Title

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

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Occupational Applications

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

Abstract

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

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

Keywords

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

1 - INTRODUCTION

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

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

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

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

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

Insert figure 1

Insert figure 2

2 - METHODS

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

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

3 - RESULTS AND DISCUSSION

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

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

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

Insert table 1

Consequences of using EXO_{BK} on back muscle activity

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

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

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

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

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

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

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

Consequences of using EXO_{BK} on back muscle fatigue

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

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

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

Consequences of using EXO_{BK} on spine loading

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

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

Consequences of using EXO_{BK} on perceived efforts

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

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

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

Consequences of using EXO_{BK} on posture

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

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

Summary and prospects

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

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

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

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

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

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

Insert table 2

Consequences of using EXO_{UL} on shoulder muscle efforts

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

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

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

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

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

Consequences of using EXO_{UL} on perceived efforts

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

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

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

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

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

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

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

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

Summary and prospects

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

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

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

4 - CONCLUSIONS

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

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

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

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

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Figure 1:

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

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Figure 2:

Diagrammatic representation of an upper limb exoskeleton (EXO_{UL}) (Exhauss Stronger, Exhauss, France) (Theurel et al., 2018). © Deledda for INRS.

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 $\times$ 0.45 cm $\times$ 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
		The exoskeleton consists of a pelvic cuff, a pair of shoulder harnesses, and two thigh cuffs with foot straps. Extension springs connect these three sections to realize the pushing and pulling forces. The pelvic cuff is considered to be rigidly connected to its wearer's pelvis. A pair of extension springs (thorax spring) is utilized to link the pelvic cuff with the shoulder belts to hold back the upper torso during spine flexion. The pushing force is generated by employing a cable-tension mechanism connected to an extension spring (lumbar spring) that is attached to the thigh cuff. This actuates a rotating cam that is pinned around a slight offset on the pelvic cuff, to push the lower back along with hip rotations during spine flexion/extension. Both the belt connection between shoulder harness and pelvic cuff and cable connection between pelvic cuff and thigh cuffs are length adjustable to secure the functionality of the design for different users. Finally, foot straps are used to connect the hip and pelvic cuffs to the feet, whose lengths are also adjustable to fit on different subjects to contain the thigh cuffs from sliding up on the human body during torso flexion.	(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

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 graduallyincreasing 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 graduallyincreasing 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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