Exoskeletons for industrial application and their potential effects on physical work load

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Abstract

The aim of this review was to provide an overview of assistive exoskeletons that have specifically been developed for industrial purposes and to assess the potential effect of these exoskeletons on reduction of physical loading on the body. The search resulted in 40 papers describing 26 different industrial exoskeletons, of which 19 were active (actuated) and 7 passive (non-actuated). For 13 exoskeletons, the effect on physical loading have been evaluated, mainly in terms of muscle activity. All passive exoskeletons retrieved were aimed to support the low back. 10 to 40% reductions in back muscle activity during dynamic lifting and static holding have been reported. Both lower body, trunk and upper body regions could benefit from active exoskeletons. Muscle activity reductions up to 80% have been reported as an effect of active exoskeletons. Exoskeletons have the potential to considerably reduce the underlying factors associated with work-related musculoskeletal injury.

Practitioner Summary

Worldwide, a significant interest in industrial exoskeletons does exist, but a lack of specific safety standards and several technical issues hinder mainstay practical use of exoskeletons in industry. Specific issues include discomfort (for passive and active exoskeletons), weight of device, alignment with human anatomy and kinematics, and detection of human intention to enable smooth movement (for active exoskeletons).

1. Introduction

Despite the on-going trend in automation and mechanization in industry, many workers are still exposed to physical workloads due to material handling (over 30 % of the work population in the EU), repetitive movements (63%), and awkward body postures (46 %) (Eurofound, 2012). These data, which have been relatively stable over the past decade, contribute to the fact that work-related musculoskeletal disorders (WMSDs) still affect a considerable number of workers. In the European Union, yearly more than 40 % of the workers suffer from low back pain or neck and shoulder pain (Eurofound 2012).

Full-automation would solve these problems, but this is not always feasible. For instance, in dynamic manufacturing or warehousing environments a high product mix and relatively small order sizes dictate high levels of flexibility and in such cases full-automation is either not possible or prohibitively expensive. In such a context of continuously varying products and tasks, the human capacity to observe, decide and adopt proper actions within split seconds, is still required. Thus, workers are still exposed to various production activities such as assembling or material handling and hence are exposed to the associated risks for developing WMSDs. There is a growing movement in modern industry towards human robot collaboration to improve use of robotics while retaining the flexibility of humans (MacDougall, 2014). For manual handling tasks one solution is to use exoskeletons. The main benefit of the application of an exoskeleton above any type of robot system (classical robots, full-automation systems or humanoid robots), would be that, specifically in dynamic environments, one will fully profit from the human's creativity and flexibility, while he is the one I charge, and there is thus no need for robot programming or teaching of robots.

An exoskeleton can be defined as a wearable, external mechanical structure that enhances the power of a person. Exoskeletons can be classified as 'active' or 'passive'. An active exoskeleton comprises one of more actuators that augments the human's power and helps in actuating the human joints. These actuators may be electric motors, hydraulic actuators, pneumatic muscles, or other types (Gopura and Kiguchi 2009). A strictly passive system does not use any type of actuator, but rather uses materials, springs or dampers with the ability to store energy harvested by human motion and to use this as required to support a posture or a motion. A passive exoskeleton for instance may store energy when a person bends forward, and while in this position, this energy may support the person to keep that position or to erect the body while lifting an object.

We can also distinguish exoskeletons by the supported body part(s): providing power or support to the lower limbs (lower body exoskeletons), to the upper extremities (upper body exoskeletons), and to both upper and lower extremities (full body exoskeletons). Additionally, some single-joint exoskeletons have been described in literature.

Finally, exoskeletons can be classified according to the level that the exoskeleton fits or resembles the human anthropometry. Anthropomorphic exoskeletons have exoskeleton joints with rotational axes that are aligned with the rotational movement of the human joints, which is not the case in the non-anthropomorphic types. A fully anthropomorphic type enables the exoskeleton robot to make the same motions as the wearer thereby offering a large freedom of motion. But these systems pose major design challenges to ensure close fit for different size users while simultaneously accommodating natural movements by the user. Non-anthropomorphic types are generally simpler and can be designed to have an optimized structure for specific tasks to be performed allowing more effective energy consumption than anthropomorphic systems (Lee et al. 2012a).

The main application area of exoskeletons has been for medical /rehabilitation purposes where the devices are aimed to support physically weak, injured, or disabled people to perform a wide range of motions involved in activities of daily living, such as walking, traversing stairs, sitting and standing up, reaching and grasping (Viteckova *et al*. 2013). A small number of exoskeletons have also been designed for military applications for soldiers to lift or carry heavy loads.

Several scientific literature reviews have addressed the technical aspects of exoskeletons (Yang *et al.* (2008), Gopura and Kiguchi (2009), Lee *et al*. (2012) and Viteckova *et al*. (2013) with few, if any addressing the effect on the human wearer. Vitechkova et al. (2013) conclude from their technical review that, despite much progress in the field of supportive robotic technologies, such as power sources, small and sensitive sensors, powerful computers, and lightweight materials, there is still a need to further develop lightweight exoskeletons compatible with operators. Some key technical issues that must be addressed: the design of actuators and artificial muscles, fast and effective control loops, the anthropometric fit, and battery life-times.

In this literature review, we address the impact of exoskeletons on the user. We focus on exoskeletons developed for use in occupational fields to support shop floor workers perform physically demanding activities. The aim of this review is (1) to provide an overview of ‘industrial’ exoskeletons that have been developed or are under development, and (2) to assess the potential effect of these exoskeletons in terms of physical load reduction on the wearer.

2. Methods

This review was based on an electronic literature search using the Scopus search engine which accesses an estimated 40 million scientific papers. The authors’ personal databases were also included in the search. To be included, papers had to be published in peer-reviewed journals in the English language from January 1995 until August 2014. The review was confined to publications in the formal scientific literature and did not include books or ‘grey’ research reports. The references retrieved by this search were first screened on the basis of their titles and abstracts. In cases where abstracts did not provide sufficient information, screening took place on full paper texts. Papers fulfilling the inclusion criteria (see below) were included in this review. The literature retrieved in this way was supplemented with relevant studies cited in the retrieved papers.

The following search terms were used: exoskeleton, wearable device, assistive device, and wearable robot. An additional inclusion criteria was that papers considered exoskeletons with an occupational purpose, i.e. to give physical support to workers in occupational settings. A simple reference to ‘work’, ‘worker’, ‘profession’, or an ‘occupational activity’ was considered to be sufficient for inclusion, however, papers considering other applications outside of occupational settings (e.g. rehabilitation, medical, tele-operations, military, and virtual reality), were excluded. We included all types of exoskeletons, i.e. passive and active, anthropomorphic or not, and lower body, upper body and full-body exoskeletons. But exoskeletons covering the hand and wrist only, were excluded from the review as they were not considered suitable for manual handling tasks. We included all papers on industrial exoskeletons irrespective of stage of design, ranging from early stage prototypes tested in laboratory settings to commercially available products ready to be used in practice.

Hence the retrieved studies were summarized to provide an overview of industrial exoskeletons (first aim of the study) while the scientific findings of the papers were used to summarise the efficacy of active and passive exoskeletons (second aim) in terms of physical load reduction provided.

3. Results

The search resulted in 40 papers in which an exoskeleton with an industrial purpose was described. In these papers a total of 26 different industrial exoskeletons were described (Table 1). These were broken down as 20 upper body, 4 full body, and 2 lower body exoskeletons, with 19 being active and 7 passive.

The exoskeletons were most frequently aimed to support: stooped working postures, static holding of a load, dynamic lifting (and lowering) of a weight, and to support. Some studies also mentioned carrying as an activity to be supported. Finally, some job specific activities were mentioned, i.e. patient lifting and transfer (for three different exoskeletons), construction work, agricultural and overhead carpentry work.

For 13 out of the 26 industrial exoskeletons, some evaluations of the physical load reductions were performed (see Table 2 and 3, for passive and active exoskeletons, respectively). However, most evaluations included only 1 to 3 participants. Scientific evaluation including statistical testing has only been performed for five exoskeletons, i.e. PLAD (Personal Augmentive Lifting Device), the Muscle Suit, BNDR (Bending Non-Demand Return), the HappyBack and the Bendezy.

All studies evaluating exoskeletons involved a repeated measures type experimental design to include within-subject comparisons of with and with-out exoskeleton use. Remarkably, all studies took place in a laboratory setting, except for one, namely the evaluation of PLAD by Graham *et al*. (2009).

Physiological parameters studied included muscle activity (i.e. effort) in the back, shoulder, arm and leg region mainly, as determined by the amplitude of the EMG signal, and muscle fatigue as determined by the combination of amplitude increase and decrease in frequency content over time in the EMG signal. Biomechanical parameters studied included the loading on the back expressed by the estimated net joint torque, spinal compression and shear forces for the lumbar or thoracic regions. Generally, positive effects, either tested statistically or not, have been reported for the physiological (EMG) and biomechanical parameters, both for the passive and the active exoskeletons.

4. Discussion

The development of passive and active exoskeletons to support humans date back to the 1960s and 1970s. Currently available lightweight materials and new technologies in sensing and actuating enable the development of a next generation of exoskeletons. Most exoskeletons have been developed to give support to disabled people in their daily activities. The development of exoskeletons suitable for industrial applications lags behind. This review extracted a total of 40 papers from the literature presenting 26 different exoskeletons. Eighteen of these papers have been published in 2010 or later, showing the current, high interest in industrial exoskeleton applications.

Effects of passive exoskeletons on physical load

For six passive exoskeletons the effectiveness in terms of physical load reduction has been evaluated for the activities of dynamic lifting and static trunk bending. The amount of assistance by the PLAD device in dynamic lifting and lowering has been evaluated in a series of laboratory experiments (Abdoli-Eramaki et al. 2006, 2007, 2008, Frost et al. 2009, Godwin et al. 2009, Lotz et al. 2009, Sadler et al. 2011, Whitfield et al. 2014). The PLAD principle comprises elastic elements that are situated in parallel to the erector spinae, so as to permit a sharing of the load between the spine, shoulders, pelvis and lower extremities. When the PLAD is worn during lifting tasks, energy is stored within the elastic elements as the upper body is lowered and/or the trunk is flexed. On the ensuing upward phase, this stored energy is released (Abdoli-Eramaki et al. 2006). As a result, the muscular activity required to lift is lowered. Back muscle EMG amplitude decrease ranged from 10 to 40% across several studies (Abdoli-Eramaki et al. 2006, Abdoli-Eramaki et al. 2008, Frost et al. 2009, Whitfield et al. 2014). As an effect of this, the manifestation of muscle fatigue in the EMG signal (as defined as the combination of an amplitude increase and a frequency content decrease (Basmajian and DeLuca, 1985) is dramatically less in the case of prolonged repetitive lifting and lowering over 45 minutes (Godwin et al. 2009, Lotz et al. 2009). Another effect that is mentioned are the lowered internal forces on the lumbar spine when wearing PLAD, e.g. L4/L5 compression estimated to be 23-29% lower (Abdoli-Eramaki et al. 2007). Finally, some other positive effects of PLAD, e.g. post-trial endurance and maximal back strength, further support the above findings.

For the BNDR device, a reduction of muscle activity was also reported in dynamic lifting, but only for those subjects not experiencing the flexion-relaxation phenomenon of the back muscles at deep back flexion (Toussaint et al. 1995). The BNDR was also found to reduce torso flexion in stooped lifting (Ulrey and Fathallah, 2013a). The reductions in back muscle activity when wearing BNDR were attributed to the device's ability to limit torso flexion rather than a transferring of loads (Ulrey and Fathallah, 2013a and b).

The effects of passive exoskeletons in static trunk bending were investigated by Graham et al. 2009 and by Ulrey and Fathallah (2013a) for PLAD and BNDR, respectively. Both studies showed positive effects on back muscle activity during static trunk bending (decrease ranging from 10-25%), spinal loading (estimated lumbar compression force decreased by 12-13%) (Graham et al. 2009, Ulrey and Fathallah 2013a).

In a short conference paper, Barret and Fathallah (2001) describe the effects of the BNDR, HappyBack and Bendezy during static bending while holding loads. These three passive exoskeletons differed with respect to materials and mechanism, but all showed positive effects, ranging from 21-31% reduction in erector spinae activity when using the devices.

Beside the positive effects described above, some concerns should be mentioned. Depending on lifting technique, reduced back muscle activity might be accompanied with increased activity of other muscles (Frost et al. 2009). An increase in leg muscle activity (tibialis anterior) has been reported for the HappyBack and Bendezy (Barrett and Fathallah 2001). The BNDR also showed a significant increase in lower leg muscle activity (Ulrey and Fathallah, 2013a). The increase in leg muscle activity could be explained by the fact that external forces applied by the equipment needs to be counteracted to retain balance, both in static holding and in dynamic lifting activities. For the PLAD, subjects were observed changing their lifting technique towards a more squat-like lifting pattern (Sadler et al 2011), which might also may be an explanation for higher muscle activity in the leg muscles when wearing a passive exoskeleton.

In prolonged lifting and lowering work, increased leg muscle activity could be expected to require increase oxygen uptake. However, for PLAD, in prolonged repetitive lifting and lowering, oxygen consumption was not affected (Whitfield et al. 2014). Whitfield et al. conclude that the biomechanical advantage in terms of unloading the back was not accompanied by an increase in energy consumption.

Other concerns relate to subjective reports of localised discomfort (e.g. shoulders or knees). Exoskeletons need to apply pressure on the body to function. If not carefully designed these contact areas may experience discomfort and possibly injury, which may lead to user reluctance to use the exoskeleton.

Effects of active exoskeletons on physical load

For several active exoskeletons, the effects in terms of physical load reduction have been evaluated, but statistical comparison data has only been reported for the Muscle Suit (Muramutsu et al. 2011, Kobayashi and Nozaki 2007). Originally the Muscle Suit was intended to aid the physically challenged, but for reasons of ethics and safety, it was decided to deploy the device for use by manual workers to help solve problems of work-related musculoskeletal disorders (Muramutsu et al. 2011). The Muscle Suit covers the thighs, trunk and upper extremities and includes three joints, at waist, shoulder and elbow level. For the complex shoulder joints, a 4 degrees of freedom mechanism was constructed allowing rotation around three orthogonal axes and transversal sliding of the centre of rotation. The Muscle Suit was constructed to give support to shoulder flexion, elbow flexion and trunk flexion in the sagittal plane. The McKibben artificial muscle (Chou and Hannaford 1996) was selected as the Muscle Suit actuator because of its light weight.

Experiments including static holding and dynamic lifting showed positive effects of the Muscle Suit for a large range of muscles in the upper extremities. Muscle activity reductions were reported in the range of 20-35% for the Deltoideus Anterior in dynamic lifting and up to 40-65% for the Flexor Carpi Radialis in dynamic lifting and static holding (Muramutsu et al. 2011). While holding a weight above the head the suit resulted in a decrease in muscle activity for the Biceps Brachii (30-70%) and the Trapezius pars transversa (40-70%). These results show the Muscle Suit's potential for reducing the physical load on the shoulder and arms for a large range of occupational activities including dynamic lifting and carrying, static work in a forward bended posture and overhead work.

Aside from the Muscle Suit seven other active exoskeletons with potential effects on physical loading were evaluated (see Table 3). However, these evaluations involved between one and three participants, and thus, statistical tests have not been performed on the data. These exoskeletons vary a lot with respect to body structures supported (either lower, upper or full body), the materials used and the activation type. For the technical descriptions we refer to the individual papers shown in Table 3. With regard to their effect on physical load, it can be concluded that these papers show the potential of decreasing muscle activity in both the lower extremities (for instance in walking and stairs climbing), the back (in lifting and static bending), and in the shoulders and upper extremities (in various types of hand-arm work).

Practical implementation of exoskeletons

Despite the high interest for exoskeletons with an industrial application purpose, a large-scale implementation of exoskeletons in industry has still a long way to go. Actually, for the exoskeletons considered in this review, all evaluations took place in the laboratory, except for the study on PLAD of Graham et al. (2009). The exoskeleton devices reviewed are largely at an experimental stage and not ready yet to be used in practice. Technical issues need to be considered and solved first.

Even the more simple passive devices are not yet widely used in practice. One reason might be the level of discomfort associated with wearing the exoskeleton. In a few studies, some concerns about this aspect have been reported (e.g. Abdoli-Eramaki et al. 2007). With the biomechanical advantage being established, the elimination of discomfort at the physical user interface with the equipment could be the next challenge in the design of exoskeletons, bearing in mind that even a minimal level of discomfort might hinder user's acceptance. The latter might be different from the exoskeletons aimed at supporting disabled people, where the exoskeleton could determine being able to walk or grasp or not. Another concern with regard to the passive devices concerns the potential increased activity of leg muscles. This aspect certainly needs consideration in further developments towards final ready-to-be-used products.

Active exoskeletons may have a larger potential of reducing physical loads. While passive exoskeletons mainly have a potential of unloading the back, the active devices may unload many joints throughout the body. However, with increasing numbers of joints (each requiring actuators and power supply) the weight of the exoskeleton will increase. For instance, an upper body exoskeleton with lightweight actuators like the MuscleSuit, already has a total weight of 9 kg (Muramutsu et al. 2011). To unload the worker from this constant weight burden, an extension of the exoskeleton towards the ground would be beneficial, but this increases the complexity of the design.

The exoskeletons reviewed in this paper were all anthropomorphic. That is, the exoskeleton has a similar skeletal structure compared to the human body involving a series of many actuated joint. The main advantage is that the footprint of the exoskeleton is relatively small as it adheres directly to the body, and the movements should in theory be unrestricted. The movements of the worker are copied by the exoskeleton, i.e. the limbs of the human and the exoskeleton are aligned during motion. This necessitates detection of human movement intention to initiate the appropriate responses of the exoskeleton's actuators. Distinction of intended from unintended movements is often difficult and results in systems with many different kinds of sensors and complex signal processing. Yang *et al*. (2008) address the necessity for improved control strategies to enable smooth movements at a normal to fast pace, but the cooperation and function allocation, man-machine information exchange, real-time motion planning and safety control are the difficulties faced by building such a control strategy.

It remains a challenge for anthropomorphic active exoskeletons to reflect the human anatomy, kinematics and kinetics to enable natural and comfortable movements. We mentioned the shoulder as a complex joint to incorporate in exoskeletons as it comprises three orthogonal axes of rotation plus transversal sliding of the center of rotation. The knee may also form a challenge as the center of rotation shifts during flexion. Moreover, rotational movement in any joint requires movement between the skin and skeletal structure. To accommodate this during movement the exoskeleton should ideally extend or shorten. This is a design feature that was not readily observed in the exoskeletons observed.

The industrial use of passive and active exoskeletons requires consideration of several specific safety issues. Varying risk scenarios can be defined for the worker wearing an actuated exoskeleton in the occupational field, for example on the shop floors in production industry, in warehouses, in hospitals, or outdoors in agriculture or construction. Exoskeletons used in the context of robots for personal care are governed by ISO 13482. However, to date, international safety standards for industrial application of exoskeletons does not yet exist and this is a significant barrier to their adoption.

A final concern has been raised earlier by Eisinger et al. (1996) with regard to lumbar orthoses (i.e. close fitting rigid lumbar supports). They reported that prolonged use of orthoses could be associated with deconditioning of trunk muscles. Therefore they recommend either to limit the duration of their use or to combine the use with strengthening exercises. The same phenomenon and recommendation may hold for exoskeletons used in industry.

Conclusions

This review shows a wide interest in passive and active exoskeletons for industrial purposes, but most developments are at an early stage of technology development with many concepts not tested beyond the lab.

Passive industrial exoskeletons are aimed at supporting or unloading the lower back region and appear to be quite successful herein for both dynamic lifting or static holding activities. Some concerns have been raised regarding the potentially negative effects associated with increasing leg muscle activity, high levels of discomfort and muscle deconditioning.

The potential effect in reducing physical loads seems to be even higher for active exoskeletons. Both lower body, trunk and upper body regions could benefit from large reductions in loading. Exoskeletons thus have the potential to considerably reduce the underlying factors associated with developing work-related musculoskeletal injuries. The true impact on potentially reducing injury prevalence however, still needs to be determined, as until now significant technical challenges and a lack of specific safety standards stands in the way of large-scale implementation in workplaces.

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Table 1. Overview of retrieved exoskeletons, references, aimed type of industrial application, and type of exoskeleton

	name or description of exoskeleton	references	industrial activity to be supported	power supply mechanism	part of body
1	PLAD Personal Augmentive Lifting Device	Abdoli-Eramaki et al. 2006 Abdoli-Eramaki et al. 2007 Abdoli-Eramaki et al. 2008 Frost et al. 2009 Godwin et al. 2009 Graham et al. 2009 Lotz et al. 2009 Sadler et al. 2011 Whitfield et al. 2014	lifting/lowering static holding	passive elastic straps	upper
2	Muscle Suit	Kobayashi et al. 2009 Kobayashi and Nozaki 2008 Kobayashi and Nozaki 2007 Muramatsu et al. 2011a Muramatsu et al. 2011b	lifting static holding	active McKibben artificial muscle	upper
3	'quasi-active exoskeleton'	Kim et al. 2009 Kim et al. 2013	carrying lifting	(quasi-)active electric motors for knee only	lower
4	PARM Power Assisted Robot Arm	Kadota et al. 2009	lifting	active pneumatic artificial rubber muscle	upper
5	SRL Supernumerary Robotic Limbs	Davenport et al. 2012	static holding	active electric motor and viscoelastic elements	upper
6	'strengthen upper limb exoskeleton'	Deng et al. 2013	lifting	active hydraulic actuators	upper
7	HAL Hybrid Assistive Limb	Kawabata et al. 2009	heavy lifting carrying	active	full
8	'power assist wear'	Li t al. 2013	lifting static holding	active pneumatic actuators	upper
9	IKO IKerlan's Orthosis	Martinez et al. 2008	static holding	active, cable-drive transmission, electric motor, pneumatic muscles	upper
10	'myosignal-based powered exoskeleton'	Rosen 2001	static holding	active electric servo motor	upper
11	'human-robot integrated exoskeleton'	Ryu 2012	heavy lifting	active (mechanism not mentioned)	full
12	ESA EXARM	Schiele 2009	static holding	active (mechanism not mentioned)	upper
13	PAS Power-assisted Suit	Toyama and Yonetake 2007	patient lifting patient transfer	active ultrasonic motors	full
14	'wearable agrirobot'	Toyama and Yamamoto 2010	farming: kneeling, arm lifting, stooped work	active electric motors	full
15	Skil Mate	Umetani et al. 1999	construction work	active McKibben artificial muscle	upper
16	EXO-UL7	Yu and Rosen 2010	static holding	active electric servo-motor	upper
17	'power assist suit'	Tsuzura et al. 2013	patient lifting patient transfer	passive torsion springs	upper
18	'lower limb assistive device'	Hasegawa and Muramutsu 2013	patient lifting patient transfer	passive gas spring	lower
19	'wearable robot'	Naito et al. 2007	carpentry overhead work	active motor and springs	upper
20	'exoskeleton power assis system'	Naruse et al. 2003	lifting lowering	active motor and cables	upper
21	'exoskeleton'robot'	Lee et al. 2012b	static holding	active (mechanism not mentioned)	upper
22	'wearable moment restoring device'	Wehner et al. 2009	lifting	passive springs	upper
23	WSAD Wearable Stooping-Assist Device	Luo and Yu 2013	stooped work	active servo-motor	upper
24	BNDR Bending Non-Demand Return	Ulrey and Fathallah 2013a Ulrey and Fathallah 2013b Barret and Fathallah 2001	lifting stooped work	passive springs	upper
25	Happyback	Barret and Fathallah 2001	stooped work	passive bungee cords	upper
26	Bendezy	Barret and Fathallah 2001	stooped work	passive springs	upper

Table 2. Effects of passive exoskeletons in terms of physical load reductions

exo-skelet	publication	type of study	subj.	effect on muscle activation	effect of on biomechanical parameters	other effects
PLAD	Abdoli-Eramaki et al. 2006	laboratory asymmetric lifting of 5, 15, 25 kg, three lifting styles	9 ♂	Erector Spinae T9 AMP ▼ 14.4% Erector Spinae L4 AMP ▼ 27.6% External Oblique, Rectus Abdominus AMP NS	lumbar flexion, pelvis flexion NS trunk acceleration ▼	
	Abdoli-Eramaki et al. 2007	laboratory symmetric lifting of 5, 15, 25 kg, three lifting styles	9 ♂		compression L4/L5 ▼ 23%-29% shear L4/L5 ▼ 8-9% moment L4/L5 ▼ 22-26%	all subjects reported the feeling of PLAD assisting them in the up phase of lift
	Abdoli-Eramaki et al. 2008	laboratory asymmetric lifting of 5, 15, 25 kg, three lifting styles	9 ♂	Erector Spinae T9 contralat. AMP ▼ 15.9% Erector Spinae L4 contralat. AMP ▼ 22.6% Erector Spinae T9 ipsilat. AMP ▼ 24.4% Erector Spinae L4 ipsilat. AMP ▼ 23.9%	lateral bending moment L4/L5 ▼ 30% rotational moment L4/L5 ▼ 24% flexion/extension moment L4/L5 ▼ 19.5%	all subjects felt supported in down and up phase, 10% of all subjects complained about shoulder discomfort and 40% about knee discomfort when wearing PLAD
	Frost et al. 2009	laboratory symmetric lifting of 15kg, three lifting styles	13 ♂	Erector Spinae T9 AMP ▼ 11-43% Erector Spinae L4 AMP ▼ 10-40%	moment L4/L5 ▼ 17-19%	
	Godwin et al. 2009	laboratory lifting/lowering for 45 min, load 20% of max. back extensor strength	12 ♀	Erector Spinae T9 AMP increase ▼ 96% Erector Spinae T9 MPF decrease▼ 81% Erector Spinae L3 AMP increase ▼ 84% Erector Spinae L3 MPF decrease▼ 56%		maximal isometric back strength (post-trials) ▲ endurance (post-trials) NS heart rate, perceived exertion, NS
	Graham et al. 2009	field automotive assembly activities	2 ♀ 8 ♂	Erector Spinae T9 AMP ▼ 25% Erector Spinae L3 AMP ▼ 15% Rectus Abdominis AMP NS	compression T9 ▼ 18% compression L3▼ 12%	RPE ▼ 16% Subjective estimate of 52% off-loading of the low back
	Lotz et al. 2009	laboratory lifting/lowering for 45 min, load 20% of max. back extensor strength.	10 ♂	Erector Spinae T9 AMP increase ▼ 78% Erector Spinae T9 MPF decrease▼ 70% Erector Spinae L3 AMP increase ▼ 97% Erector Spinae L3 MPF decrease▼ 98%		heart rate, endurance NS perceived exertion increase ▼ (25%) max. back extension strength (post-trials) NS endurance (post-trials) ▲ 20%
	Whitfield et al 2014	laboratory lifting/lowering of 10 kg for 15 min	15 ♂	Biceps Femoris AMP ▼ 10% (lifting pase) Erector Spinae T9 AMP ▼ 24% (lowering) Rectus Femoris, Erector Spinae T9, Erector Spinae L3, Gluteus Maximus AMP NS		oxygen consumption NS
'lower limb assist. dev.'	Hasegawa and Muramutsu 2013	laboratory patient transfer	2 ♂ 2 ♀		ground reaction force ▼ 67-80%	
'wearable moment restoring device'	Wehner et al. 2009	laboratory repetitive lifting of 4.5 and 13.5 kg	5 ♂ 1 ♀	4.5 kg: Erector Spinae (lumbar) ▼ 44% 13.5 kg: Erector Spinae (lumbar) ▼ 54%	4.5 kg: compression force L5/S1▼ 60% 13.5 kg: compression force L5/S1 ▼ 36%	
BNDR	Ulrey and Fathallah2013a	laboratory static bending in 0-100% trunk flexion postures	11 ♂ 7 ♀	Erector Spinae (lumbar) AMP ▼ 13.7% Erector Spinae (thoracic) AMP ▼ 10.3% Rectus Abdominis NS Biceps Femoris AMP ▼ 13.6% Tibialis Anterior AMP ▲ 73%	L5/S1 compression force ▼ 13.5% L5/S1 shear force ▼ 12.1% L5/S1 medio-lateral force NS L5/S1 active extensor moment ▼ 15.0% Ankle axial moment ▼ 30.9% Knee axial moment ▼ 31.1%	
	Ulrey and Fathallah2013b	laboratory static bending and lifting of 0, 4 and 9 kg	11 ♂ 7 ♀	*Static bending* Erector Spinae (lumbar) AMP NS Erector Spinae (thoracic) AMP NS Rectus Abdominis AMP NS	*Static bending* Total torso angle ▼ 17.4% *Lifting (flexion movement)*	

				Biceps Femoris AMP ▼ 17% Tibialis Anterior AMP NS *Lifting* Erector Spinae (lumbar) AMP ▼ 15.2% Erector Spinae (thoracic) AMP ▼ 10.0% Rectus Abdominis AMP NS Biceps Femoris AMP ▼ 9.5% Tibialis Anterior AMP NS	Total torso angle ▼ 16.7% *Lifting extension movement)* Total torso angle ▼ 17.1%	
	Barret and Fathallah 2001	Laboratory static bending and holding of 0, 4 and 9 kg	4 ♂ 5 ♀	Erector Spinae (lumbar) ▼ 31%		
Happyback	Barret and Fathallah 2001	Laboratory static bending and holding of 0, 4 and 9 kg	4 ♂ 5 ♀	Erector Spinae (lumbar) ▼ 23%		
Bendezy	Barret and Fathallah 2001	Laboratory static bending and holding of 0, 4 and 9 kg	4 ♂ 5 ♀	Erector Spinae (lumbar) ▼ 21%		

▼ and ▲ = significantly lower and higher value respectively, for condition with exoskeleton vs. without exoskeleton

▼ and ▲ = not statistically evaluated differences between conditions with vs. without exoskeleton

± = estimated effects based on figures

AMP = amplitude of EMG signal

MPF = mean power frequency of EMG signal

Table 3. Effects of active exoskeletons in terms of physical load reductions

exo-skelet	publication	type of study	subj.	effect on muscle activation	effect of on biomechanical parameters	other effects
MUSCLE SUIT	Kobayashi et al. 2009	laboratory: holding 10 kg while bending field: tire assembly laboratory: lifting 12.5 kg	2 ♂ 1 ♂ 2 ♂	*holding:* Erector Spinae AMP▼ 40%, Trapezius AMP ▼ 80%, Biceps Brachii AMP▼ 70% *tire assembly*: Erector Spinae AMP ▼ 31%, Trapezius AMP▼ 37%, Biceps Brachii AMP ▼ 69% *lifting:* Erector spinae AMP ▼ 41%		
	Kobayashi and Nozaki 2008	laboratory holding of 0, 5, 10 and 15 kg while bended	3 ♂	Erector Spinae AMP ▼ 30-60%		
	Kobayashi and Nozaki 2007	laboratory holding load of 10 kg above head	5 ♂	Biceps Brachii AMP ▼ 30-75% Trapezius AMP ▼ 40-70% Erector Spinae AMP NS		
	Muramatsu et al. 2011a	laboratory holding 20 kg while bended lifting/lowering/carrying of 20 kg	10 ♂	*holding:* Flexor Carpi Radialis AMP ▼ ±50-60% Flexor Carpi Ulnaris AMP ▼ ±30-45 Biceps Brachii AMP ▼ ±30-60% Deltoid Ant. AMP ▼ ±25% Deltoid Post. AMP ▼ ±45-50% *lifting/lowering/carrying:* Flexor Carpi Radialis AMP ▼ ±45-65% Flexor Carpi Ulnaris AMP ▼ ±30-45% Biceps Brachii AMP ▼ ±20-55% Deltoid ant. AMP ▼ ±20-35% Deltoid post. AMP ▼ ±30-55%		'subject felt less fatigued when wearing MUSCLE SUIT'
'quasi-act. exo-skeleton'	Kim et al. 2013	laboratory walking flat and stairs with 20 kg and 30 kg	1 ♂	Quadriceps, Gastrocnemius AMP ▼ 32-49% (flat) and ▼ 11-24% (stairs)		
PARM	Kadota et al. 2009	laboratory lifting and lowering 10 kg	1 ♂	Biceps Brachhii, Brachioradialis AMP ▼ (not quantified)		
'power assist wear'	Li et al. 2013	laboratory stooped posture (no load) lifting 12.6 kg.	1 ♂	*holding*: Erector Spinae AMP ▼ 19% *lifting*: Erector Spinae AMP ▼ 29-38%		
'wearable robot'	Naito et al. 2007	laboratory upper arm holding of 3 kg standing upright with load at shoulder level	3 ♂	Forearm Flexors AMP ▼ 56% Biceps Bracchii AMP ▼ 29% Deltoid muscle AMP ▼ 77%		
'exo-skeleton robot'	Lee et al. 2012b	laboratory holding of 10 kg in elbow flex/extension and shoulder flex/extension.	1 ♂	Biceps brachii AMP ▼ 46% (elbow); ▼ 86% (shoulder) Triceps brachii AMP ▼ 64%(elbow); ▼ 87% (shoulder) Deltoid post AMP ▼ 49% (elbow); ▼ 67% (shoulder) Deltoid ant ▼ 23% (elbow); ▼ 45% (shoulder)		

WSAD	Luo and Yu 2013	laboratory, stooped postures for 5 min with trunk flexion at 30º, 60º and 90º	1 ♂	at 30º Erector Spinae (thoracic) AMP ▼ 30%, Erector Spinae (lumbar) AMP ▼ 34% Latissimus Dorsi AMP ▼ 18% Rectus Abdominis AMP ▼ 4% at 60º Erector Spinae (thoracic)AMP ▼ 35%, Erector Spinae (lumbar) AMP ▼ 40% Latissimus Dorsi AMP ▼ 22% Rectus Abdominis AMP ▼ 6% at 90º Erector Spinae (thoracic) AMP ▼ 42%, Erector Spinae (lumbar) AMP ▼ 47% Latissimus Dorsi AMP ▼ 28% Rectus Abdominis AMP ▼ 9%		

▼ and ▲ = significantly lower and higher value respectively, for condition with exoskeleton vs. without exoskeleton
▼ and ▲ = not statistically evaluated differences between conditions with vs. without exoskeleton
± = estimated effects based on figures
AMP = amplitude of EMG signal
MPF = mean power frequency of EMG signal