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Occupational Exoskeletons: Overview of Their Benefits and Limitations in Preventing Work-Related Musculoskeletal Disorders

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1 Title

2 Occupational Exoskeletons: Overview of their Benefits and Limitations in Preventing Work-related
3 Musculoskeletal Disorders

4 Authors : **Jean Theurel & Kevin Desbrosses**

5 Occupational Applications

6 There is a growing interest in industry towards the use of occupational exoskeletons, with claimed
7 efficiency in reducing physical workload at work. In this paper, we review existing evidence regarding
8 the benefits and risks of using these technologies to attenuate the injury mechanisms for occupational
9 musculoskeletal disorders (MSDs). More specifically, we focus on the underlying mechanisms of low
10 back pain and shoulder tendinopathies, since these are the conditions targeted by the current use of
11 exoskeletons for industrial application. While the potential for occupational exoskeletons to attenuate
12 muscular demand in the back or upper limbs appears fairly promising, we conclude that the current state
13 of knowledge does not allow for an unreserved endorsement of the use of these technologies for the
14 prevention of MSD. Unwanted consequences of using exoskeletons during handling tasks were also
15 discussed here, such as postural strains and modified kinematics. Several gaps in current knowledge are
16 also highlighted, notably related of the impacts of physical assistance on neuromuscular coordination
17 and joint movements, the occurrence of muscle fatigue, and chronic physiological adaptations.

18

19 Abstract

20 **Background:** To address the prevalence of work-related musculoskeletal disorders (MSDs) in
21 physically demanding tasks, research is now focusing on new approaches, such as the use of
22 exoskeletons. **Purpose:** Based on the available evidence underlying the claimed efficiency of
23 occupational exoskeletons in reducing biomechanical strains at work, the aim of this paper is to relate
24 the claimed effectiveness of exoskeletons at reducing muscle demand to the pathophysiological
25 mechanisms underlying MSDs. A further aim is to analyse the literature to highlight the main
26 deficiencies in current knowledge, in order to guide the research necessary to develop future generations
27 of exoskeletons. **Methods:** A narrative review was completed, based on an electronic literature search,
28 considering occupational applications of exoskeletons from January 1980 to January 2019. **Results:**

29 Thirty articles, each of which evaluated the effects of occupational exoskeletons on the physical
30 workload, were considered relevant to discuss with respect to the pathophysiological origins of MSDs.
31 We found 22 studies that were directly related to back assistive exoskeletons. Studies mainly focused
32 on back muscle activity, but additional factors contributing to low back pain are also considered (muscle
33 fatigue, spine loading, perceived pain, and posture). Eight papers were directly related to upper limb
34 exoskeletons. **Conclusion:** Within the scope of the specific task for which exoskeleton use has been
35 designed, exoskeletons have been found to have clear potential in limiting local muscular demand.
36 However, the current state of knowledge does not support an unreserved endorsement for using these
37 technologies for MSD prevention. Additional research is needed to better understand posture and
38 movement control mechanisms, when the postural and/or upper limb muscular chains are assisted. The
39 impacts of movement assistance on neuromuscular coordination and joints kinematics also need to be
40 clarified. Several questions remain also to be examined, in particularly including the occurrence of
41 muscle fatigue and chronic adaptations.

42

43 Keywords

44 Assistive devices, Low back pain, Shoulder tendinopathy, Wearable robots, Workload.

45 1 - **INTRODUCTION**

46 Occupational manual handling activities expose individuals to considerable biomechanical strains
47 and increased risks of musculoskeletal disorders (MSDs) (Ayoub, 1982; Rempel, 1992; Straker, 1999;
48 Cole & Grimshaw, 2003). Despite the development of modern technology, many tasks still require
49 manual handling, resulting in the fact that more than 40% of workers in the European Union continue to
50 suffer from back and shoulder pains (Eurofound, 2012). Many researchers and practitioners are now
51 focusing on new approaches, such as the use of exoskeletons (de Looze et al., 2016).

52 Defined as wearable, mechanical structures that enhance the physical capacity of a person,
53 occupational exoskeletons are designed to physically assist workers in performing their tasks, and thus
54 reduce their exposure to associated physical demands (de Looze et al., 2016). Exoskeletons are typically
55 classified as passive, using spring/elastic materials, or active, using one or more actuators (de Looze et
56 al., 2016). Exoskeletons have also been categorized by the body part they are designed to support, such
57 as the upper-body, lower-body, or full-body (Lee et al., 2012). But the most common applications are
58 back-support exoskeletons (EXO_{BK}, Figure 1), that have been designed to prevent low back pain (LBP:
59 *e.g.* Huysamen et al. (2018b)), and upper limb exoskeletons (EXO_{UL}, Figure 2), that have been designed
60 to prevent shoulder MSDs (*e.g.* Huysamen et al. (2018a)). In their earlier systematic review, de Looze
61 et al. (2016) listed the main items of evidence of the effectiveness of using occupational exoskeletons in
62 reducing local muscular demand. More precisely, EXO_{BK} primarily reduce the efforts of hip extensor
63 and spine extensor muscles during tasks involving forward bending (*e.g.* Bosch et al. (2016); Huysamen
64 et al. (2018b)), while EXO_{UL} mainly reduces the efforts of shoulder muscles associated with lifting the
65 arms (*e.g.* Rashedi et al. (2014); Kim et al. (2018a); Theurel et al. (2018)).

66 Although excessive muscular stress are considered predominant risk factors for the occurrence of
67 LBP (Burdorf & Sorock, 1997; Hoogendoorn et al., 1999; Dreistadt et al., 2016), and shoulder MSDs
68 (Frost et al., 2002; Miranda et al., 2005; Silverstein et al., 2008; van Rijn et al., 2010; Roquelaure et al.,
69 2011), muscle activity should not be the only factor taken into account in preventing musculoskeletal
70 injuries. For example, back muscle fatigue (Hoogendoorn et al., 2002), spine loading (Burdorf &
71 Sorock, 1997), and the intensity of perceived pain at the end of a working day (Reenen et al., 2008) are

72 also recognised as important risks factors for the occurrence of LBP. Concerning the pathological origin
73 of shoulder tendinopathies, in most cases these are due to contact between tendons and the boneligament
74 arch of the acromion, specifically impingement syndrome (Hebert et al., 2002; Bey et al., 2007).
75 Although reducing the forces exerted by the shoulder flexor muscles can effectively limit the closure of
76 the subacromial space (Bey et al., 2007), perfect coordination and synchronisation of the agonist and
77 antagonist muscles is required to ensure an optimal and healthy kinematics of the joint (Hebert et al.,
78 2002; Bey et al., 2007). In addition, unwanted physiological consequences were also observed when
79 using EXO_{BK} or EXO_{UL} (de Looze et al., 2016), which might contribute to new biomechanical strains

80 Consequently, the real impact of using exoskeletons on the risks of MSDs remains, to a large extent,
81 unknown. To our knowledge, there is a lack of longitudinal studies addressing this issue. Given the
82 accelerated transformation of the occupational world, and the growing implementation of exoskeleton
83 technologies, we believe it is essential to anticipate, to the extent possible, the impacts of using
84 exoskeletons on the health and safety of workers. In this context, the present work draws on the latest
85 publications providing new perspectives on occupational exoskeletons. The main purpose of our report
86 is to relate the claimed effectiveness of exoskeletons at reducing muscle demand to the
87 pathophysiological mechanisms underlying those MSDs that exoskeleton designers intend to prevent by
88 using these technologies. A further aim of this narrative review is to highlight the main gaps in current
89 knowledge in order to guide the research necessary to develop future generations of EXO.

90

91 *Insert figure 1*

92 *Insert figure 2*

93 **2 - METHODS**

94 This narrative overview (Green et al., 2006) was based on electronic and personal database searches.
95 First, a literature analysis from the MEDLINE database was performed using the terms: “exoskeleton”
96 and “assistive device”, and “work” or “occupational” from January 1980 to January 2019. To be
97 included, articles had to be published in peer-reviewed journals and present physiological results relating

98 to the use of exoskeletons intended for occupational activities. More precisely, articles had to address
99 potential risks reduction of exoskeletons, based on the pathophysiological mechanism underlying MSDs
100 in the back and shoulder region. The literature retrieved in this way was supplemented with relevant
101 studies cited in the articles identified. Papers considering other applications, outside occupational
102 settings, and exoskeletons covering the hands or lower limbs, were excluded from our review.

103 **3 - RESULTS AND DISCUSSION**

104 Among the publications evaluating the effects of occupational exoskeletons on the physical
105 workload, 30 articles, of which 13 were published since 2018, were considered relevant in terms of
106 relating to the pathophysiological mechanisms underlying MSDs. In the subsequent material, we
107 summarize the evidence in these articles, separately for exoskeletons designed for the back and upper
108 limbs.

109 **3.1. Advantages and limitations of EXO_{BK} in preventing LBP**

110 We found 22 studies that were directly related to EXO_{BK}. Eleven EXO_{BK} models were examined in
111 the studies retrieved, of which five were passive and four were active (table 1). Twenty studies were
112 laboratory experiments, whereas only two studies investigated the use of exoskeletons in real work
113 conditions. If most of the previous studies focused on the consequences of using an EXO_{BK} on back
114 muscle activity, some studies also considered additional factors contributing to the occurrence of LBP,
115 such as lumbar muscle fatigue ($n=5$), spine loading ($n=6$), perceived pain ($n=4$), and posture ($n=4$).

116

117

Insert table 1

118

Consequences of using EXO_{BK} on back muscle activity

119

120

Excessive and/or repeated stress on the back muscles are considered to be important risk factors in
the occurrence of LBP (Burdorf & Sorock, 1997; Hoogendoorn et al., 1999; Dreistatdt et al., 2016). The

121 recent literature agrees on the effectiveness of passive EXO_{BK} devices to reduce lumbar muscular
122 demand during handling operations involving trunk flexion/extension in the sagittal plane. It seems that
123 Ulrey and Fathallah (2013b) were alone in not reporting significant reductions in erector spinae muscular
124 activity using an EXO_{BK} (BNDR; table1) during a static forward bending task. During laboratory studies,
125 the reductions in back muscles activity were 10-44% in handling tasks (Frost et al.,
126 2009), and from 10% (Ulrey & Fathallah, 2013a) to 57% (Koopman et al., 2019) in static postures.
127 Research carried out in real work conditions has also revealed significant reductions (20-25%) in spinal
128 muscular activity when using a passive EXO_{BK} during an online assembly process requiring forward
129 bending and static holding in the car manufacturing sector (Graham et al., 2009). In addition to spinal
130 muscles activity, significant reductions in the activity of hip extensor muscles (biceps femoris muscle, -
131 24%) and neck muscles (trapezius muscle, -50%) were also observed when using a passive EXO_{BK}
132 during laboratory-based static bending tasks (Bosch et al., 2016). The latter study suggests that a large
133 muscular chain (hip, lumbar, dorsal and cervical) could benefit from using an EXO_{BK}. Finally, regarding
134 the back muscle activity, it seems that Ulrey and Fathallah (2013b) were alone in not reporting
135 significant effectiveness of using an EXO_{BK} (BNDR; table1) during a forward bending task. The
136 considerable disparities in the protocols of previous studies – including population, task modalities,
137 postures adopted (*i.e.* trunk inclination), and exoskeleton designs – likely account for the substantial
138 differences in the magnitude of observed reductions in back muscle activity when using these systems.
139 Three sources of variability seem to be of particularly importance.

140 First, the benefits obtained from EXO_{BK} regarding back muscle activity appear to be dependent on
141 the posture adopted (*i.e.* trunk inclination) during the experimental tasks. In the study by Lamers et al.
142 (2018), the reductions in back muscle activity observed with a passive custom-made EXO_{BK} (table 1)
143 varied from 23 to 43% for the leaning tasks, respectively performed at 30° and 90° (with a 4 kg load).
144 In the study by Koopman et al. (2019), the reductions in back muscle activity observed during static
145 bending tasks with a passive EXO_{BK} (Laevo V2) varied from 11 to 57%, depending on the experimental
146 postures (five different hand heights). Moreover, the relationships between the amplitude of muscle
147 activity reduction and the trunk posture were highly variable across subjects, probably as a function of
148 individual kinematics and/or anthropometric characteristics (Zhang et al., 2016; Koopman et al., 2019).

149 Second, the mass of the load handled may also affect the relative effects of using a passive
150 exoskeleton. EXO_{BK} were indeed designed to target different ranges of masses, notably according to the
151 assistive torque they are able to deliver. At a constant stiffness, the relative effectiveness of using these
152 devices during trunk bending tasks reach a limit as the mass of handled loads increases. For example,
153 Abdoli et al. (2006) noted that the reduction in EMG activity of the erector spinae muscles with an
154 EXO_{BK} (PLAD) was ~14% when handling a 5 kg load, though this reduction was only 7% for a 25 kg
155 load. In contrast, by using a custom made EXO_{BK} (table 1) Lamers et al. (2018) recently reported that
156 the relative reduction in back muscle activity was similar when lifting a 24 kg load (-16%), than a 13 kg
157 load (-14%). To facilitate the comparison of the studies evaluating the effects of using EXO_{BK}, it appears
158 necessary that future testing should be done within the designed masses range of exoskeletons, if the
159 manufacturers indicated it.

160 EXO_{BK} design, and particularly its mechanical characteristics (*e.g.* PLAD, Laevo V1 and V2, and
161 BNDR; table 1) is probably the third important source of variability in the magnitude of muscular activity
162 reductions. There is little information available on this issue. To our knowledge, only Frost et al. (2009)
163 have considered this influence, by gradually increasing the mechanical stiffness of the PLAD during
164 different handling sessions. They demonstrated a positive relationship between device stiffness and the
165 relative magnitude of lumbar muscular activity reduction compared with a control condition. However,
166 an excessive stiffness (assistive torque) of the EXO_{BK} may lead to an increase in trunk flexor muscle
167 activity during the trunk bending phase (*i.e.* tensioning of the system). This could prove to be
168 counterproductive from the standpoint of LBP prevention, affecting the balance of forces and hence the
169 stability of the spine (Adams et al., 2002). The main challenge posed by stiffness optimisation in the
170 context of LBP prevention should be effectively matching the physical assistance delivered and the
171 mechanical strains induced by the tasks (posture, load handled, anthropometric characteristics). The
172 results of previous studies are not consistent in this point. Koopman et al. (2019) recently reported an
173 increase of 2 - 6% in abdominal muscle activity when using an EXO_{BK} (Laevo V2, table 1) during static
174 bending tasks., while the use of the PLAD (table 1) did not result in any significant changes in the EMG
175 activity of the abdominal muscles during handling tasks (Abdoli et al., 2006; Abdoli & Stevenson, 2008;
176 Whitfield et al., 2014). In the absence of clear consensus, additional research appears necessary, though,

177 to determine practical recommendations for using and adjusting passive EXO_{BK} at work. The impacts
178 of exoskeleton design, load, and posture need to be considered in particular.

179 On the other hand, studies that have evaluated active EXO_{BK} have found more consistent results, in
180 that the use of these technologies caused significant reductions in back muscle activity during trunk
181 bending tasks, from -10% (Ko et al., 2018) to -60% (Kobayashi & Nozaki, 2008). Some of these studies
182 (Kobayashi & Nozaki, 2008; Kobayashi et al., 2009) indicated large reductions (30 to 60%) in the
183 activity of erector spinae muscles when using a Muscle Suit (table 1). Recently, Huysamen et al. (2018b)
184 reported more moderate reductions in erector spinae muscle activity (12-15 %) when using a Robomate®
185 (table 1) during sagittal plane lifting tasks. Moreover, and contrary to passive EXO_{BK}, active devices
186 may be capable of generating higher levels of torque to assist with straightening the body without
187 increasing the work of the antagonist muscles. For example, during a load lifting task in the laboratory,
188 Ko et al. (2018) also reported significant reductions in back muscle activity (10-30%) when using a H-
189 Wex (table 1), while no significant differences in the activity of antagonist muscles (rectus abdominis)
190 were found.

191 Consequences of using EXO_{BK} on back muscle fatigue

192 Work tasks generating back muscle fatigue can result in the development of chronic LBP
193 (Hoogendoorn et al., 2002). Regarding the impact of EXO_{BK} on muscle fatigue, no clear consensus was
194 evident in the literature. In laboratory studies, signs of reduced back muscle fatigue were generally
195 observed during prolonged bending tasks using an EXO_{BK} (Godwin et al., 2009; Lotz et al., 2009; Bosch
196 et al., 2016), although this reduction was not verified in a field study (Dewi & Komatsuzaki, 2018).
197 Laboratory studies on active and passive EXO_{BK} have demonstrated the potential for these systems to
198 limit the development of back muscle fatigue during prolonged tasks. For example, Bosch et al. (2016)
199 reported an increase of endurance time (x 3) when using a passive EXO_{BK} (Laevo V1) during a static
200 forward bending task in laboratory conditions. Similar results have recently been reported with an active
201 EXO_{BK} (HAL) during repetitive stoop lifting movements of a 12 kg box (Miura et al., 2018). When using
202 an exoskeleton, the latter authors found an increase in lifting performance, as indicated by an increase
203 in the maximum number of lifts (+45%) and lifting time (+44%), and a reduction in perceived lumbar

204 muscle fatigue (-26%). Other studies have identified a reduction in the occurrence of back muscle fatigue
205 by analyzing the EMG spectrum of the erector spinae muscles (Godwin et al., 2009; Lotz et al., 2009).
206 They demonstrated that the use of a passive EXO_{BK} (PLAD) during a 45 minutes repeated lifting task
207 led to a significant reduction in back muscle fatigue. Godwin et al. (2009) also found evidence for a
208 reduction in muscle fatigue, as indicated by a lesser reduction in the maximal voluntary torque generated
209 by the back extensor muscles after using an EXO_{BK} compared to a control condition. In simulated
210 farming tasks, however, Dewi and Komatsuzaki (2018) did not observe any effect of using a passive
211 EXO_{BK} (PAS) on digging performance (m³/min).

212 The disparities in exoskeletons designs, as well as in the nature, intensity, and duration of the tasks
213 investigated, make comparisons between previous studies difficult. Moreover, to our knowledge, there
214 is no published work regarding the impact of EXO_{BK} on fatigue caused by a work task longer than 2
215 hours. In future studies, it would therefore be interesting to compare the occurrence of back muscle
216 fatigue during a whole working day (4 to 8 hours) of handling, both with and without assistance.
217 Evaluating variations in the motor capacity of these muscles over a week or more would also be relevant
218 for simulating realistic occupational use conditions. At present, it is not obvious that using EXO_{BK} limits
219 back muscle fatigue in real working conditions, or that this use limits the risks of LBP occurrence.

220 Consequences of using EXO_{BK} on spine loading

221 Substantial levels of lumbar disc compression can occur with high levels of contraction required by
222 the back muscles, thereby increasing the risk of injuries and pain in the lumbar region (Burdorf & Sorock,
223 1997). Moreover a lack of spinal stability can also result in the unsuccessful transmission of compressive
224 and shear forces, thereby increasing injury risk (Cholewicki & McGill, 1996). Regarding PLAD,
225 previous reports are consistent that the use of EXO_{BK} may be efficient to reduce internal compressive
226 forces on the lumbar vertebrae during handling tasks (Abdoli et al., 2006; Graham et al., 2009; Ulrey &
227 Fathallah, 2013b). For example, biomechanical evaluations conducted in previous studies (Graham et
228 al., 2009; Ulrey & Fathallah, 2013b) showed that using a PLAD (table 1) in manual handling activity
229 involving trunk bending could result in a 23-29% reduction in compressive forces on the lumbar
230 vertebrae. More recently, Koopman et al. (2019) revealed that the L5/S1 moments generated by static

231 bending at five different hand heights were also significantly reduced (15-20%) by using a Laevo V2
232 (table 1). In the study by Lamers et al. (2018), model predictions, based on a simple moment balance,
233 indicated that offloading the low back muscles with their custom-made EXO_{BK} (table 1) was expected
234 to reduce intervertebral disc compression force. In addition, during repetitive lifting, Graham et al.
235 (2011) even estimated that the local dynamic stability of the lumbar spine was increased by the use of
236 PLAD. Kinematic analyses showed that the decrease in back muscle activity recorded when using the
237 PLAD was due mainly to a reduction of trunk rotation (-24%) and lateral flexion (-30%) (Abdoli &
238 Stevenson, 2008). Thus, it appears that EXO_{BK} can provide a real benefit in preventing back injury risks.
239 Further studies with other models of passive and active EXO_{BK}, however, are nevertheless needed to
240 confirm these results.

241 Consequences of using EXO_{BK} on perceived efforts

242 The intensity of perceived LBP at the end of a working day is recognised as a risk factor in the
243 occurrence of low back disorders (Reenen et al., 2008). Nociceptive feedback from lumbar regions
244 during postural activity appears to cause increased stiffness in the muscles involved (Clarke & Harris,
245 2004), a phenomenon that aggravates LBP (Hoogendoorn et al., 2002). Furthermore, LBP usually causes
246 individuals to adopt antalgic postures, which may be harmful to static balance (Nies & Sinnott, 1991).
247 For example, the postural oscillations recorded during quiet stance are generally greater in patients with
248 LBP than those in healthy subjects (Hamaoui et al., 2002).

249 Previous studies have reported significant reductions in perceived efforts in the back when wearing
250 an EXO_{BK} during forward bending tasks. This is a consistent outcome, in studies of both active
251 (Robomate (Huysamen et al., 2018b)) and passive (PLAD (Graham et al., 2009); Laevo V1 (Baltrusch
252 et al., 2018)) device, whether the experimental task was static (Graham et al., 2009; Baltrusch et al.,
253 2018) or dynamic (Huysamen et al., 2018b), and whether the task duration was a few minutes (Baltrusch
254 et al., 2018; Huysamen et al., 2018b) or nearly 2 hours (Graham et al., 2009). These findings were
255 reinforced by those of Bosch et al. (2016), who reported a significant increase (+200%) in the effort time
256 before pain developed, when using a passive exoskeleton (Laevo V1) during a static bending task. It
257 thus appears that there is a convergence of evidence supporting that using an EXO_{BK} reduces

258 perceived back efforts during handling tasks, and thus potential benefits for preventing LBP can be
259 expected.

260 Consequences of using EXO_{BK} on posture

261 Although limited, previous studies that investigated the impact of using EXO_{BK} on postural
262 adaptations have reported slight changes in the postures adopted by users. For example, Bosch et al.
263 (2016) observed a significant hyper-extension of the knees among operators wearing a passive EXO_{BK}
264 (Laevo V1) when they bent forward. Abdoli et al. (2006) found a significant increase in plantar flexion
265 (+5.5%) when using a passive EXO_{BK} (PLAD) during a static task (*i.e.* 30° trunk flexion in the sagittal
266 plane). In the study by Sadler et al. (2011), movement analyses also indicated that using a PLAD affected
267 the lifting kinematics, demonstrating less lumbar and thoracic flexion and significantly greater hip and
268 ankle flexion.

269 Although these studies suggest that wearing an EXO_{BK} induces changes in postural strategies, a large
270 number of issues remain to be clarified. For example, we suggest that it is essential to examine the
271 impacts of using active and passive EXO_{BK} on the muscle activity of the whole postural chain (*i.e.* all
272 the synergist muscles working to maintain postural balance). By way of comparison, antalgic postures
273 adopted by patients with LBP generally impact the entire postural chain due to insufficient knee
274 extension (Nies & Sinnott, 1991). Greater activation of the erector spine muscles can thus be observed
275 during walking (Arendt-Nielsen et al., 1996; Mok et al., 2004). Future research therefore seems
276 necessary to ensure that wearing an EXO_{BK} does not involve major risks for the integrity of the postural
277 chain.

278 Summary and prospects

279 Existing evidence tends to confirm the potential benefit of EXO_{BK} use for preventing LBP. These
280 devices could significantly curtail spinal muscular effort and its associated pain, not only during load
281 handling tasks involving trunk flexion/extension movements, but also for work activities involving static
282 bending postures. In both situations, however, our analysis of extant experimental results suggests that
283 particular attention should be given to the influence of the mechanical characteristics of physical

284 assistive devices (passive exoskeletons). Using this type of exoskeleton could lead to antagonist muscle
285 compensations and/or spinal imbalance, which could, counterproductively, increase the risk of LBP.
286 Consequences of changes in postural strategies also need to be clarified, as such changes have been
287 observed previously at different stages of the kinematic chain (*e.g.* ankle (Abdoli et al., 2006; Sadler et
288 al., 2011), knee (Bosch et al., 2016), hip and trunk (Sadler et al., 2011)). Finally, the impact of these
289 technologies on the occurrence of spinal muscle fatigue must also be clarified, in particular during
290 prolonged bending posture and handling tasks exceeding 2 hours.

291 In future work, we suggest it is necessary to extend previous research to other work situations. To
292 date, the tasks studied involving trunk flexion/extension did not reflect the variety and complexity of
293 real work situations. In addition to the joints directly assisted by the exoskeleton, it would be interesting
294 to acquire wider knowledge of the muscular and kinematic consequences of using this type of
295 technology. There is also little existing information on the muscular activity of the whole postural chain,
296 including the upper limb chain, when performing a work task using an EXO_{BK}. Furthermore, existing
297 evidence also leaves many open questions concerning postural adaptations induced by the use of this
298 type of exoskeleton, and which should be investigated: What is the impact of the design and mechanical
299 characteristics of an EXO_{BK} on the magnitude of postural adaptations? What are the consequences of
300 changes in postural strategy on the muscles or joints? Do these devices have an impact on the adjustment
301 and maintenance of static and dynamic postural balance?

302 **3.2. Advantages and limits of EXO_{UL} in preventing upper limb musculoskeletal disorders** 303 **(UL MSDs)**

304 Eight papers were found that were directly related to EXO_{UL}, all of which were laboratory
305 experiments. One study concerned active exoskeletons (Sylla et al., 2014), while the remaining ones
306 focused on passive exoskeletons. Knowing that excessive forces applied by the shoulder flexor muscles
307 are involved in pain development (Cote & Bement, 2010), joint disorders (Marras et al., 2006) and soft
308 tissue injuries (Stauber, 2004) at the shoulder, previous studies usually evaluated the consequences of
309 using an EXO_{UL} on the deltoid muscles activity. Most also considered additional unwanted effects of

310 EXO_{UL} on subjective perception, back muscles demand and postural control. Finally, most of these
311 studies ($n=7$) focused on experimental tasks requiring the arms to be lifted above the head. We found
312 only one study that evaluated EXO_{UL} during lifting/lowering tasks (Theurel et al., 2018).

313

314

Insert table 2

315 Consequences of using EXO_{UL} on shoulder muscle efforts

316 Previous studies are consistent in demonstrating the effectiveness of EXO_{UL} in limiting shoulder
317 flexor muscles activity (Rashedi et al., 2014; Huysamen et al., 2018a; Kim et al., 2018a; Alabdulkarim
318 & Nussbaum, 2019) and localized perceived effort (Rashedi et al., 2014; Alabdulkarim & Nussbaum,
319 2019), which thus argues in favor of the potential for EXO_{UL} in preventing shoulder MSDs. For example,
320 Kim et al. (2018a) reported a significant reduction in shoulder muscle activity during simulated drilling
321 and light assembly tasks using a passive EXO_{UL} (EksoVest). Huysamen et al. (2018a) and Alabdulkarim
322 and Nussbaum (2019) reported similar results, specifically reductions of the activation of deltoid
323 muscles and biceps brachii muscles, respectively using a custom EXO_{UL} (table 2) and a WADE (table
324 2) during overhead works (OHW; i.e., tasks requiring to maintain the arms above the head). Theurel et
325 al. (2018) also reported similar results during dynamic handling tasks, mobilising the shoulders over a
326 greater range of motion (*i.e.* lifting and lowering). These latter authors reported a significant reduction
327 in the EMG activity of the anterior deltoid muscles (-50%) when using a bilateral passive EXO_{UL}
328 (Exhauss Stronger; table 2).

329 The specific reduction in shoulder muscle activity during OHW using EXO_{UL}, though, seems to
330 depend on the tool mass handled. For example, Rashedi et al. (2014) assessed a custom-made unilateral
331 passive EXO_{UL} (WADE; table 2) during a simulated OHW assembly task with three tool masses (1, 3,
332 and 8 kg). Reductions of shoulder muscle activity indeed depended on the loads handled, being
333 nonsignificant with 1kg, -34% with 3 kg, and -45% with 8 kg. Moreover, it appears that the reduction of
334 shoulder muscle activity during OHW when using a passive EXO_{UL} depends on the exoskeleton design.
335 Alabdulkarim and Nussbaum (2019) compared the influence of two passive EXO_{UL}. The first was a
336 custom-made exoskeleton (WADE; table 2). The other was the ShoulderX which primarily provides

337 shoulder support. Only the ShoulderX model significantly reduced shoulder muscle activity during
338 OHW.

339 Although using passive EXO_{UL} during handling tasks seems effective for reducing shoulder muscle
340 demand, it could have unexpected consequences on the coordination between the agonist and antagonist
341 muscles. For example, in the study by Theurel et al. (2018), using an Exhauss Stronger (table 2) during
342 a load lifting/lowering task led to a significant increase in the activity of the triceps brachii muscle, which
343 is antagonist to the assisted movement. In addition, the impact of EXO_{UL} does not seem to be uniform
344 among the muscles mobilising the shoulder during an OHW task. In the study by Rashedi et al. (2014),
345 the activity of the medial deltoid muscle was not significantly affected by using the EXO_{UL}, contrary to
346 the activity of the anterior deltoid muscle, and the activity of the triceps brachii muscle was only reduced
347 during the task involving an 8 kg tool.

348 In order to prevent MSDs, it therefore appears essential to conduct further studies to ensure that the
349 use of EXO_{UL} does not lead to negative consequences on the functional behaviour of the shoulder.
350 Coordination and synchronisation of the agonist and antagonist muscles is indeed required to limit the
351 risks of impingement syndrome (Bey et al., 2007). Future studies should thus include EMG, kinematics
352 analyses, and ultrasound imagery (McCreesh et al., 2013), and test different levels of assistance during
353 a task mobilising the shoulder.

354

355 Consequences of using EXO_{UL} on perceived efforts

356 Previous studies have reported significant reductions in perceived efforts or discomfort in the upper
357 limb when wearing an EXO_{UL} during OHW (Rashedi et al., 2014; Huysamen et al., 2018a; Kim et al.,
358 2018b; Alabdulkarim & Nussbaum, 2019) or during load carrying tasks (Theurel et al., 2018). However,
359 the impact of using and EXO_{UL} on the perceived effort does not appear consistent for all types of tasks.
360 For example, the use of EXO_{UL} (Exhauss Stronger, table 2) did not have any effect on the perceived
361 efforts on the shoulder during a load-lifting task, (Theurel et al., 2018).
362 Moreover, the EXO_{UL}'s effects on the perceived discomfort concern different regions of the upper limb,
363 probably depending on the design of the device. Kim et al. (2018a) reported a decrease in the perceived
364 discomfort in the forearm region with the use of a custom-made EXO_{UL}, while wearing this device did

365 not have any effect on the perceived discomfort at the shoulder and upper arm regions. Rashedi et al.
366 (2014) observed a reduction of the perceived discomfort in the upper arm and shoulder regions, by using
367 the WADE (table 2) during OHW, especially when the payload exceeded 3 kg . The two EXO_{UL} (WADE
368 and ShoulderX, table 2), evaluated by Alabdulkarim and Nussbaum (2019), led a reduction of the
369 perceived discomfort in the upper arm, while only the ShoulderX (Table 2) demonstrated significant
370 benefits in the perceived discomfort at the shoulder. In the contrary to the study by Rashedi et al. (2014),
371 wearing the WADE did not have any effect on the shoulder perceived discomfort, in this last study
372 (Alabdulkarim & Nussbaum, 2019).

373 Consequences of using EXO_{UL} on back muscles demand and postural control

374 Most of the studies ($n=6$) focused primarily on shoulder muscles efforts, but the consequences of
375 using an EXO_{UL} on back muscles demand and postural control were also investigated. There was no
376 obvious consensus on the impact of using EXO_{UL} on back muscle activity, but it appears that wearing
377 an EXO_{UL} alters postural control (Rashedi et al., 2014; Kim et al., 2018b; Theurel et al., 2018).

378 Significant disparities in the design of the EXO_{UL} studied previously could partly explain the lack of
379 consensus concerning the impact of using an EXO_{UL} on the back muscles demand. Rashedi et al. (2014)
380 and Weston et al. (2018) reported an increase of back muscle activity during OHW when using the
381 WADE (table2). In contrast, Huysamen et al. (2018a) did not observe any negative effects on the muscle
382 activity of the trunk and lower body when using a different passive EXO_{UL} (Custom made; table 2)
383 during similar OHW. Kim et al. (2018a) even observed a significant reduction in spine loading (-30%)
384 during a drilling OHW when using the EksoVest (table 2). Contrary to the studies of Rashedi et al.
385 (2014) and Weston et al. (2018), Huysamen et al. (2018a), Kim et al. (2018a), and Kim et al. (2018b)
386 each used a bilateral EXO_{UL}. Importantly, the mass and balance of the EXO_{UL} differ between the
387 unilateral and bilateral models. In the study by Alabdulkarim and Nussbaum (2019), the use of a bilateral
388 EXO_{UL} during OHW (ShoulderX) did not affect back muscle activity, while the use of a unilateral
389 EXO_{UL} (custom-made; table 2) resulted, on the contrary, in an increase in peak back muscle activity
390 (90th percentile). It therefore appears probable that using an EXO_{UL} has the potential for harmful impacts
391 on the postural muscular chain, in particular with unbalanced-mass exoskeletons.

392 A balance disturbance induced by arm lifting causes postural adjustments that are necessary for
393 maintaining balance and movement efficiency (Fourcade et al., 2014). The intensity of these postural
394 responses are directly dependent on the speed of the movement initiated, the forces exerted by the
395 movement, and the inertia of the segments mobilised (Bouisset et al., 2000). It seems probable that using
396 an EXO_{UL} can have considerable consequences on movement characteristics and postural adjustments
397 during handling activities. Moreover, movement assistance could also compromise the control of
398 postural adjustments by also affecting sensory feedback (*e.g.* perceived load, external force developed).

399 Recent studies provide some support for these hypotheses, by demonstrating an increase in the
400 magnitude (Theurel et al., 2018) and velocity (Kim et al., 2018b) of postural oscillations when using
401 passive EXO_{UL} (Exhauss and EksoVest, respectively). Theurel et al. (2018) also found an increase in
402 plantar extensor muscle activity during a task performed with the EXO_{UL}, thereby suggesting an increase
403 in the demand applied to the whole postural chain. Furthermore, Sylla et al. (2014) observed significant
404 postural changes when performing an OHW task with an active unilateral EXO_{UL} (ABLE). In that study,
405 operators tended to amplify the supporting forces exerted by the right foot (*i.e.* under the action arm),
406 thereby relieving the contralateral support. The weight and balance (*i.e.* weight distribution) of the
407 EXO_{UL} could explain these observations, but it is also probable that they provide evidence of kinematic
408 and muscular adaptations of the postural chain in response to modifications in the performance strategy
409 implemented by the focal chain (Bernshtein, 1967).

410 The lack of more detailed information on postural control appears to be a major drawback in relation
411 to using these new technologies for occupational risk prevention. If it turns out that postural control is
412 adversely affected by using an EXO_{UL}, operators could be exposed to additional muscular risks involving
413 the postural chain (*e.g.* LBP).

414 Summary and prospects

415 The shoulder joint experiences the severe and recurrent occupational UL pathologies. Using an
416 EXO_{UL} capable of attenuating intense and/or repeated demand on the arm elevating muscles could
417 contribute to preventing the occurrence of tendinopathies. Those studies that have assessed the benefits
418 of EXO_{UL} have shown an overall efficacy during OHW and manual handling tasks (*e.g.* Rashedi et al.

419 (2014); Sylla et al. (2014); Theurel et al. (2018)). Nevertheless, it also appears that assisting UL elevation
420 can have repercussions on shoulder muscle coordination, and thus constitutes a risk of prevalence of
421 tendinopathies. Reducing anterior deltoid muscular tension is insufficient to demonstrate that tendon and
422 muscle structures would be conserved by an EXO_{UL}. In most shoulder tendinopathy cases (>70%), the
423 supraspinatus muscle is affected because it is compressed between the head of the humerus and the
424 coracoacromial arch (Hebert et al., 2002; Bey et al., 2007). Preserving the integrity of the neural control
425 system, and ensuring the coordination and synchronisation of the agonist and antagonist muscles, and
426 joint kinematics, are the principal factors to be taken into account. We thus argue that it is necessary to
427 assess the impacts of this movement assistance during UL elevation on joint functional behaviour, before
428 promoting this type of technology for preventing shoulder MSDs.

429 The postural chain also seems to be affected by using an exoskeleton, in terms of both movement
430 control (*i.e.* inertia, force, speed trajectory) and balance control (*i.e.* additional mass and center of mass
431 displacement). The muscular consequences of these neuromotor changes remain difficult to ascertain
432 without conducting specific experiments. Future research should aim for a better understanding of the
433 adaptation and interaction mechanisms in the UL and postural chains during an exoskeleton-assisted
434 task. It is necessary to ensure that UL assistance does not result in other biomechanical strains. It should
435 also be emphasized that existing studies have furnished only partial support regarding the benefits of
436 EXO_{UL} in preventing MSDs.

437 **4 - CONCLUSIONS**

438 Our objective in this paper was to discuss the effectiveness of upper limb and back exoskeletons for
439 limiting the biomechanical risk factors related to MSDs. More specifically, this work focused on the
440 physiopathological mechanisms of LBP and shoulder tendinopathies, since these are the conditions
441 targeted by the current use of exoskeletons for industrial applications. Within the scope of the specific
442 task (*e.g.*, arm elevation, trunk sagittal extension) for which exoskeleton use has been designed, passive
443 and active EXO technologies have been found to have clear potential in limiting local muscular demand.

444 Conclusions of earlier research are generally consistent in supporting the use of these assistance
445 technologies in an occupational context.

446 Nevertheless, we argue that a decrease in only local muscular activity is not sufficient to eliminate
447 the risks of musculoskeletal pathologies, in particular for the shoulder. Moreover, most previous studies
448 have focused mainly on local muscular adaptations, leading to a number of gaps in knowledge, especially
449 with regard to general physiological responses to exoskeleton use. Existing evidence is also generally
450 limited to describing the acute physiological impacts of implementing these new technologies, whereas
451 several questions remain to be examined, notably including the occurrence of muscle fatigue and chronic
452 adaptations.

453 While the potential for industrial exoskeletons to attenuate muscular demand in the back or ULs
454 appears fairly promising, we concluded that the current state of knowledge does not allow for an
455 unreserved endorsement of the use of these technologies for the prevention of work-related MSD such
456 as LBP and shoulder tendinopathies. Important issues were highlighted in this literature review, which
457 we believe should be a priority for future investigation. These issues specifically involve obtaining a
458 greater understanding of: 1) posture and movement control mechanisms, when the postural and/or UL
459 muscular chains are assisted; 2) the impacts of movement assistance on the neuromuscular coordination
460 and functional behaviour of the joints; and 3) the acute and chronic physiological consequences of using
461 exoskeletons under real working conditions.

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645 **Figure 1:**



646

647 *Diagrammatic representations of passive (left) and active (right) back exoskeletons (EXO_{BK}) ©*

648 *Deledda for INRS.*

649

650 **Figure 2:**

651



652

653 *Diagrammatic representation of an upper limb exoskeleton (EXO_{UL}) (Exhauss Stronger, Exhauss,*

654 *France) (Theurel et al., 2018). © Deledda for INRS.*

655

656 **Table 1:** Overview of the papers retrieved regarding back exoskeletons (EKO_{BK}), including the type 657 of exoskeleton, a description, references, and the type of research reported.

658

Exoskeleton Type	Name	Description	References	Research Type
Passive EXO_{BK}	BNDR	The BNDR (Bending Non-Demand Return) exoskeleton consists of five main components: two curved lower bars that contact each thigh, one upper component that contacts the chest, and two torsional springs provide passive resistance during sagittal flexion. The device is worn around the waist with a padded belt.	(Ulrey & Fathallah, 2013b)	Static bending Laboratory
			(Ulrey & Fathallah, 2013a)	Static bending, lifting Laboratory
	Custommade EXO_{BK}	The prototype of exoskeleton is composed of an upper-body interface (shirt), lower-body interface (shorts), and elastic bands which run along the back, coupling the upper and lowerbody interfaces (Fig. 2). The lower-body interface was comprised of thigh sleeves with a high friction elastomer interior and a sturdy fabric exterior, which served as an anchoring point for the elastic bands. The upper and lower interfaces distribute forces across the surface area of the shoulders and thighs, respectively, allowing them to support substantial loading. The elastic bands (6.3 cm × 0.45 cm × 29 cm, 800 N/m stiffness) were connected to clasps on the shoulders, allowing the slack length in the bands to be adjusted. The exoskeleton mass has = 2.0 Kg	(Lamers et al., 2018)	Static bending, lifting Laboratory
			(Zhang et al., 2016)	Static bending, Lifting Laboratory

	Laevo V1	This exoskeleton consists of three types of pads: two chest pads, one back pad, and two upper leg pads. On both sides of the body, the pads are connected through a circular tube with spring like characteristics. The exoskeleton is intended to transfer forces from the lower back to the chest and leg pads. The Laevo has mass = 2.2 kg	(Baltrusch et al., 2018)	Functional tests, static bending, carrying Laboratory
			(Bosch et al., 2016)	Static bending Laboratory
	Laevo V2	This exoskeleton version is designed similarly to the previous one (Laevo V1). The device applies forces at three places on the body: thighs, pelvis, and on the chest. While bending forward, pressure is applied at the chest and on the legs, due to a spring-loaded joint in series with an elastic beam, generating a moment in parallel to the back muscle moment. The Laevo joint includes an end stop. Beyond this angle, no further rotation in the joint is possible. The Laevo has mass = 2.2 kg	(Koopman et al., 2019)	Static bending Laboratory
	PLAD	The PLAD (Person Lift Augmentation Device) exoskeleton is worn like a coverall suit. It is anchored at the feet, pelvis, and shoulders. Elastic elements run nearly parallel but are offset from the spinal column. The upper elastic elements are held in place by shoulder straps of a dismantled back pack and a pelvic spacer bar on the waist belt. The lower elastic elements travel from the pelvic spacer on the waist belt to anchors attached to the back of knee pads.	(Abdoli et al., 2006)	Lifting Laboratory
			(Abdoli & Stevenson, 2008)	Lifting Laboratory
			(Frost et al., 2009)	Static bending, lifting Laboratory
			(Graham et al., 2009)	Assembly process forward bending, static holding Car manufacturing
			(Graham et al., 2011)	Repetitive lifting Laboratory
			(Godwin et al., 2009)	Repetitive lifting Laboratory
			(Lotz et al., 2009)	Repetitive lifting Laboratory
			(Sadler et al., 2011)	Lifting Laboratory
(Whitfield et al., 2014)	Repetitive lifting Laboratory			
PAS	The PAS (Personal Assist Suit) exoskeleton is similarly designed to the PLAD. The PAS has a posterior elastic system extending from the knee to the upper back, to transfer force and moment from the spinal column to the shoulders, pelvic girdle, and knees. The PAS has mass = 0.5 kg.	(Dewi & Komatsuzaki, 2018)	Digging tasks Agricultural works	

Active EXO_{BK}	HAL	The HAL (Hybrid Assisted Limb) is composed of an exoskeleton frame, power units, and lumbar and thigh molds. The exoskeletal frame is outfitted by fastening the lumbar and thigh molds. Power units are located bilaterally on the wearer's greater trochanters. Electrodes on the skin surface over the lumbar muscles detect muscle action potentials as bio-electrical signals, to sense the intention of lifting motion. The HAL has mass = 3.1 kg	(Miura et al., 2018)	Repetitive lifting Laboratory
	H-Wex	This is an electrically-powered, waist-assistive exoskeleton, wire-driven by only one actuator. The exoskeleton is connected to the user with straps at the shoulders, waist, and crotch. A back side plate, including the battery, controller, and actuator module, is as thin as 50mm. The H-Wex has mass = 4.5 kg..	(Ko et al., 2018)	Static bending, lifting Laboratory
	Muscle Suit	The Muscle Suit covers the thighs, trunk and upper extremities and includes three joints, at the waist, shoulder, and elbow. The device was designed to give support to trunk flexion in the sagittal plane, as well as to shoulder and elbow flexion. An artificial muscle was used as an actuator.	(Kobayashi & Nozaki, 2008)	Static holding (bended) Laboratory
			(Kobayashi et al., 2009)	Lifting, static holding Laboratory Tire assembly Field
	Robomate	Robomate is a wearable active exoskeleton. It is attached to the trunk and the thighs and is articulated to coincide with rotation about the hip region. The exoskeleton is comprised of three linked segments: a back unit, with two leg units for each thigh. The exoskeleton is worn like a backpack. Physical assistance is adjusted in real time by actuators (maximum torque: 20 ± 5 Nm). The Robomate has mass = 11 kg	(Huysamen et al., 2018b)	Lifting/Lowering Laboratory

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661 **Table 2:** Overview of the papers retrieved regarding upper limb exoskeletons (EXO_{UL}), including
662 the type of exoskeleton, a description, references and the type of research reported.

Exoskeleton -type	Name	Description	References	Researches-type
Passive EXO_{UL}	Custom made exoskeleton	This exoskeleton is composed of three segments: a single back unit with mass = 2.8 kg, with two arm attachments having mass = 4.1 kg each, totaling 11 kg. The exoskeleton is worn by the user as a backpack. It reduces upper limb effort by means of springs mounted in support arms (see Altenburger et al. (2016)). The exoskeleton is connected to the body by several straps on the back unit and the arms. The assistive support is adjustable.	(Huysamen et al., 2018a)	Static holding OHW Laboratory
	EksoVest	The EksoVest is a bilateral EXO_{UL} . The vest includes neck (similar to U-shape neck pillow) and back pads, as well as adjustability in trunk length. The vest has a moment generation mechanism that is connected to an upper arm cuff and provides a gradually increasing support moment as the arm elevates. The support moment can be easily turned off. The exoskeleton has mass = 4.3 kg.	(Kim et al., 2018a)	OHW Laboratory
			(Kim et al., 2018b)	OHW Laboratory
	Exhauss Stronger	The Exhauss, model Stronger, consists of two mechanical arms (bilateral) activated by springs. The arms are linked to a rigid wearable jacket, with joints, allowing free 3D movements. The distal extremities of the mechanical arm have short belts used to strap the user's hands. This exoskeleton provides non-linear arm lift assistance over an angular range from 0 to 135° of the shoulder anterior flexion. The exoskeleton has mass = 9 kg.	(Theurel et al., 2018)	Sagittal lifting, rotational lifting, carrying Laboratory
	ShoulderX	ShoulderX (SuitX v2) is a bilateral exoskeleton. The exoskeletal device is worn by the user as a backpack. It has a moment generation mechanism that is connected to an upper arm cuff and provides a gradually increasing support moment as the arm elevates. The support moment can be easily turned off. ShoulderX has mass = 5.3 kg.	(Alabdulkarim & Nussbaum, 2019)	Drilling OHW Laboratory
	WADE	The Wearable Assistive Device (WADE) is a custom made unilateral exoskeleton. The exoskeleton consisted of one mechanical assistance arm (Zero G, Equipois Inc., Los Angeles, CA, USA) attached on an exoskeletal vest (Fawcett EksoVest, The Tiffen Company, Hauppauge, NY, USA). The mechanical arm was connected on the left side of the body. The exoskeleton has mass = 5 kg.	(Alabdulkarim & Nussbaum, 2019)	OHW Laboratory

			(Rashedi et al., 2014)	OHW Laboratory
			(Weston et al., 2018)	Static Holding Laboratory
Active EXO_{UL}	ABLE	The ABLE arm is an electrically-powered unilateral exoskeleton. The exoskeleton is designed to assist the shoulder, elbow and right wrist joints. The exoskeleton is composed of seven non-anthropometric axes whose combinations allow following human arm movements (see Garrec et al. (2008)). The controller is based on two major functions: dry friction compensation and weight compensation. The exoskeleton is used to support the weight of the operator's arm, as well as the tool.	(Sylla et al., 2014)	OHW Laboratory

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