

330

### 331 **5. Conflict of interest statement**

332 There were no known conflicts of interest.

333

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338

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419 **Figure Captions:**

420 **Figure 1:** (A) Simulated working tasks investigated: the static forward bending (left panel) and the  
421 repetitive lifting and lowering task (right panel). Right hip and knee joint angles were collected from  
422 goniometers. For the hip, one of the goniometer arms was placed laterally over the participant's trunk  
423 and the other arm was placed over the lateral midline of participant's femur. On the knee, the  
424 goniometer was mounted laterally on the leg. (B) Positioning of electrode grids on the low back  
425 muscles bilaterally. The lower edge of the 16x4 electrode grids was roughly positioned at L5 level and  
426 ~2 cm laterally from the lumbar spinous process mid-point.

427

428 **Figure 2:** Data analysis for the dynamic task. (A) Identification of lifting (dark grey) and lowering (light  
429 grey) phases from the height of the box during one cycle of the dynamic task. Knee and hip angle are  
430 also showed. (B) Single-differential surface EMGs sampled from the fourth column of the two grids of  
431 electrodes positioned on the left side during one cycle of the dynamic task without the exoskeleton.  
432 EMG epochs corresponding to the lifting and lowering phases are highlighted in the dark and light  
433 grey rectangles respectively. (C) Expanded view of EMGs epochs in (B) during the lifting phase (dark  
434 grey rectangle). Note action potentials do not appear with equally high amplitude in the channels,  
435 indicating an uneven distribution of muscle activity.

436

437 **Figure 3:** Single-differential (SD) surface EMGs and RMS distribution of low back muscles activity  
438 during the repetitive lifting task and without the exoskeleton. Surface EMGs epochs, sampled during  
439 the lifting phase by the electrode on the right side at the beginning (A) and the end (B) of the dynamic  
440 task. (C) Average RMS map (interpolation by a factor 8) computed for the lifting phase at the beginning  
441 (upper panel) and the end (lower panel) of the task. White and black circles respectively indicate the  
442 channels with RMS smaller and higher than the 70% of the maximal RMS value in the map.

443

444 **Figure 4:** (A-B) Single-differential (SD) surface EMGs collected from the electrode grids positioned  
445 on the right side at the end of the static task without (A) and with the passive device (B). Maps of RMS  
446 distribution of low back muscles' activity (interpolation by a factor 8) during the static task without (C)

447 and with the passive exoskeleton (D). Note the redistribution of muscle activity to the caudal direction  
448 toward the end of the task in both conditions.

449

450 **Figure 5:** Mean ( $\pm$ SE) of the electromyographic indices estimated for the start, middle and end of the  
451 static holding with trunk flexion, performed without (white circles) and with (black circles) the passive  
452 exoskeleton. The endurance time of non-exoskeleton condition was used to define the duration of the  
453 contraction for both conditions. The average RMS (A) and average MNF (B) values were normalized  
454 to the highest value obtained between the conditions without and with the exoskeleton. \* indicates a  
455 main effect of Exoskeleton; # indicates a significant interaction between Exoskeleton and Time ( $p <$   
456 0.05).

457

458 **Figure 6:** Maps of RMS distribution (interpolation by a factor 8) of low back muscles' activity at the  
459 start, middle and end of the dynamic task for the lifting (A) and lowering (B) phases without (top) and  
460 with (bottom) the exoskeleton (same subject than Figure 4). Note the redistribution of muscle activity  
461 to the caudal direction toward the end of the task for the condition without exoskeleton in both phases  
462 of the dynamic task.

463

464 **Figure 7:** Time course of electromyographic indices (mean  $\pm$  SE) estimated for the lifting phases of  
465 dynamic task. White circles correspond to mean values without exoskeleton, while black circles  
466 represent mean values with exoskeleton. # indicates significant interaction between Exoskeleton and  
467 Time ( $p < 0.05$ ).

468

469 **Figure 8:** Time course of electromyographic indices (mean  $\pm$  SE) estimated for the lowering phases  
470 of dynamic task. White circles correspond to mean values without exoskeleton, while black circles  
471 represent mean values with exoskeleton. \* indicates a main effect of Exoskeleton; # indicates a  
472 significant interaction between Exoskeleton and Time ( $p < 0.05$ ).

473

474 **Figure 9:** Mean ( $\pm$ SE) of the maximum and minimum hip (A) and knee (B) angle for the start, middle  
475 and end of the lifting and lowering phases of the dynamic task, without (white circles) and with (black

476 circles) the passive exoskeleton. \* indicates a main effect of Exoskeleton; # indicates a significant  
477 interaction between Exoskeleton and Time ( $p < 0.05$ ).