

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

Original

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1 **Title**

2 Changes in the distribution of muscle activity when using a passive trunk exoskeleton depend on the
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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 ± 2.8 years; body mass: 74.5 ± 7.5 kg;
93 height: 178 ± 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 2nd-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 ($\sim 10\%$) was found with exoskeleton
188 ($p<0.005$) and between the beginning and end of the task ($\sim 5\%$; $p=0.001$; 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 ± 13.34 degrees) than at the beginning of the task (9.34 ± 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 ± 3.40 min) than without exoskeleton (6.107
198 ± 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 (~ 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 (~ 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 ± 0.05 s; lowering: 1.463 ± 0.054 s) and with exoskeleton (lifting: 1.341 ± 0.06 s; lowering: 1.446
231 ± 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

339 **7. References**

- 340 Abdoli-E, M., Agnew, M.J., Stevenson, J.M., Abdoli-Eramaki, M., Agnew, M.J., Stevenson, J.M., 2006.
341 An on-body personal lift augmentation device (PLAD) reduces EMG amplitude of erector spinae
342 during lifting tasks. *Clinical Biomechanics* 21, 456–465.
- 343 Abdoli-Eramaki, M., Damecour, C., Christenson, J., Stevenson, J., 2012. The effect of perspiration on
344 the sEMG amplitude and power spectrum. *Journal of Electromyography and Kinesiology* 22, 908–
345 913.
- 346 Alessa, F., Ning, X., 2018. Changes of lumbar posture and tissue loading during static trunk bending.
347 *Human Movement Science* 57, 59–68.
- 348 Amell, T., Kumar, S., 2001. Work-related musculoskeletal disorders: design as a prevention strategy.
349 a review. *Journal of Occupational Rehabilitation* 11, 255–65.
- 350 Arjmand, N., Shirazi-Adl, A., 2005. Biomechanics of changes in lumbar posture in static lifting. *Spine*
351 30, 2637–48.
- 352 Baltrusch, S.J., van Dieën, J.H., Bruijn, S.M., Koopman, A.S., van Bennekom, C.A.M., Houdijk, H.,
353 2019. The effect of a passive trunk exoskeleton on metabolic costs during lifting and walking.
354 *Ergonomics* 62, 903–916.
- 355 Bonato, P., Boissy, P., Della Croce, U., Roy, S.H., 2002. Changes in the surface EMG signal and the
356 biomechanics of motion during a repetitive lifting task. *IEEE Transactions on Neural Systems and*
357 *Rehabilitation Engineering* 10, 38–47.
- 358 Bosch, T., van Eck, J., Knitel, K., de Looze, M., 2016. The effects of a passive exoskeleton on muscle
359 activity, discomfort and endurance time in forward bending work. *Applied Ergonomics* 54, 212–217.
- 360 Buckle, P.W., Jason Devereux, J., 2002. The nature of work-related neck and upper limb
361 musculoskeletal disorders. *Applied Ergonomics* 33, 207–217.
- 362 Carayon, P., Smith, M.J., Haims, M.C., 1999. Work Organization, Job Stress, and Work-Related
363 Musculoskeletal Disorders. *Human Factors: The Journal of the Human Factors and Ergonomics*

364 Society 41, 644–663.

365 Cerone, G.L., Botter, A., Gazzoni, M., 2019. A Modular, Smart, and Wearable System for High Density
366 sEMG Detection. *IEEE Transactions on Biomedical Engineering* 66, 3371–3380.

367 Cifrek, M., Medved, V., Tonković, S., Ostojić, S., 2009. Surface EMG based muscle fatigue evaluation
368 in biomechanics. *Clinical Biomechanics* 24, 327–340.

369 De Looze, M.P., Bosch, T., Krause, F., Stadler, K.S., O'sullivan, L.W., 2016. Exoskeletons for
370 industrial application and their potential effects on physical work load. *Ergonomics* 59, 671–681.

371 Elders, L.A.M., Heinrich, J., Burdorf, A., 2003. Risk Factors for Sickness Absence Because of Low
372 Back Pain Among Scaffolders. *Spine* 28, 1340–1346.

373 Falla, D., Gizzi, L., Tschapek, M., Erlenwein, J., Petzke, F., 2014. Reduced task-induced variations in
374 the distribution of activity across back muscle regions in individuals with low back pain. *Pain* 155,
375 944–953.

376 Falla, D., Jull, G., Russell, T., Vicenzino, B., Hodges, P., 2007. Effect of Neck Exercise on Sitting
377 Posture in Patients With Chronic Neck Pain. *Physical Therapy* 87, 408–417.

378 Farina, D., Leclerc, F., Arendt-Nielsen, L., Buttelli, O., Madeleine, P., 2008. The change in spatial
379 distribution of upper trapezius muscle activity is correlated to contraction duration. *Journal of*
380 *Electromyography and Kinesiology* 18, 16–25.

381 Graham, R.B., Agnew, M.J., Stevenson, J.M., 2009. Effectiveness of an on-body lifting aid at reducing
382 low back physical demands during an automotive assembly task: Assessment of EMG response and
383 user acceptability. *Applied Ergonomics* 40, 936–942.

384 Hartvigsen, J., Hancock, M.J., Kongsted, A., Louw, Q., Ferreira, M.L., Genevay, S., Hoy, D.,
385 Karppinen, J., Pransky, G., Sieper, J., Smeets, R.J., Underwood, M., Buchbinder, R., Hartvigsen, J.,
386 Cherkin, D., Foster, N.E., Maher, C.G., Underwood, M., van Tulder, M., Anema, J.R., Chou, R.,
387 Cohen, S.P., Menezes Costa, L., Croft, P., Ferreira, M., Ferreira, P.H., Fritz, J.M., Genevay, S., Gross,
388 D.P., Hancock, M.J., Hoy, D., Karppinen, J., Koes, B.W., Kongsted, A., Louw, Q., Öberg, B., Peul,
389 W.C., Pransky, G., Schoene, M., Sieper, J., Smeets, R.J., Turner, J.A., Woolf, A., 2018. What low
390 back pain is and why we need to pay attention. *The Lancet* 391, 2356–2367.

391 Holtermann, A., Søgaard, K., Christensen, H., Dahl, B., Blangsted, A.K., 2008. The influence of
392 biofeedback training on trapezius activity and rest during occupational computer work: a randomized

393 controlled trial. *European Journal of Applied Physiology* 104, 983–989.

394 Koopman, A.S., Kingma, I., Faber, G.S., de Looze, M.P., van Dieën, J.H., 2019. Effects of a passive
395 exoskeleton on the mechanical loading of the low back in static holding tasks. *Journal of*
396 *Biomechanics* 83, 97–103.

397 McGill, S., 2002. *Low back disorders: evidence-based prevention and rehabilitation*, First. ed. Human
398 Kinetics.

399 Merletti, R., Farina, D., Gazzoni, M., 2003. The linear electrode array: a useful tool with many
400 applications. *Journal of Electromyography and Kinesiology* 13, 37–47.

401 Neumann, W.P., Kihlberg, S., Medbo, P., Mathiassen, S.E., Winkel, J., 2002. A case study evaluating
402 the ergonomic and productivity impacts of partial automation strategies in the electronics industry.
403 *International Journal of Production Research* 40, 4059–4075.

404 Punnett, L., Fine, L.J., Keyserling, W., Herrin, G., Chaffin, D., 1991. Back disorders and nonneutral
405 trunk postures of automobile assembly workers. *Scandinavian Journal of Work, Environment & Health*
406 17, 337–346.

407 Roquelaure, Y., 2018. *Musculoskeletal Disorders and Psychosocial Factors at Work*. ETUI Research
408 Paper- Report 142.

409 Tucker, K., Falla, D., Graven-Nielsen, T., Farina, D., 2009. Electromyographic mapping of the erector
410 spinae muscle with varying load and during sustained contraction. *Journal of Electromyography and*
411 *Kinesiology* 19, 373–379.

412 Vieira, T.M.M., Merletti, R., Mesin, L., 2010. Automatic segmentation of surface EMG images:
413 Improving the estimation of neuromuscular activity. *Journal of Biomechanics* 43, 2149–2158.

414 Wickström, G., Pentti, J., 1998. Occupational factors affecting sick leave attributed to low back pain.
415 *Scandinavian Journal of Work, Environment & Health* 24, 145–152.

416 Zare, M., Bodin, J., Cercier, E., Brunet, R., Roquelaure, Y., 2015. Evaluation of ergonomic approach
417 and musculoskeletal disorders in two different organizations in a truck assembly plant. *International*
418 *Journal of Industrial Ergonomics* 50, 34–42.

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 ($p < 0.05$).