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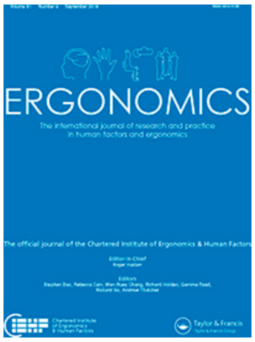

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Effects of industrial back-support exoskeletons on body loading and user experience: an updated systematic review

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Abstract

This study is an updated systematic review of papers published in the last five years on industrial back-support exoskeletons. The research questions were aimed at addressing the recent findings regarding objective (e.g. body loading, user performance) and subjective evaluations (e.g. user satisfaction), potential side effects, and methodological aspects of usability testing. Thirteen studies of active and twenty of passive exoskeletons were identified. The exoskeletons were tested during lifting and bending tasks, predominantly in laboratory settings and among healthy young men. In general, decreases in participants' back-muscle activity, peak L5/S1 moments and spinal compression forces were reported. User endurance during lifting and static bending improved, but performance declined during tasks that required increased agility. The overall user satisfaction was moderate. Some side effects were observed, including increased abdominal/lower-limb muscle activity and changes in joint angles. A need was identified for further field studies, involving industrial workers, and reflecting actual work situations.

Practitioner Summary

Due to increased research activity in the field, a systematic review was performed of recent studies on industrial back-support exoskeletons, addressing objective and subjective evaluations, side effects, and methodological aspects of usability testing. The results indicate efficiency of exoskeletons in back-load reduction, and a need for further studies in real work situations.

Keywords: Industrial ergonomics, Equipment design, User testing, Manual handling, Musculoskeletal disorders

1. Introduction

Musculoskeletal Disorders (MSDs) are the most prevalent work-related health problem (de Kok et al., 2019). In 2019, 64% of EU employees were subjected to lifting or moving heavy (>11 kg) loads, and 37% to tiring or painful body positions at the workplace, which are among the leading physical risk factors for back MSDs (de Kok et al., 2019). In the study by de Kok et al. (2019), high proportions of workers reporting backache were identified in the agriculture, forestry and fishing (60%), construction (52%), manufacturing (46%), and transportation and storage sector (46%).

Overexertion is a risk factor for back MSDs, and a common preventive measure for mitigating overexertion risks is the provision of equipment to assist with lifting or moving loads, increasingly by means of robotization (de Kok et al., 2019). However, robotization is not always optimal or feasible, especially when flexibility is required. Thus, wearable, external mechanical structures known as exoskeletons are one option to support workers' physical performance (de Looze et al., 2016; Howard et al., 2020), thereby reducing biomechanical loads (Lowe et al., 2019). These technologies are commonly referred to as occupational or industrial exoskeletons. While the term "occupational" covers a broader spectrum of work tasks, including, for example, nursing, the term "industrial" is still more predominantly used. Compared to autonomous robots and cobots, industrial exoskeletons by their wearable nature allow for greater mobility and control by the user, and also serve to a certain degree as personal protective equipment (Lowe et al., 2019).

In a broad sense, exoskeletons can be classified as active (i.e. powered through electric, hydraulic, pneumatic or other types of actuators), or passive (i.e. unpowered; able to store energy harvested by human motion in spring-like structures) (Bostelman et al., 2017; de Looze et al., 2016; Gopura & Kiguchi, 2009). Exoskeletons that directly support the body can be grouped into leg-support, back-support and arm-support exoskeletons. Most commercially available industrial exoskeletons provide support or assist with movements of the back and arms (Bogue, 2018; Theurel & Desbrosses, 2019;

Wesslén, 2018). Back-support exoskeletons are primarily designed to reduce biomechanical loads on lower-back structures during spine-loading tasks by applying assistive forces/torques between the user's torso and thighs (Toxiri et al., 2019).

A systematic review by de Looze et al. (2016; including two of the current authors) reported on the effects of 26 exoskeletons focused on industrial use, ranging from early stage prototypes to commercially available products. That review included studies from the years 1995-2014, regarding the efficacy of physical load reduction provided by different types of industrial exoskeletons. At that time, industrial exoskeletons were mainly at a research stage with new concepts being reported in the literature at a relatively embryonic level. The review identified reports of 40% back-muscle activity reductions during dynamic lifting and static holding with passive exoskeletons, and up to 80% reductions with active exoskeletons (de Looze et al., 2016).

Two other review papers on industrial back-support exoskeletons and their potential effects have been published in the past year (Theurel & Desbrosses, 2019; Toxiri et al., 2019). Toxiri et al. (2019) reviewed technological advances and trends in terms of physical design, actuation mechanisms and control strategies of 21 back-support exoskeletons. That study did not review the effects of exoskeletons on body loading, user performance, or satisfaction. Theurel and Desbrosses (2019) performed a narrative overview of 11 back-support exoskeletons, focused mainly on objective assessments of their impact on muscle activity, muscle fatigue, spine loading, and posture. Subjective assessments of perceived effort and pain were briefly addressed. A thorough review of user performance and satisfaction was not provided, and it was not a systematic review, possibly leaving out other relevant studies.

Since 2016, there has been a substantial expansion in the field of industrial exoskeleton development and user testing (Amandels et al., 2018; Motmans et al., 2019; Baltrusch et al., 2020b; Koopman et al., 2020), which was not addressed by the abovementioned reviews. This supports the need for an updated systematic review, including to address specifically user experience aspects of industrial back-support exoskeletons, which is an important factor for their successful implementation in the workplace. Thus, the primary research questions of this systematic review were 1. to determine the magnitude of effects of exoskeletons recently (since our last review – de Looze et al. 2016), including objective (i.e. body loading and user performance) and subjective measures (i.e. perceived discomfort, fatigue, and user satisfaction); and 2. to report on potential side effects of industrial back-support exoskeletons in testing studies. In addition, we comment on recent trends and evolving approaches to exoskeleton usability testing.

2. Method

2.1 Literature search and study selection

A systematic literature search was performed on June 30, 2020 using the Scopus search engine. The search was limited to conference papers and journal articles in the English language. Of interest were studies published after the year 2014, as our previous review (de Looze et al., 2016) included papers published from January 1995 until August 2014.

The keywords used in the search, study selection criteria, and results, are presented in Figure 1. Selected were studies on exoskeletons intended specifically for back/trunk support in the workplace. Excluded from the review were papers that focused on animal exoskeletons, upper- and lower-limb exoskeletons, exoskeletons for military use, rehabilitation, assistance with gait or activities of daily living, and studies that did not include human testing. Also excluded were studies where the effects of exoskeleton use were not assessed directly on human participants during activities similar to industrial-work tasks, and studies that did not involve statistical analysis of the data obtained. TK and AWdV performed the search and selection independently, and LWOS resolved any disagreement between TK and AWdV. The studies selected for review were abstracted by TK, and all authors reviewed and agreed the final results of data extraction.

[Insert Figure 1 about here]

2.2 Data extraction and synthesis

The following data were extracted from the selected studies: (1) exoskeleton properties: name, manufacturer, design stage (prototype/commercial), type (active/passive, rigid/soft), general mode of assistance; (2) study design: test participants, testing procedure, study variables, type of evaluation (objective/subjective, quantitative/qualitative); and (3) findings: benefits and potential side effects of exoskeleton use on user effectiveness, efficiency and satisfaction.

3. Results

3.1 Exoskeleton types and trends

The systematic search identified 33 studies, 13 of which were on active and 20 on passive back-support exoskeletons. The earliest study was published in 2016 and performed on a passive exoskeleton, followed by 8 studies in 2018 (6 on active, 2 on passive exoskeletons), 9 studies in 2019 (3 on active, 6 on passive exoskeletons) and 15 studies in 2020 (4 on active, 11 on passive exoskeletons). Of the 16 different exoskeleton models studied, 8 were active and 8 passive; one active (HAL™ for Care Support) and four passive exoskeletons (BackX™ model AC, FLx™, Laevo™ V2, V22™) were commercially available at the time of writing. One active (soft exoskeleton suit) and one passive device (VT-Lowe's Exoskeleton) were described by the authors as "soft" exoskeletons. The reviewed studies are summarized in Table 1 (active exoskeletons), and Table 2 (passive exoskeletons); listed are only statistically significant results.

[Insert Tables 1 and 2 about here]

3.2 Study design

Of the 33 studies reviewed only 2 were field studies (Amandels et al., 2018; Motmans et al., 2019), the remaining 31 being performed in the laboratory. The field studies involved complex/variable tasks, i.e. 30 minutes of frequent far reaching for items with bending and 1.5 hours of load picking. Both were performed with Laevo™ and included workers with low back pain (LBP). Laboratory studies, on the other hand, tended to examine the effects of exoskeletons in relatively simple repetitive or single lifting tasks, or static bending tasks. Laboratory studies were mostly performed on healthy participants. In four studies on passive exoskeletons, a functional performance test battery involving 12 different tasks was used which reflects a move to more variable testing scenarios.

The number of test participants per study ranged from 5 to 24, with an overall median of 11 participants (10 for active and 12 for passive exoskeletons). Twenty-one studies were performed only on males, nine on males and females, and three studies did not report participants' sex. Twenty-five studies were performed only on healthy participants, three only on participants with LBP, and three on both healthy participants and those with LBP. In two studies, participants' medical condition was not reported. Six studies (2 on Laevo™, 4 on SPEXOR) involved participants that were occupationally exposed to spine-loading conditions, including luggage handling in airline industry, assembling and sorting in automotive industry, order picking in cheese manufacturing, and multitasking work on production shop floors.

3.3 Evaluation approaches

The usability of back-support exoskeletons, as interpreted from ISO 9241-11:2018 and ISO/IEC 25022:2016, was evaluated using both objective and subjective assessment methods in 14 studies, 18 studies only applied objective methods, and 1 study only applied subjective methods. Objective measures included back loading, energetic loading, user performance, and side effects (Table 3).

[Insert Table 3 about here]

Muscle activity was by far the most studied objective measure. Figure 2 details the frequency of study of specific muscles across the studies. In most of the reviewed studies, only back-muscle, or back- and abdominal-muscle activity were measured (8 studies each). In other studies, different combinations of abdominal, upper- and lower-limb muscles were investigated in conjunction with back muscles.

[Insert Figure 2 about here]

Table 4 provides a summary of subjective evaluation measures used across the studies. The measures include perceived general and local discomfort, perceived task difficulty, exertion and fatigue, interference of exoskeletons with movement and task performance, and users' impression of the exoskeleton. One study also employed qualitative techniques to assess user experience, namely focus groups and double interviews.

[Insert Table 4 about here]

3.4 Main findings of the reviewed studies

3.4.1 Objective measures

Changes in back-muscle activity were investigated in 27 studies (11 on active, 16 on passive exoskeletons), and significant results were found in 22 studies (10 on active, 12 on passive exoskeletons). The impact of back-support exoskeletons on m. Erector Spinae (ES) activity across the studies by exoskeleton and task type is presented in Figure 3. The mean change in ES activity during lifting was -25% (range -6% to -48%) with active exoskeletons, and -18% (range -6% to -35%) with passive exoskeletons. During static bending, the change in ES activity was -12% in one study with an active exoskeleton, and -36% (range -14% to -61%) with passive exoskeletons, where back muscle activity varied with the angle of lumbar flexion. An unexpected increase in ES by 44% and 64% was also reported with a passive exoskeleton in 2 of 3 conditions during assembly work at below-floor height (Madinei et al., 2020a). During a complex 1.5-hour activity that involved bending and load handling, a significant decrease in ES activity (-11%) was observed with a passive exoskeleton (Motmans et al., 2019).

[Insert Figure 3 about here]

Changes in the activity of the abdominal muscles were investigated in 15 studies (3 on active, 12 on passive exoskeletons), with significant differences identified in 4 studies on passive exoskeletons only. Both significant increases and decreases were reported during repetitive lifting (+4%, -8.7%) and during static bending (+106%, -24%) with passive exoskeletons. Abdominal muscle activity varied with the angle of lumbar flexion and the type of support by the exoskeleton. During walking, a significant increase in abdominal muscle activity was found with a passive exoskeleton (Baltrusch et al., 2019).

Changes in lower-limb-muscle activity were investigated in 11 studies (4 on active, 7 on passive exoskeletons); significant differences were identified in 5 studies (3 on active, 2 on passive exoskeletons). A significant reduction was reported during lifting with active (m. Gluteus Maximus -41%, m. Biceps Femoris (BF) -5%) and passive exoskeletons (net BF and m. Vastus Lateralis (VL) -16%), and during static bending with passive exoskeletons (BF -22%). In one case of repetitive lifting with an active exoskeleton, a significant increase in m. Rectus Femoris (RF) activity was found (+40%).

Changes in L5/S1 moments and/or spinal compression forces were investigated in 7 studies (2 on active, 5 on passive exoskeletons); significant results were found in all but 1 study on active exoskeletons. Participants' L5/S1 moments were reduced by the active Robo-Mate exoskeleton (mean -13%, range -10% to -14%) and passive exoskeletons (mean -8%, range -3% to -23%). Likewise, spinal compression forces were reduced by the Robo-Mate exoskeleton (mean -19%, range -14% to -22%), and SPEXOR during lifting (-14%) and bending (-17%).

Changes in metabolic cost were investigated in 6 studies (1 on active, 5 on passive exoskeletons). Significant reductions were found in all studies on passive exoskeletons during repetitive lifting (mean -11%, range -6% to -18%). During static bending, one passive exoskeleton significantly reduced metabolic cost (-22%). An increase from baseline was observed during walking with and without a passive exoskeleton, but the increase was 5% larger when wearing the exoskeleton.

Different aspects of performance were investigated in 8 studies (2 on active, 6 on passive exoskeletons), and significant results were found in all. The number of lifting cycles until exhaustion was increased with an active (+30%) and a passive exoskeleton (+26%), and the number of scoops until exhaustion during snow-shoveling was increased 186% with an active exoskeleton. Snow-shoveling time increased by 149%, and shoveling distance by 269% with an active exoskeleton. Significant decline in performance was also observed with passive exoskeletons. Task completion time increased for ladder- and stair-climbing (+10% and +8% respectively), load carrying (+8%) and sit-to-stand (+9%); preferred walking speed decreased (-4%); walking and wide-stance distance decreased (-7% each), and fingertip-to-floor distance increased (+21%). Endurance time during static bending was increased with passive exoskeletons by 14% (median +7%, range 3-60%), more prominently with SPEXOR (+36%) than with Laevo™ V2.5 and BackX™ (+5% each).

3.4.2 Subjective measures

Changes in perceived exertion, physical capacity, perceived task difficulty and/or fatigue were investigated in 10 studies (3 on active, 7 on passive exoskeletons), with significant differences reported in all studies. Perceived exertion was significantly reduced during lifting with an active exoskeleton (-10%) and passive exoskeletons at the lower back (-36%), abdomen (-36%), lower limb (-25%) and upper limb (-23%). During static bending, passive exoskeletons reduced perceived exertion for females when unsupported by a chair (-41%), but increased it in males when sitting on a backless chair (+75%). Perceived physical capacity was increased (+7%), and perceived task difficulty decreased in repetitive lifting (-67%), static bending (-51%) and 3-point kneeling (-80%) with passive exoskeletons. Sit-to-stand, trunk rotation and wide stance were perceived as more difficult wearing a passive exoskeleton (+9%, +7% and +20% respectively). Fatigue was reduced with an active exoskeleton during lifting (-13% and snow shoveling (-47%).

Changes in general discomfort, local discomfort and/or local perceived pressure were investigated in 10 studies (1 on active, 9 on passive exoskeletons). Significant differences were reported in all but one study on passive exoskeletons. Local perceived pressure was evaluated with one active exoskeleton (Robo-Mate) at the back (27% max. LPP), hip (26% max. LPP) and thigh (40% max. LPP) during lifting. Changes in local discomfort were assessed with passive exoskeletons. Significant reductions were found in the lower and upper back, abdomen and upper legs during static bending (-43%, -87%, -72% and -33% respectively); and significant increase in local discomfort was found at the chest (+33%). Also reported was discomfort in armpits with Laevo™ V1. During 3-point kneeling, local discomfort was significantly reduced at the lower and upper back (-73% and -34% respectively); and during sit-to-stand, lower-back discomfort increased by 80% with one passive exoskeleton (SPEXOR). With passive exoskeletons, general discomfort was reportedly highest during walking (SPEXOR) and static bending (Laevo™), and lowest during 3-point kneeling (SPEXOR) and trunk rotation (Laevo™). One passive exoskeleton (SPEXOR) significantly reduced general discomfort during repetitive lifting, static bending and 3-point kneeling (-74%, -84% and -82% respectively).

Users' impressions were investigated in 7 studies on passive exoskeletons. The fit of Laevo™ and BackX™ was perceived as moderate, with BackX™ better compared to Laevo™. The adjustability of Laevo™ and SPEXOR was considered easy to moderate, and their donning/doffing easy to somewhat difficult. Interference of Laevo™ and SPEXOR with work tasks was perceived as low, and the restriction of range of motion as slight to moderate. Restriction of movement was larger with BackX™

than Laevo™. The efficacy of Laevo™ and SPEXOR was perceived as low to modest, and the support of tasks and reduction of back loading by SPEXOR as moderate. The efficiency (e.g. fast, practical, organized (Laugwitz et al., 2008)), perspicuity (e.g. clear, easy to learn, easy to understand (Laugwitz et al., 2008)) and dependability (e.g. predictable, secure (Laugwitz et al., 2008)) of Laevo™ were considered neutral, as were its attractiveness and stimulation (e.g. exciting, interesting (Laugwitz et al., 2008)); whereas the novelty of Laevo™ (e.g. creative, innovative (Laugwitz et al., 2008)) was rated positive. BackX™ was preferred over Laevo™ in two studies, and Laevo™ was rated as more helpful than BackX™ in one study. Also in two studies, the median overall grades of SPEXOR were 4 and 6 on a 0-10 scale, and the exoskeleton was rated rather unlikely to be used at work.

4. Discussion

The present systematic review includes 33 studies on back-support exoskeletons for occupational use published over the past 5 years. Fifteen of the studies were published in the year 2020, reflecting the increasing activity of research of this topic recently. A majority (20) focused on passive exoskeletons. Twelve studies on passive and two on active exoskeletons involved commercially available devices. There has been an increase in the testing of commercial devices. None of the exoskeletons included in the present work were discussed in our 2016 review (de Looze et al., 2016), and 9 additional studies were identified that were not reported in Theurel & Desbrosses (2019) (4 on active and 5 on passive exoskeletons). In the reviewed studies, the effects of exoskeletons on low-back loading, user performance and user satisfaction were assessed, as well as some side effects of their use.

4.1 Effects of industrial back-support exoskeletons during user testing

4.1.1 Effects of back-support exoskeletons on low-back loading

Back-support exoskeletons aim to provide a torque that contributes to back-extending torque as required in lifting or forward bending. Consequently, less muscle force of the back extensors is required, which results in lower compression of the lumbar intervertebral disks. Another effect of lower-back muscle activation is postponed onset of muscle fatigue.

The most commonly investigated objective measure was of back-extensor-muscle activity (of which peak values have been mainly reported). Overall, both active and passive exoskeletons were successful in significantly reducing the activity of back muscles, both in lifting (up to -48% for active, up to -35% for passive devices) and static bending (up to 61%). This is in line with the conclusion from previous reviews of de Looze et al. (2016) and Theurel and Debrosses (2019), although both reported somewhat higher maximal reductions for lifting. For static bending however, the maximal reductions reported in the previous reviews compared to the current review were lower (-25% (de Looze et al., 2016) and -57% (Theurel & Desbrosses, 2019)). These findings could be due to differences across individual studies in tested exoskeletons and their adjusted levels of support, but also tasks studied (simple vs. complex tasks) and task parameters (lifted weight, trunk angles, range of motion). While the results of studies cannot be directly compared unless the methodologies are identical, there are some general observations which are indicative of such variatoins. By way of example, regarding passive exoskeletons, Frost et al. (2009) in our first review found a 43% reduction in back-muscle activity, whereas Alemi et al. (2019) in the current review observed a 35% reduction. However, the study by Frost et al. (2009) was of PLAD during lifting 15-kg loads from floor level, whereas the study by Alemi et al. (2019) of VT-Lowe's exoskeleton tested lifting of 16 kg from 50 cm above floor height. Regarding active exoskeletons, the study in our previous review by Kobayashi and Nozaki (2008) of Muscle suit found over 60% of a reduction in muscle activity during holding of 15-kg loads for 4 s in a stoop position, whereas the study in our current review by Wei et al. (2020) of Hip Active Exoskeleton observed a 48% reduction during semi-squat lifting of 8-kg loads.

Reduction in back muscle activity is meaningful when leading to lower or postponed muscle fatigue. Support for this assumption has been found in various studies showing increased endurance times, up to 60% in static bending with a passive exoskeleton and by 149% in snow shoveling with an active exoskeleton. Back-muscle activity reduction is also meaningful when leading to lower spinal compression. Here, it should be noted that small differences in spinal angle may have a very large effect on muscle activity when bending forward. This occurs due to the fact that at a certain point, passive low back structures take over the torque-providing role of back muscles, i.e. the 'flexion-relaxation phenomenon' (Toussaint et al., 1995). Consequently, the differences in muscle activity found by this review could be a result of different trunk angles across the tested conditions, rather than a direct effect of exoskeleton support. Thus, the relationship between back-muscle activity and spinal compression may be obscured if the trunk angle is not controlled for (Koopman et al., 2019b).

Abdominal-muscle activity was also addressed in some reviewed studies. An increase in abdominal-muscle activity contributes to increased spinal compression and is therefore considered an unwanted side effect. Mixed results were obtained in terms of abdominal muscle activity: both increases and decreases were reported for static bending. It is difficult to explain these mixed results, as beside the type of exoskeleton, other task-related factors may play a role.

Six studies investigated the effect of active and passive exoskeletons on the torque generated by the participant. They found reductions in L5/S1 moments which were generally larger for the active versus passive exoskeletons tested. In five studies, spinal compression forces were estimated based on inverse dynamics and an EMG-driven muscle model incorporate both the active and passive contributions to the net joint torque. It was found that spinal compression forces were significantly reduced by the exoskeletons during lifting, to a larger extent for active designs (up to -22%) than passive (-14%). Earlier results on spinal compression and passive exoskeletons showed reductions up to -29% for dynamic lifting (Abdoli-Eramaki et al., 2006) and -13.5% for static bending (Ulrey & Fathallah, 2012).

Trunk flexion angle has also been used as a measure to evaluate exoskeleton effects. The amount of flexion at the lumbar spinal discs may be a risk factor in itself for developing injury. For dynamic lifting, the trunk flexion angle has been found to decrease with active exoskeletons (up to -35%), but increase with passive exoskeletons (up to +22%).

However, performance in terms of productivity in real work can not be predicted from the above data as they were largely laboratory studies. Ultimately, testing in actual work settings is necessary to fully evaluate this.

4.1.2 Effects of back-support exoskeletons on user performance

There has been an increased emphasis on studying the effects of exoskeletons on user performance in recent years, with some mixed findings. Back-support exoskeletons increased user performance in terms of endurance time and the number of lifting cycles. Endurance time for static bending increased up to 60% with passive exoskeletons, and 1.5-fold for snow shoveling with an active exoskeleton. A 20% increase in endurance time was previously also reported by de Looze et al. (2016) for lifting with a passive exoskeleton. The number of lifting cycles increased with both active (+30%) and passive devices (+26%). Performance significantly decreased during ladder- and stair-climbing, load carrying, walking, sit-to-stand, and forward-bending tasks, due to physical hindrance by passive exoskeletons. These aspects were not reflected in the previous reviews. However, performance in terms of productivity in real work cannot be predicted form the above data as they were largely laboratory studies. Ultimately testing in actual work settings is necessary to fully evaluate this.

4.1.3 Studies involving subjective evaluations

Users' impressions (as an aspect of user experience) were specifically investigated on passive exoskeletons in 6 studies. Overall satisfaction was moderate. Efficacy was rated low to modest, and likelihood to use at work unlikely in one instance (Baltrusch et al., 2020a). In a number of studies, participants reported some negative impressions regarding the practical nature of designs, ease of understanding, dependability, attractiveness, and issues with exoskeleton fit and ease of donning/doffing. Given users' satisfaction can affect their willingness to try/adopt technologies (Shore et al., 2020), exoskeleton design should include these aspects in addition to effectiveness and efficiency.

4.2 Side-effects of back-support exoskeletons

There is also a growing focus on studying negative side-effects of exoskeletons during use. Howard et al. (2020) highlighted potential risks associated with industrial exoskeletons. Example include muscle strain due to kinematic mismatch between exoskeletons and users, increased antagonist muscle activity, reduced postural balance and overall mobility, increased chest/spine loading, and pressure-related tissue injuries. Negative side effects are expected to be considerably more prevalent and elevated in dynamic/variable and restricted work settings versus tightly controlled laboratory testing scenarios. It is recommended therefore that studies should specifically assess potential risks and side effects during exoskeleton testing. Further, it is recommended that there is increased testing of exoskeletons in varied real-world industrial tasks and involving workers.

Increased leg-muscle activity is also a potential undesirable effect as it contributes to increased energy expenditure and accelerates the onset of fatigue. Active exoskeletons were noted to cause a reduction in hip-extensor activity (up to -41%) and an increase in hip-flexor activity in one case (+40%). A passive exoskeleton caused a 24% decrease in hip-extensor activity during static bending (Bosch et al., 2016). In one study on a passive exoskeleton, the net activity of a hip extensor/knee flexor (BF) and knee extensor (VL) was significantly reduced (up to -23%) during lifting (Alemi et al., 2019). In conclusion, the observation of unwanted increases in leg-muscle activity are scarce, while a limited number of studies showed opposite findings.

Knee over-extension and increased trunk flexion was observed during static bending with passive exoskeletons, as well as increased durations of detrimental back-rotation and knee-flexion angles.

During lifting, back flexion decreased with active (up to -35%) and increased with passive exoskeletons (up to +22%). In contrast, de Looze et al. (2016) found decreases in back flexion (up to -17%) with passive exoskeletons, and changes of lifting technique towards squatting (knee flexion). These findings mainly show that negative side effects may occur at the knee and low-back level. Evaluation of these effects should considered during exoskeleton evaluation studies.

4.3 Recent trends and considerations regarding industrial exoskeleton testing

Positive developments were observed in the approach to exoskeleton usability testing since our previous review. Early studies of industrial exoskeletons often comprised relatively simple tasks involving a narrow range of movements, whereas the recent trend is towards increased variability and variety of tasks, while also including more subjective elements in usability assessments. There is also recently a broader consideration for effectiveness as per differing relevant metrics for different workplaces. Moreover, there has been an increased focus on the study of usability of exoskeletons, but also more holistically various aspects under the theme of user experience.

Based on the reviewed studies, however, certain methodological aspects of exoskeleton usability testing would benefit from improvement, especially regarding the choice of participants , the study settings, types of evaluation, and methods of testing and data reporting. The median number of test participants was 10 (range 5-20) for active and 12 (range 8-24) for passive exoskeletons. In their recent commentary, Howard et al. (2020) recommend that in excess of 15 participants be involved in exoskeleton evaluation studies. Roughly two-thirds of studies were only performed on men, with three-quarters only on healthy subjects. Just 2 studies (Amandels et al., 2018; Motmans et al., 2019) were performed on intended workers at the workplace, and involved somewhat longer periods (30 and 90 minutes) of continuous exoskeleton use (Laevo™ V2.4 and V2.5) during complex tasks (repetitive far reaching with bending, load picking). In general, studies on passive exoskeletons involved larger numbers of participants that were also more representative of the intended exoskeleton-user group and tested more often in realistic settings.

In the past three years, different studies have cautioned about the limited value of laboratory studies in laboratory settings using university students / staff as they lack many constraints of real work environments and tasks, as well as the acceptance assessment of the intended users (Spada et al., 2018; Theurel & Desbrosses, 2019). Less than half of the studies involved subjective evaluation, and those that did were mainly of further developed concepts by way of commercially available exoskeletons. There is a lack of evidence of user experience studies being performed during prototypes stage testing.

User satisfaction is one of the three main components of product usability (ISO/IEC 25022:2016), and users' attitudes toward such technology is considered a crucial aspect affecting industrial workers' acceptance (Dwivedi et al., 2019; Elprama et al., 2020). It is recommended that there is increased user experience and usability assessment of exoskeletons over longer periods of time, and involving industrial workers in their actual workplaces.

The development of exoskeletons would greatly benefit from increased guidance and standardization of testing and reporting methods. We noted variability with anatomical nomenclature, and justification for the study of certain muscle groups/regions. Lowe et al. (2019) describe the presently ongoing efforts by ASTM Committee F48 to develop and standardize instruments for usability assessment of exoskeletons and exosuits. Similar activity is being progressed through ISO TC 299 WG1. Four related studies were included in this review that employed a functional performance test battery involving 12 tasks to assess the support and hindrance of the user by the exoskeleton (Baltrusch et al., 2018; Baltrusch et al., 2020a; Baltrusch et al., 2020c; Kozinc et al., 2020). The related test battery is based on an established method for assessing work-related physical performance, building on the methods of Reneman et al. (2004), with additional tasks reflecting real workplace situations (Baltrusch et al., 2018). It is recommended that there is continued research regarding standardization of exoskeleton testing methodologies.

Varying approaches were also noted in the reporting of data. For EMG data, it is recommended that peak and mean values be reported for dynamic tasks (e.g. lifting), and mean values (at a minimum) for static tasks (e.g. bending and holding loads). A special caution is necessary regarding interpreting percentage changes involving small initial absolute values. Caution is also recommended regarding subjective measures with non-normal distributions, e.g. standard deviations 5-times the mean values. In such case, reporting interquartile ranges might be more appropriate.

4.4 Limitations

The authors acknowledge certain limitations to this study. There may be other studies that fall outside the search and inclusion criteria of this systematic review. However, 33 new studies have been identified since our previous review, and we expect these are a reasonable reflection of the present technological developments and associated ergonomics evaluation approaches.

The study notes trends and comparisons regarding active and passive exoskeletons. However, they are often tested in different experimental settings and during different tasks. Therefore, such comparisons need to be considered with caution.

5. Conclusions

This systematic review identified 33 studies of industrial back-support exoskeletons since our previous review (de Looze et al., 2016). The current review was expanded to specifically detail objective and subjective evaluations.

Thirteen studies were of active and nineteen of passive back-support exoskeletons. Over the past five years, there has been an important increase in the evidence regarding the effectiveness of industrial exoskeletons in reducing back-muscle activity. Significant reductions were identified during lifting (up to -48% for active and up to -35% for passive devices) and static bending tasks (up to -12% for active and up to -61% for passive devices). Significant reductions were also found regarding participants' peak L5/S1 moments (up to -14% for active and up to -23% for passive devices) and spinal compression forces (up to -22% for active and up to -14% for passive devices) during lifting. Spinal compression forces were reduced up to 17% with passive exoskeletons during static bending tasks.

Since our previous review there has been a trend towards studies investigating users' performance and subjective experiences of industrial exoskeletons. Some exoskeletons were shown to increase users' performance, decrease perceived task difficulty, and decrease exertion and fatigue during the tasks they were designed to assist with (e.g. repetitive lifting, static bending). However, it has been noted in instances that additional weight and restricted movement of some designs can lead to decreased performance and increased perceived task difficulty. It is clear that the technology landscape of industrial exoskeletons has evolved considerably and that they can have an important benefit on the loading of workers' bodies. A remaining challenge for mainstream adoption of these technologies in industry is for the designs to provide further superior usability and user experience in the absence of negative side-effects. To support this aim, there is a need for increased emphasis on field studies, involving industrial workers rather than surrogates, and including exoskeleton use for durations comparable to actual work situations. Regarding methodological considerations, there is a need for standardization of test methods and reporting of findings.

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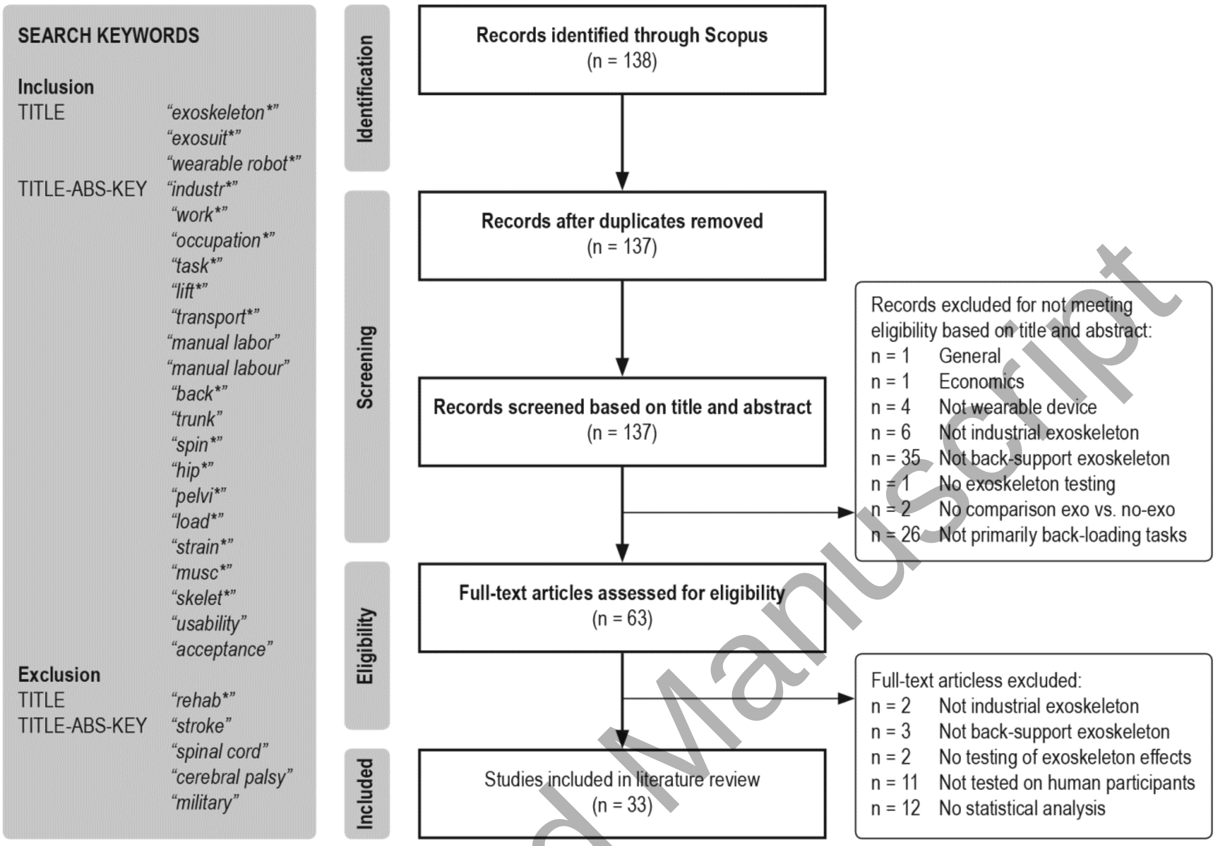

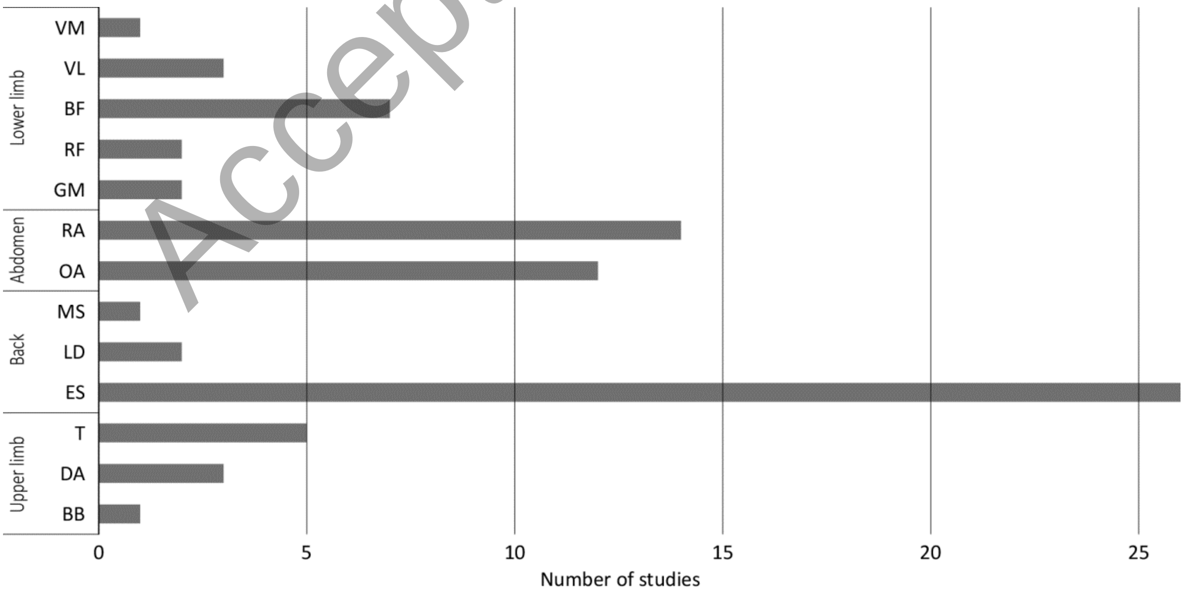

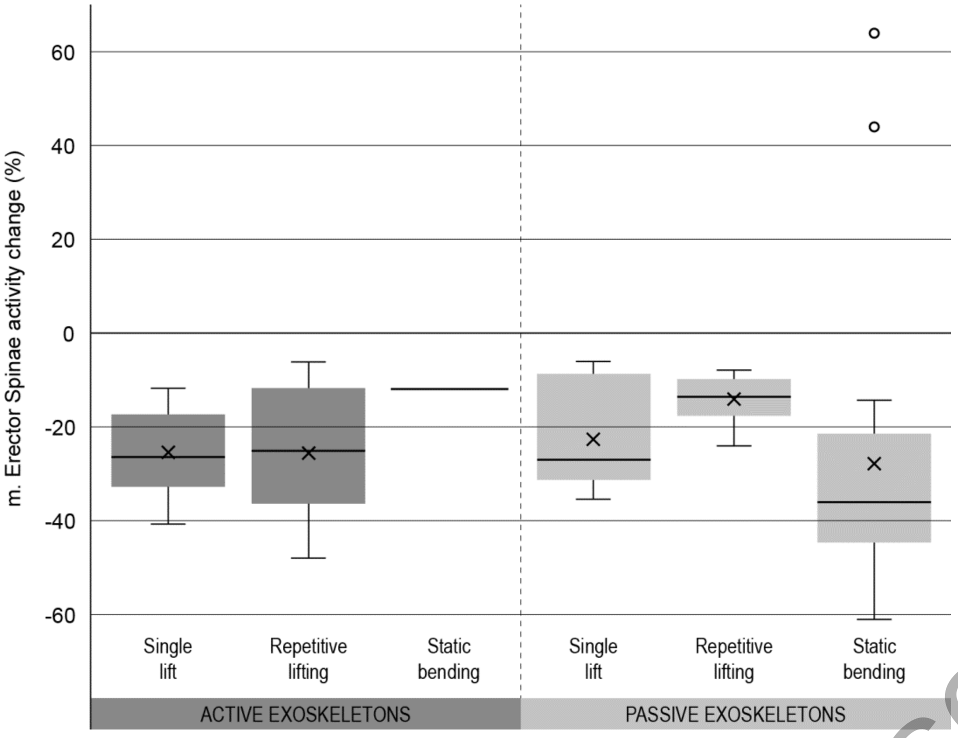
m. Erector Spinae activity change (%)
60
40
20
0
-20
-40
-60
Single lift
Repetitive lifting
Static bending
Single lift
Repetitive lifting
Static bending
ACTIVE EXOSKELETONS
PASSIVE EXOSKELETONS

Table 1: Summary of reviewed studies on active back-support exoskeletons for occupational use.
Listed alphabetically by exoskeleton name.

EXOSKELETON	**STUDY**	**TESTING**			**RESULTS**
Name *(manufacturer)* Stage of design **Type** Purpose		**Participants**	**Study design**	**Study variables**	
Active Pelvis Orthosis – APO *(BioRobotics Institute of Scuola Superiore Sant'Anna)* Prototype **Active, rigid** Assistive torque at the hip for hip/trunk flexion/extension in lifting tasks.	(Chen et al., 2018)	7♂ Healthy 27.9 ± 2.3 yrs	**Laboratory study** 3 tasks performed with APO in transparent/active mode: A) Lifting 5-kg load from stand (20 cm) to table (90 cm), returning to upright posture; lowering 5-kg load from table to stand, returning to upright posture; 10 repetitions, 5 lifting conditions. B) Standing from stool (40 cm), walk toward load, lift/lower once as in A), walk back, sit; 4 repetitions, 5 lifting conditions as in A). C) Standing up from stool (40 cm), walking toward load, lifting/lowering 3-times as in A) with freestyle lifting technique, walking back, sitting down; 10 repetitions, 3 lifting speeds. **Measurements** <u>Objective:</u> EMG: left ES-L, ES-T, ESI.	<u>Independent:</u> Exoskeleton: APO transparent mode (TM), APO active mode (AM). 5 lifting conditions (A, B): – 3 lifting techniques (stoop, squat, freestyle); – 3 load starting positions (front, left, right). 3 lifting conditions (C): – freestyle lifting technique, front load starting position; – 3 lifting speeds: normal (personal preferred), slow, fast. <u>Dependent:</u> Changes in median EMG activity during lifting (trunk extension).	<u>EMG:</u> ▼ ES-L (30.0%); ▼ ES-T (34.1%); ▼ ESI (30.4%).
	(Lanotte et al., 2018)	5♂ Healthy 29 ± 3 yrs	**Laboratory study** 2 tasks performed with APO: A) Lifting 5-kg load from stand (20 cm) to table (90 cm), returning to upright posture; B) Lowering 5-kg load from table to stand, returning to upright; 30 repetitions at 10-times/min.; 10 min inter-trial recovery. **Measurements** <u>Objective:</u> – EMG: unilaterally ES-L, ES-T, ESI, BF, RF; – Trunk extension time.	<u>Independent:</u> Exoskeleton: APO in transparent mode (TM), active mode (AM). <u>Dependent:</u> Changes in EMG activity; Changes in trunk extension time.	<u>EMG:</u> A) ▼ ES-T (6%); B) ▼ ES-L (33.0%); ▼ ES-T (10.1%); ▼ ESI (8.9%); ▲ RF (40.1%). <u>Trunk extension time</u>: ▼ 19.1% (median).
Custom exoskeleton robot *(Incheon National University, Kwangwoon University, Rehabilitation Engineering Research Institute Korea, HMH Co.)* Prototype **Active, rigid** N/A	(Hussain et al., 2020)	3♀, 7♂	**Laboratory study** Lifting load from floor, using preferred lifting technique, with/without exoskeleton. **Measurements** <u>Objective:</u> Lifting posture (photographs). *Analysis using 3DSSPP (University of Michigan)*	<u>Independent:</u> Exoskeleton: none, exoskeleton, exoskeleton - neglecting its weight and assistive force; Load: 5, 10, 15 kg *(randomly assigned to participants).* <u>Dependent:</u> Mean low back compression.	No statistically significant effects found.

HAL™ for Care Support *(Cyberdyne)* Commercial **Active, rigid** EMG-controlled (erector spinae muscle) assistive torque at the hip for back load reduction during lifting/ lowering tasks.	(Miura et al., 2018)	9♂ Healthy 26-44 yrs	**Laboratory study** Snow-shoveling task performed with straight-shaft shovel (106-cm length, 24.5-cm width, 756-g mass), with/without HAL™: Scooping as much snow as possible, throwing it over personal stature (i.e. 80.5-90 cm) as fast as possible until fatigued; 5-min inter-trial rest. **Measurements** Objective: – Number of scoops and shoveling time until fatigued; – Mean shoveling distance; – Heart rate and blood pressure before and after trial. Subjective: Lumbar fatigue perception: VAS (100-mm).	Independent: Exoskeleton: none, HAL™; Dependent: Changes in number of scoops until fatigued; Changes in shoveling time until fatigued; Changes in shoveling distance; Changes in heart rate and blood pressure; Changes in lumbar fatigue perception.	Number of scoops: ▲ 186%; Shoveling time: ▲ 149%; Shoveling distance: ▲ 269%; Lumbar fatigue perception: ▼ 47%.
	(Tan et al., 2019)	7♀, 13♂ Healthy 31.5 ± 6.6 yrs	**Laboratory study** Stoop lifting/placing of 12-kg (♂) /6-kg (♀) load at 30-times/min., until exhaustion, with/without HAL™; 15 min inter-session recovery. **Measurements** Objective: – Number of lifting cycles until exhaustion; – EMG: BB, ES, GM, LD; – Motion capture of acromion, trochanter major, malleolus lat. Subjective: Fatigue perception at the end of each session: VAS (0 - 10).	Independent: Exoskeleton: none, HAL™; Fatigue: non-fatigued, fatigued. Dependent: Changes in number of lifting cycles until exhaustion; Changes in EMG activity; Changes in hip angular velocity; Changes in fatigue perception.	Number of lifting cycles: ▲ 30%. EMG - non-fatigued: ▼ Right LD (NMV); ▼ Left LD (NMV); ▼ Right ES (NMV); EMG - fatigued: ▼ Right LD (NMV). Hip angular velocity: Generally higher with HAL™ when non-fatigued; With HAL™ when fatigued, similar to non-fatigue and fatigue conditions without exoskeleton. Fatigue: ▼ 13%.
Hip Active Exoskeleton *(College of Optoelectronics Science and Engineering, Micro-Nano Automation Institute)* Prototype **Active, rigid** Assistive torque at the hip and spine for lower-back load reduction during semi-squat lifting.	(Wei et al., 2020a)	A) 3 participants of different stature (170 ± 5.0 cm) and body mass (70 ± 5 kg) 24 ± 3 yrs B) 7♂ Healthy 25 ± 3 yrs	**Laboratory study** 5 min. of repetitive lifting/lowering 8-kg load from floor to 0.5-m platform and back at controlled frequency, using semi-squat lifting technique, with/without exoskeleton; 3 repetitions (A). **Measurements** Objective: – Metabolic cost (A); – EMG: ES-L, ES-T (B); – Motion capture (B).	Independent: Exoskeleton: none, exoskeleton; Dependent: Changes in metabolic cost. Changes in EMG activity;	EMG: ▼ ES-L left (47%); ▼ ES-L right (30%); ▼ ES-T left (48%); ▼ ES-T right (37%).
Portable Pneumatic Back Support Exoskeleton *(Advanced Institute of Science and Technology Korea, Shirley Ryan AbilityLab Chicago)* Prototype **Active, rigid** Assistive torque at the hip for lower-back load reduction during lifting tasks.	(Heo et al., 2020)	10♂ Healthy 22.3 ± 1.7 yrs	**Laboratory study** Stoop-lifting of load from 30 cm above floor to upright posture; 6 lifts/1 min., with/without exoskeleton. **Measurements** Objective: EMG: ES-L, ES-T.	Independent: Exoskeleton: none, exoskeleton; Load: 10 kg, 20 kg. Dependent: Changes in mean EMG activity.	EMG (10/20 kg): ▼ ES-L (25.5/24.7%); ▼ ES-T (18.3/18.7%).

Robo-Mate *(Robo-Mate project consortium)* Prototype **Active, rigid** Assistive torque at the hip for back load reduction during lifting/lowering tasks.	(Huysamen et al., 2018)	11♂ Healthy 27 ± 2 yrs	**Laboratory study** 5 cycles of lifting/lowering 2 loads from mid-shin to waist height with/without Robo-Mate; min. 5 min inter-trial recovery. **Measurements** Objective: – EMG at right side of body: BF, ES, RA; – Contact pressure at left side of body. Subjective: – Perceived exertion: Borg CR-10 scale (0 - no physical exertion, 10 - almost maximal exertion); – Perceived musculoskeletal pressure: LPP (0 - no pressure, 10 – extremely strong pressure); – Exoskeleton usability: SUS (1 - strongly disagree, 5- strongly agree; SUS > 70 - acceptable).	Independent: Exoskeleton: none, Robo-Mate; Load: 7.5 kg, 15 kg. Dependent: Changes in peak EMG activity; Contact pressure at: – left shoulder (S); – left hip (H); – left thigh (T). Changes in perceived exertion; Changes in perceived musculoskeletal pressure at: – back/shoulders (B); – belly/hips (H); – thighs (T). Perception of exoskeleton usability.	EMG (7.5/15-kg load): ▼ ES (12/15%); ▼ BF (5/5%). Contact pressure for 7.5/15-kg load: **S** 48.0/51.9 kPa; **H** 91.6/93.6 kPa; **T** 69.1/81.2 kPa. Perceived exertion (7.5/15-kg load): ▼ B (9.5/11.4%). Local perceived pressure (7.5/15-kg load): **B** 25/28% max.LPP; **H** 24/27% max.LPP; **T** 35/44% max.LPP. SUS>70: 6/10 participants.
	(Lazzaroni et al., 2019)	7 participants Healthy	**Laboratory study** Lifting/lowering 2 loads using preferred lifting technique, with/without Robo-Mate at 3 lifting speeds. **Measurements** Objective: EMG: ESI.	Independent: Exoskeleton: none, Robo-Mate inclination control strategy, Robo-Mate dynamic control strategy; Load: 5 kg, 10 kg. Lifting speed: slow, normal, fast. Dependent: Changes in peak EMG activity.	No statistically significant effects found.
Robo-Mate Mk2b *(Robo-Mate project consortium)* Prototype **Active, rigid** Assistive torque at the hip for back load	(Toxiri et al., 2018)	11♂ Healthy 25.0 ± 6.9 yrs	**Laboratory study** 3 cycles of lifting/lowering 2 loads from mid-shin height to upright posture using preferred lifting technique and speed, with/without Robo-Mate. **Measurements** Objective: EMG: ESI.	Independent: Exoskeleton: none (A), Robo-Mate inclination control strategy (B), Robo-Mate sEMG control strategy (C), Robo-Mate hybrid control strategy (D); Load: 7.5 kg, 15 kg. Dependent: Changes in peak EMG activity.	Peak ESI (7.5/15-kg load): B)▼ (33.3/31.5%); C)▼ (28.2/29.3%); D)▼ (34.5/31.8%).

reduction during lifting/lowering tasks.	(Koopman et al., 2019a)	10♂ Healthy 25.0 ± 6.9 yrs	**Laboratory study** Lifting/lowering 15-kg load from 10 cm above ankle height to upright posture with/without Robo-Mate, using 3 lifting techniques; 5 min inter-trial recovery. **Measurements** Objective: – EMG: ESI, ESL-L, OEA, OIA, RA; – Ground reaction force; – Trunk and hip inclination angle; – Hip actuator torque.	Independent: Exoskeleton: none (A), Robo-Mate inclination control strategy (B), Robo-Mate sEMG control strategy (C), Robo-Mate hybrid control strategy (D); Lifting technique: stoop, squat, freestyle. Dependent: Changes in net lumbar EMG activity (ESI, ESL-L); Changes in net abdominal EMG activity (OEA, RA); Changes in peak lumbar flexion angle; Changes in peak spine compression forces; Changes in peak L5/S1 moment; Changes in peak trunk angular velocity.	Net lumbar EMG: B)▼ freestyle (21.5%), squat (23.3%), stoop (16.2%); C)▼ freestyle (18.5%), squat (23.3%), stoop (11.8%); D)▼ freestyle (20.0%), squat (24.7%), stoop (14.7%). Peak lumbar flexion angle: B)▼ freestyle (35.2%), squat (31.0%), stoop (29.2%); C)▼ freestyle (29.6%), squat (19.0%), stoop (29.2%); D)▼ freestyle (33.3%), squat (28.6%), stoop (29.2%). D-squat < C-squat. Peak spinal compression force: B)▼ freestyle (19.8%), squat (22.2%), stoop (16.9%); C)▼ freestyle (18.3%), squat (20.3%); D)▼ freestyle (19.1%), squat (21.4%), stoop (14.2%); B-stoop < D-stoop. Peak subject L5/S1 moment: B)▼ freestyle (13.6%), squat (12.4%), stoop (13.7%); C)▼ freestyle (13.2%), squat (12.8%), stoop (9.8%); D)▼ freestyle (13.2%), squat (11.5%), stoop (13.2%). Peak trunk angular velocity: B)▼ freestyle (28.6%), squat (27.8%), stoop (25.9%); C)▼ freestyle (28.1%), squat (25.7%), stoop (24.1%); D)▼ freestyle (27.1%), squat (24.1%), stoop (23.5%).

Soft Exoskeleton Suit *(Hiroshima University, Daiya Industry Co.)* Prototype **Active, soft** Assistive torque at the hip to support bending motions of the upper body in construction work.	(Tsuneyasu et al., 2018)	5 participants	**Laboratory study** 5 s upright posture, 5 s bending forward position, return to upright posture on balance Wii board, with/without exosuit. **Measurements** Objective: – EMG: ES; – CoM.	Independent: Exoskeleton: none, exosuit with angle-based control (A), exosuit with torque-based control (T). Dependent: Changes in EMG activity; Changes in CoM standard deviation.	EMG: ▼ ES (12%); T > A. CoM standard deviation: ▼ (4 mm).
Hyundai Waist Assistive Exoskeleton version I (H-WEXv1) *(Hyundai)* Prototype **Vs.** **Hyundai Waist Assistive Exoskeleton version II (H-WEXv2)** *(Hyundai)* Prototype **Active, rigid** Assistive torque and upper body support during stoop and crouch lifting.	(Hyun et al., 2020)	10♂ Healthy 34.9 ± 2.1 yrs	**Laboratory study** 5 repetitions of lifting/lowering 15-kg load from knee height to pelvic height with/without H-WEX; 2 lifting techniques. **Measurements** Objective: EMG: BF, ES, GM, RA, RF.	Independent: Lifting technique: stoop, semi-squat; Exoskeleton: none, H-WEXv1 (one-directional power-transmission - hip extension), H-WEXv2 (two-directional power-transmission - hip flexion/extension). Dependent: Changes in EMG activity	EMG: ▼ ES-stoop (H-WEXv2 40.7%); ▼ ES-semi-squat (H-WEXv2 33.0%); ▼ GM-stoop (H-WEXv2 41.1%); ▼ GM-semi-squat (H-WEXv2 41.6%).

▼Significant decrease, ▲ Significant increase, NMV – No mean value provided; BB – m. Biceps Brachii, BF – m. Biceps Femoris, ES – m. Erector Spinae, ES-L – m. Erector Spinae - Lumbar, ES-T – m. Erector Spinae - Thoracic, ESI – m. Erector Spinae - Iliocostalis, ESI-L – m. Iliocostalis Lumborum, ESL – m. Erector Spinae - Longissimus, ESL-L – m. Longissimus Lumborum, GM – m. Gluteus Maximus, LD – m. Latissimus Dorsi, MS – m. Multifidus spinae, OEA – m. Obliquus Externus Abdominis, OIA – m. Obliquus Internus Abdominis, RF – m. Rectus Femoris; CoM – Centre of Mass, EMG – Electromyography, LBP – low back pain, LPP – Local Perceived Pressure Scale, SUS – System Usability Scale, VAS – Visual Analog Scale, yrs – years of age.

Table 2: Summary of reviewed studies on passive back-support exoskeletons for occupational use.
Listed alphabetically by exoskeleton name.

EXOSKELETON **Name** *(manufacturer)* Stage of design **Type** Purpose	**STUDY**	**TESTING**			**RESULTS**
		Participants	**Study design**	**Study variables**	
Laevo™ V1 *(InteSpring)* Commercial **Passive, rigid** Force transfer from lower back to chest and thighs.	(Bosch et al., 2016)	9♀, 9♂ Healthy 25 ± 8 yrs	**Laboratory study** 2 tasks performed with/without Laevo™: A) Simulated assembly work: 10 cycles of repetitive pick-and-place actions at 15 cm below trochanter major (40° trunk flexion), 40-times/min. + moving bins to shoulder height; 30 s inter-cycle recovery. B) Static holding task: Maintenance of 40° trunk flexion with upper limbs hanging down until "somewhat severe" discomfort (Borg = 2). **Measurements** Objective: – EMG: BF, ESI, ESL, OEA, RA, TA; – Motion capture of trunk angle (processus spinosus C7-L5). Subjective: Local discomfort: LPD (0 - no discomfort, 10 - extreme discomfort); rating every 2nd work cycle (A) or every 30 s (B).	Independent: Exoskeleton: none, Laevo™; Work cycle (A). Dependent: Changes in EMG activity; Changes in endurance time; Changes in trunk posture; Changes in LPD scores.	EMG: A)▼ TA (44%); ▼ ESL (35%); ▼ ESI (38%); ▼ BF (20%). B)▼ TA (50%); ▼ ESL (37%); ▼ ESI (44%); ▼ RA (N/A); ▼ BF (24%). Joint angle: A) Knee over-extension; ▲ Trunk flexion (5.2°). LPD: A)▼ Back (NMV); ▲ Chest (NMV); Discomfort in armpits. Endurance: B)▲ 3-fold.
	(Baltrusch et al., 2018)	18♂ Healthy 27.7 ± 5.1 yrs	**Laboratory study** 12 tasks performed with/without Laevo™: A) Repetitive lifting 20-kg load from ankle height in 2 min; B) Carrying a 20-kg box 10 m; C) Performing a high-precision manual task on a table at knee height with 30-60° trunk flexion, max. 5 min.; D) Performing a high-precision manual task in three-point kneeling position with one hand on the floor, max. 5 min.; E) Walking as far as possible in 6 min; F) 5 sit-to-stand and stand-to-sit as quickly as possible; G) Climbing up/down 20 stairs as fast as possible; H) Climbing up and down a ladder twice; I) Forward bend with knees extended; J) Standing with feet 20 cm apart, increasing distance by 20 cm; K) 5 trunk rotations to both sides; L) 3 squats with heels on the ground. **Measurements** Objective: – Number of lifts (A); – Carrying time (B), holding time (C, D), sit-to-stand time (F), stair-/ladder-climbing time (G, H); – Walking distance (E), fingertip-to-floor distance (I); wide-stance distance (J). Subjective: – Perceived level of general discomfort, local discomfort, task difficulty: VAS (0 - no difficulty/discomfort, 10 - maximum difficulty/discomfort), rating at the end of each task. – Users' impression questionnaire: VAS (0 - 10), rating at the end of session.	Independent: Exoskeleton: none, Laevo™. Dependent: Changes in mean objective performance: A) Maximal number of lifts; B) Carrying time; C) Holding time; D) Holding time; E) Walking distance; F) Sit-to-stand time; G) Stair-climbing time; H) Ladder-climbing time; I) Fingertip-to-floor distance; J) Maximal wide-stance distance. Changes in perceived task difficulty; General discomfort; Changes in local discomfort: chest, abdomen, upper back, lower back, upper legs ventral and upper legs dorsal side; Users' impression: – Adjustability of Laevo™; – RoM with Laevo™; – Laevo™ efficacy; – Interference of Laevo™ with tasks.	Performance: B)▼ 8.3%; E)▼ 7.6%; G)▼ 7.6%; H)▼ 12.7%; I)▼ 20.5%. Perceived task difficulty: C)▼ 58,5%; F)▲ 225%; J)▲ 444%; K)▲ 650%; L)▲ 750%. General discomfort: Highest: trunk bending (5.35 ± 3.4); Lowest: trunk rotation (2 ± 1.85). Local discomfort: C)▲ chest 133%; ▼ lower back 70%; ▼ upper legs 76%; D)▼ upper back 71%. Users' impression: Adjustability: easy/moderate; RoM: moderate; Efficacy: limited; Interference with tasks: low.

Laevo™ V2.4 *(InteSpring)* Commercial **Passive, rigid** Force transfer from lower back to chest and thighs.	(Amandels et al., 2018)	9♂ LBP 45.6 ± 11.6 yrs Multitasking workstation on shop floor workers.	**Field study** 3 weeks of Laevo™ use at 2 workstations. 30 min. of work at the workstation (frequent far reaching for items with bending) with/without Laevo™. **Measurements** Objective: – EMG: dominant BF, ES, TD; – Motion capture. Subjective: – Perceived level of local discomfort: 10-point Likert-scale (0 - no discomfort, 10 - extreme discomfort) – User-experience questionnaire: 26 questions, 7-point rating scale (−3 - +3; negative < −0.8, neutral −0.8 - +0.8, positive > +0.8).	Independent: Exoskeleton: none, Laevo™; Dependent: Changes in EMG activity; Changes in joint angles; Changes in perceived local discomfort at 9 locations; User experience: – Attractiveness of Laevo™; – Perspicuity of Laevo™; – Efficiency of Laevo™; – Dependability of Laevo™; – Stimulation of Laevo™; – Novelty of of Laevo™.	EMG: ▲ TD 26% (median RMS). Joint angle: ▲ Duration of detrimental back-rotation and knee-flexion angles. Local discomfort: ▲ Chest (NMV); ▲ Thigh (NMV). User-experience: Attractiveness: neutral (-0.17); Perspicuity: neutral (+0.17); Efficiency: neutral (+0.28); Dependability: neutral (-0.14); Stimulation: neutral (+0.00); Novelty: positive (+0.92).
Laevo™ V2.5 *(InteSpring)* Commercial **Passive, rigid** Force transfer from lower back to chest and thighs most pronounced at user bending angle 35°.	(Motmans et al., 2019)	10♂ 5 LBP in previous year 37 ± 8 yrs Order pickers of cheese.	**Field study** 1.5 h of load picking at the workplace with/without Laevo™. **Measurements** Objective: – EMG: ES, TD; – Motion capture. Subjective: Users' impression: 5-point scale – Perceived effect of Laevo™ on work task; – Perceived comfort of human-Laevo™ interface; – Perceived effectivity of Laevo™.	Independent: Exoskeleton: none, ; Lifting technique: stoop, squat, freestyle. Dependent: Changes in EMG activity; Perceived ease of donning/doffing Laevo™ Perceived ease of taking a box from pallet with Laevo™ Perceived ease of stepping on/off pallet jack with Laevo™ Perceived ease of placing the box in cart with Laevo™ Perceived ease of walking with Laevo™ Perceived comfort of chest support Perceived comfort of upper-leg support Perceived comfort of hip belt Perceived physical back load reduction Perceived fatigue reduction Perceived effect on back posture % time of awkward back/shoulder position	EMG: ▼ ES (right 12%, left 9%) Fatigue during downward movement (2.25) Users' impression: Highest: back load reduction (4.50); Lowest: stepping on/off pallet jack (1.75); Positive: – Handling box, walking, chest support, back posture (3.75); – Upper-leg support, hip belt (3.5); – Donning/doffing (3.25).
MeBot-EXO *(MeBot Intelligent Technology Company)* Prototype **Passive, rigid** Load transfer from lower back to abdomen and lower limbs for torso stabilization during forward bending.	(Wei et al., 2020b)	8♂ Healthy 24.0 ± 2.5 yrs	**Laboratory study** A) 5 min. of forward torso flexion with/without exoskeleton; 3 repetitions. B) 30 s of 50–55° forward torso flexion with/without exoskeleton; 3 repetitions. **Measurements** Objective: – Metabolic cost (A); – EMG: ES-L, ES-T (B).	Independent: Exoskeleton: none, MeBot-EXO. Dependent: Changes in metabolic cost; Changes in EMG activity.	EMG: ▼ ES-L left (35%); ▼ ES-L right (40%); ▼ ES-T left (61%); ▼ ES-T right (57%). Metabolic cost: ▼ (22%).

Reconfigurable Trunk Exoskeleton *(University of Wyoming)* Prototype **Passive, rigid** Variable resistance application on the user's back during bending for torso stabilization.	(Goršič et al., 2019)	1♀, 11♂ Healthy 28 ± 12 yrs	**Laboratory study** Tasks performed with/without exoskeleton: A) Walking across laboratory in straight line at preferred pace; B) Lifting 9.1-kg load from the floor to waist level using preferred lifting technique; C) Stand up from stool (height adjusted for 90° knee flexion, thighs horizontally, feet forward); D) Sitting with rope around upper trunk attached to 9.1-kg weight (4 positions: front, back, left, right), random disconnection of weight to produce unexpected perturbation. **Measurements** Objective: – EMG: ES, RA; – Peak low-back extension moment (A-C); – Peak trunk flexion angle (A-C); – Trunk deflection: 150 ms, 300 ms after perturbation, peak (D).	Independent: Exoskeleton: none, low-low (LT-LA), low-high (LT-HA), high-low (HT-LA), high-high (HT-HA) thoracic-abdominal compression; Perturbation direction: front, back, left, right. Dependent: Changes in peak EMG activity; Changes in peak low-back extension moment; Changes in peak trunk flexion angle; Changes in trunk deflection 150 ms after perturbation; Changes in trunk deflection 300 ms after perturbation; Changes in peak trunk deflection.	A,B,C) Low-back extension moment: HT-LA > HT-HA. A,B,C) Trunk flexion angle: ▲ LT-LA (16%); ▲ LT-HA (22%). D) Trunk deflection: 300 ms: LT-LA > HT-LA.
SPEXOR *(Vrije Universiteit)* Prototype **Passive, rigid** Assistive torque at the hip and spine for lower-back load reduction during lifting and static bending tasks.	(Baltrusch et al., 2020a)	24♂ 13 LBP 11 Healthy 43.6 ± 7.7 yrs Luggage handling (airline industry), assembling and sorting (automotive industry) workers	**Laboratory study** (mock-up of workplace environment) 12 tasks performed with/without SPEXOR: Support by the exoskeleton: A) Repetitive lifting 20-kg load from ankle height in 2 min; B) Carrying a 20-kg box 10 m; C) Performing a simple manual task on a table at knee height with 30-60° trunk flexion, max. 5 min.; D) Performing a simple manual task in three-point kneeling position with one hand on the floor, max. 5 min.; Hindrance by the exoskeleton: E) Walking as far as possible in 6 min; F) 5 sit-to-stand and stand-to-sit as quickly as possible; G) Climbing up/down 20 stairs as fast as possible; H) Climbing up and down a ladder twice; Effect on range of motion: I) Forward bend with knees extended; J) Standing with feet 20 cm apart, increasing distance by 20 cm; K) 5 trunk rotations to both sides; L) 3 squats with heels on the ground. **Measurements** Objective: – Number of lifts (A); – Carrying time (B), holding time (C, D), sit-to-stand time (F), stair-/ladder-climbing time (G, H); – Walking distance (E), fingertip-to-floor distance (I); wide-stance distance (J). – EMG: BB, ES, GM, LD; – Motion capture: acromion, trochanter major, malleolus lat. Subjective: – Perceived level of general discomfort, local discomfort, task difficulty: VAS (0 - no difficulty/discomfort, 10 - maximum difficulty/discomfort), rating at the end of each task. – Users' impression questionnaire: VAS (0 - 10), rating at the end of session.	Independent: Exoskeleton: none, SPEXOR; Participants' medical condition: LBP, healthy. Dependent: Changes in mean objective performance: A) Maximal number of lifts; B) Carrying time; C) Holding time; D) Holding time; E) Walking distance; F) Sit-to-stand time; G) Stair-climbing time; H) Ladder-climbing time; I) Fingertip-to-floor distance; J) Maximal wide-stance distance. Changes in EMG activity; Changes in general low-back discomfort; Changes in local discomfort; Changes in perceived task difficulty; Users' impression: – Adjustability of SPEXOR; – RoM of SPEXOR; – SPEXOR efficacy; – Probability of SPEXOR use at work.	Performance: A)▲ 26 ± 47%; C)▲ 60 ± 74%, LBP 103 ± 78%; E)▼ 7 ± 6%; G)▲ 8 ± 8%; J)▼ 5 ± 9%, LBP 9 ± 11%. Perceived task difficulty: A)▼ 67%; C)▼ 70%; D)▼ 80%. General low-back discomfort: A)▼ 74%, LBP 89%; C)▼ 84%, LBP 86%; D)▼ 82%, LBP 83%; E) slight-moderate (median 2.8). Local discomfort: C)▼ abdomen (72%, LBP > healthy); ▼ upper back (87%, LBP > healthy); ▼ lower back (84%, LBP > healthy); ▼ upper legs (46%, LBP > healthy); D)▼ upper back (58%, LBP > healthy); ▼ lower back (73%, LBP > healthy). Users' impression: Donning/doffing: easy (median 1.9); Length adjustment: easy (median 1.3) RoM: slightly restricted (median 1.4) Interference with tasks: low (median 2) Reduction of back loading: moderate (median 3.9); Support of tasks: moderate (median 4.6); Use at work: rather unlikely (median 6.8); Overall grade: 5-7.

	(Baltrusch et al., 2020b)	11♂ Healthy, LBP 47.4 ± 7.1 yrs Luggage handling (airline industry)	**Laboratory study** Lifting/lowering 10-kg load from ankle to hip height at 8-times/min., using preferred lifting technique, with/without SPEXOR for 5 min.; 5 min. inter-trial rest. **Measurements** Objective: – EMG: ESI-L, ESL-L, ESL-T, OEA, RA; – Motion capture; – Ground reaction forces; – Metabolic cost.	Independent: Exoskeleton: none, SPEXOR. Dependent: Changes in EMG activity; Changes in RoM of CoM; Changes in flexion/extension angles at knee, hip, trunk, L5/S1; Changes in angular velocity at knee, hip, L5/S1; Changes in power at knee, hip, L5/S1; SPEXOR's work; Changes in participant's work; Changes in net metabolic cost.	EMG: ▼ ESI-L 16%; ▼ ESL-L 14%; ▼ ESL-T 10%. Participant's work: ▼ Positive, unloaded 45%; ▼ Negative, unloaded 48%; ▼ Net metabolic cost (18%).
	(Baltrusch et al., 2020c)	17 participants LBP 43.4 ± 7.3 yrs Luggage handling, operators, non-loading occupations	**Laboratory study** A) Pre-intervention condition; B) Verbal explanation of the exoskeleton; C) 12 tasks performed with/without SPEXOR: Repetitive lifting 20-kg load from ankle height in 2 min; Carrying a 20-kg box 10 m; Performing a high-precision manual task on a table at knee height with 30-60° trunk flexion, max. 5 min.; Performing a high-precision manual task in three-point kneeling position with one hand on the floor, max. 5 min.; Walking as far as possible in 6 min; 5 sit-to-stand and stand-to-sit as quickly as possible; Climbing up/down 20 stairs as fast as possible; Climbing up and down a ladder twice; Forward bend with knees extended; Standing with feet 20 cm apart, increasing distance by 20 cm; 5 trunk rotations to both sides; 3 squats with heels on the ground. **Measurements** Subjective: – M-SFS: before session, after verbal explanation, after SPEXOR use; self-estimation of physical capacity for performing 20 daily activities in regard to low-back pain on 5-point Likert scale (4 - able, 3, 2, 1 - restricted, 0 - unable; total score: min. 0, max. 80, <56 predictive for non-return to work). – Focus groups and double interviews: perspectives/opinions on potential use of exoskeleton in the workplace, experience with SPEXOR.	Independent: Exoskeleton familiarity: none (A), verbal explanation (B), SPEXOR use (C). Dependent: Changes in M-SFS score.	Total M-SFS A→C: ▲ 7% (median 70 (65, 74) → median 75 (68, 78)); C > A: 28% participants; C < A: 12% participants. Lifting: C > A: 33% participants; C < A: 4% participants. Repetitive bending: C > A: 30% participants; C < A: 6% participants. Standing and walking: C > A: 33% participants; C < A: 15% participants. Static forward bending: C > A: 47% participants; C < A: 8% participants. Sitting: C > A: 12% participants; C < A: 27% participants. Others: C > A: 14% participants; C < A: 13% participants.

	(Koopman et al., 2020)	10♂ Healthy 46.4 ± 8.7 yrs Luggage handling (airline industry)	**Laboratory study** A) 5 s of bending forward to 6 predetermined heights with knees as straight as possible, with/without SPEXOR. B) Lifting/lowering 10-kg load from 10 cm above ankle height to upright position and back, using 3 lifting techniques; 3 repetitions, 10 min. inter-trial rest. **Measurements** Objective: – EMG: ESI, ESL-L, ESL-T, OEA, RA; – Motion capture; – Ground reaction forces.	Independent: Exoskeleton: none, High-cam Laevo™, Low-cam Laevo™; Hand distance from floor: 100% (standing upright), 95%, 80%, 60%, 20%, 0% (floor height); Lifting techniques: stoop, squat, freestyle. Dependent: Changes in mean (A)/peak (B) back (ESI, ESL-L) EMG activity; Changes in mean (A)/peak (B) abdominal (RA, OEA) EMG activity; Changes in mean (A)/peak (B) L5/S1 compression forces; Changes in mean (A)/peak (B) net L5/S1 moment; Changes in mean (A)/peak (B) participant's L5/S1 moment; Changes in mean (A)/peak (B) lumbar flexion; Changes in mean (A)/peak (B) trunk angular velocity.	Back EMG: A)▼ at 95% hand distance (22%); B)▼ (22 ± 5%). L5/S1 compression forces: A)▼ (13 ± 4%) at 95% hand distance; ▼ (21 ± 4%) at 0% hand distance; B)▼ (14 ± 3%). L5/S1 moment: A)▼ Net (8.1 ± 2.0%) A)▼ Participant: 23 ± 6% at 95% hand distance; 40 ± 3% at 0% hand distance. B)▼ Participant (23 ± 3%) Kinematics: A)▼ Lumbar flexion (17 ± 4%). B)▼ Trunk angular velocity (17 ± 5%).
	(Kozinc et al., 2020)	7♀, 7♂ LBP 40.5 ± 10.8 yrs Office workers, kindergarten teachers, physical education teachers, shop assistants, student.	**Laboratory study** 12 tasks performed with/without SPEXOR: A) Repetitive lifting 10-kg (♀)/15-kg (♂) load from ankle height in 2 min; B) Carrying a 20-kg box 10 m; C) Performing a high-precision manual task on a table at knee height with 30-60° trunk flexion, max. 5 min.; D) Performing a high-precision manual task in three-point kneeling position with one hand on the floor, max. 5 min.; E) Walking as far as possible in 6 min; F) 5 sit-to-stand and stand-to-sit as quickly as possible; G) Climbing up/down 10 stairs as fast as possible; H) Climbing up and down a ladder twice; I) Forward bend with knees extended; J) Standing with feet 20 cm apart, increasing distance by 20 cm; K) 5 trunk rotations to both sides; L) 3 squats with heels on the ground. **Measurements** Objective: – Number of lifts (A); – Carrying time (B), holding time (C, D), sit-to-stand time (F), stair-/ladder-climbing time (G, H); – Walking distance (E), fingertip-to-floor distance (I); wide-stance distance (J). Subjective: – Perceived level of general discomfort, local discomfort, task difficulty: VAS (0 - no difficulty/discomfort, 10 - maximum difficulty/discomfort), rating at the end of each task. – Users' impression questionnaire: VAS (0 - 10), rating at the end of session.	Independent: Exoskeleton: none, SPEXOR. Dependent: Changes in mean objective performance: A) Maximal number of lifts; B) Carrying time; C) Holding time; D) Holding time; E) Walking distance; F) Sit-to-stand time; G) Stair-climbing time; H) Ladder-climbing time; I) Fingertip-to-floor distance; J) Maximal wide-stance distance. Changes in perceived task difficulty; General discomfort; Changes in local discomfort: chest, abdomen, upper back, lower back, thigh; Users' impression: – Adjustability of SPEXOR; – RoM with SPEXOR; – SPEXOR efficacy; – Use of SPEXOR in real-life situations.	Performance: C)▲ (227.1 ± 84.6 s → 255.0 ± 65.3 s); F)▲ (11.6 ± 4.5 s → 12.7 ± 4.4 s); H)▲ (16.6 ± 5.3 s → 17.9 ± 5.5 s). Perceived task difficulty: F)▼ (0.22 ± 2.14 → 0.25 ± 0.61). General discomfort: Highest: E (median 4.5, 2.4–7.6); Lowest: D (median 1.0, 0.2–5.0). Local discomfort: C)▼ low back (5.31 ± 8.54 → 4.47± 8.65); F)▼ low back (1.60 ± 3.19 →0.32 ± 2.14). Users' impression: Adjustability: easy, somewhat difficult to don/doff; RoM: moderate; Efficacy: low/modest; Overall grade: 1-9 (median 4).

VT-Lowe's exoskeleton *(Virginia Tech, Lowe's Inc.)* Prototype **Passive, soft** Assistive torque at the hip and spine for load reduction during lifting tasks.	(Alemi et al., 2019)	12♂ Healthy 22.6 ± 4.4 yrs	**Laboratory study** A) Symmetric lift: lifting load from 50 cm above floor to upright position, and lower back to floor, using 3 lifting techniques; 4 repetitions in 1 min. B) Asymmetric lift: move load at 50 cm above floor from 60° left to 60° right of the body; 4 repetitions in 1 min. **Measurements** Objective: EMG: BF, ESL, ESI, MS, OEA, VL. Subjective: Perceived local discomfort: Borg CR-10 (0 - no discomfort, 10 - extreme discomfort).	Independent: Exoskeleton: none, VT-Lowe's; Lifting technique: stoop (A_1), squat (A_2), freestyle (A_3); Load: 0%, 20% body mass. Dependent: Changes in peak and mean EMG activity; Perceived local discomfort.	EMG: A_1)▼ peak ESI+ESL (27.0%); ▼ peak BF+VL (22.8%); ▼ mean ESI+ESL (25.9%); ▼ mean BF+VL (18.9%). A_2)▼ peak ESI+ESL (35.4%); ▼ peak BF+VL (16.5%); ▼ mean ESI+ESL (31.4%); ▼ mean BF+VL (9.0%). A_3)▼ peak ESI+ESL (32.3%); ▼ peak BF+VL (18.1%); ▼ mean ESI+ESL (30.5%); ▼ mean BF+VL (14.4%). B)▼ peak ESI+ESL (28.2%); ▼ peak BF+VL (17.4%); ▼ mean ESI+ESL (29.5%); ▼ mean BF+VL (14.6%).
FLx™ *(StrongArm Technologies)* Commercial **Passive, rigid** Application of pressure on the user's back during bending to discourage extensive torso flexion and twisting. **Vs.** **V22™** *(StrongArm Technologies)* Commercial **Passive, rigid** Application of pressure on the user's back during bending to discourage extensive torso flexion and twisting, and load transfer from upper body to lower limbs during lifting and carrying tasks.	(Picchiotti et al., 2019)	10♂ Healthy 24.9 ± 5.0 yrs	**Laboratory study** Squat-lifting the load from the lift origin to waist height in front of the body at comfortable pace with/without exoskeleton; 2 repetitions. **Measurements** Objective: – EMG: ES, LD, OEA, OIA, RA; – Motion capture: flexion angles at torso, hip, knee; – Ground reaction forces. *Data analysis using EMG-driven lumbar spine model (Adams, MSC Software).*	Independent: Exoskeleton: none, FLx™, V22™; Origin height: shin, knee, waist; Origin asymmetry angle: 0°, 45°; Load: 9.07 kg, 18.14 kg. Dependent: Changes in L5/S1 horizontal moment; Changes in spinal compression; Changes in antero-posterior spinal shear; Changes in lateral spinal shear.	Peak torso flexion: ▼ FLx™ at shin height; V22™ > FLx™. Peak L5/S1 moment: ▲ V22™; V22™ > FLx™.

Laevo™ V2.4 High-cam model *(InteSpring)* Commercial **Passive, rigid** Force transfer from lower back to chest and thighs most pronounced at user bending angle <20°. **Vs.** **Laevo™ V2.4 Low-cam model** *(InteSpring)* Commercial **Passive, rigid** Force transfer from lower back to chest and thighs most pronounced at user bending angle >20°.	(Baltrusch et al., 2019)	11♂ Healthy 28.9 ± 4.4 yrs	**Laboratory study** A) Walking on treadmill in "self-paced mode" at 2 speeds for 5 min. with Low-cam/without Laevo™; 3 min. inter-trial rest. B) Repetitive lifting/lowering 10-kg load from 2 heights 6-times/min. using preferred lifting technique for 5 min. with High-cam/Low-cam/without Laevo™; 30 s inter-trial rest. **Measurements** Objective: – EMG: BF, ESI-L, ESL-L, ESL-T, OEA, RA, VM; – Motion capture: knee, hip, trunk, lumbar angles; – Metabolic cost.	Independent: Exoskeleton: none, High-cam Laevo™, Low-cam Laevo™; Walking speed (A): preferred without exoskeleton (PWS), preferred with exoskeleton (PWSX); Lift origin height (B): ankle, knee. Dependent: Changes in EMG activity; Changes in RoM of knee, hip, trunk, lumbar joint, CoM; Changes in average stride length per cycle; Changes in metabolic cost.	EMG: A)▲ RA at PWSX ▲ OEA at PWS, PWSX B) ▲ RA - knee height (NMV) ▲ OEA – ankle height (NMV) Metabolic cost: A)▲ 12% (PWS), 17% (PWSX); B)▼ Metabolic cost with High-cam (knee 17%, ankle 16%). Preferred walking speed (A):▼ 4% Stride length at PWS (A):▼ (1.42 ± 0.13 m → 1.40 ± 0.13 m).
	(Koopman et al., 2019b)	11♂ Healthy 24.1 ± 2.7 yrs	**Laboratory study** 5 s of bending forward to 5 predetermined heights with knees as straight as possible, with/without Laevo™; 10 min. inter-trial rest. **Measurements** Objective: – EMG: ESI, ESL-L, OEA, OIA, RA; – Motion capture; – Ground reaction forces.	Independent: Exoskeleton: none, High-cam Laevo™, Low-cam Laevo™; Hand distance from floor: 100% (standing upright), 75%, 50%, 25%, 0% (floor height). Dependent: Changes in peak EMG activity; Changes in participant's peak L5/S1 flexion-extension moment; Changes in Laevo™'s peak L5/S1 flexion-extension moment; Changes in net peak L5/S1 flexion-extension moment; Changes in peak lumbar flexion; Changes in peak hip flexion; Changes in trunk inclination.	Peak EMG: ▼ ESI with Low-cam at 50% (58%); ▼ ESI with High-cam at 25% (14%); ▼ ESL-L with Low-cam at 50% (21%); RA: Low-cam > High-cam at 0%; ▲ OEA with Low-cam at 25% (196%); Low-cam > High-cam at 0% and 25%; ▲ OIA with Low-cam at 25% (16%); ▼ OIA with High-cam at 75% (24%); Low-cam > High-cam at 0%. Participant's peak L5/S1 moment: ▼ Low-cam at ≤75% (11-21%); ▼ High-cam at ≤100% (8-43%); Low-cam < High-cam at 25% and 50%; Low-cam > High-cam at 100%. Laevo™'s peak L5/S1 moment: Low-cam < High-cam at 100-75%; Low-cam > High-cam at 50-25%; Highest: High-cam at 75%, Low-cam at 0%. Peak hip flexion: ▼ with High-cam at ≤50%; ▼ with Low-cam at ≤25%.

	(Koopman et al., 2020b)	11♂ Healthy 24.1 ± 2.7 yrs	**Laboratory study** Lifting/lowering 10-kg load with preferred lifting speed/technique, with/without Laevo™; 3 repetitions, 10 min. inter-trial rest. **Measurements** Objective: – EMG: ESI, ESL-L, OEA, OIA, RA; – Motion capture; – Ground reaction forces.	Independent: Exoskeleton: none, High-cam Laevo™, Low-cam Laevo™; Lift origin: – Vertical: 10 cm above ankle, 10 cm above knee; – Horizontal: 35 cm (near), 60 cm (far) in front of ankle. Dependent: Changes in peak back (ESI, ESL-L) EMG activity; Changes in peak abdominal (OEA, RA) EMG activity; Changes in participant's peak L5/S1 flexion-extension moment; Changes in Laevo™'s peak L5/S1 flexion-extension moment; Changes in net peak L5/S1 flexion-extension moment; Changes in peak L5/S1 compression forces; Changes in peak lumbar flexion; Changes in peak trunk angular velocity.	Peak back EMG:▼ (8%); ▼ Low-cam/knee-far (8%); ▼ Low-cam/ankle-far (6%); ▼ High-cam/ankle-far (10%); Participant's peak L5/S1 moment: ▼ Low-cam (6%), High-cam (3%); ▼ Low-cam/knee-near (7%); ▼ Low-cam/knee-far (6%); ▼ High-cam/knee-far (3%); ▼ Low-cam/ankle-far (8%); ▼ High-cam/ankle-far (8%); Reduction Low-cam < High-cam/knee-near (-6% vs. -3%); Reduction Low-cam < High-cam/knee-far (-6% vs. -3%); Reduction Low-cam < High-cam/ankle-near (-2% vs. 3%). Net peak L5/S1 moment: ▲ High-cam/ankle-near (7%) L5/S1 compression forces: ▼ Low-cam/knee-far (8%) ▼ High-cam/ankle-far (7.3%) Low-cam > High-cam/ankle-far (6264 N vs. 5964 N) Lumbar flexion: ▲ High-cam/ankle-near (13%) Trunk angular velocity: ▼ Low-cam/knee-near (15%); ▼ Low-cam/knee-far (17%); ▼ Low-cam/ankle-near (13%); ▼ Low-cam/ankle-far (17%); ▼ High-cam/knee-near (18%); ▼ High-cam/knee-far (16%); ▼ High-cam/ankle-near (17%); ▼ High-cam/ankle-far (20%).

Laevo™ V2.5 *(InteSpring)* Commercial **Passive, rigid** Force transfer from lower back to chest and thighs most pronounced at user bending angle 35°. **Vs.** **BackX™ model AC** *(SuitX™)* Commercial **Passive, rigid** Force transfer from lower back to upper back and thighs.	(Alemi et al., 2020)	9♀, 9♂ Healthy 24.4 ± 4.5 yrs	**Laboratory study** 5 min. of repetitive symmetric/asymmetric lifting/lowering of 6.8 kg-load (relatively large object) at 5 cycles/min., in 2 postures, using preferred technique, with/without exoskeleton at preferred settings. **Measurements** Objective: – EMG: DA, ES-C, ES-T, ESI-L, OEA, RA, TD, VL; – Metabolic cost. Subjective: – Perceived exertion: Borg CR-10 scale; – Perceived local discomfort: 7-point Likert scale (0 - no discomfort, 6 - extreme discomfort); – Perceived balance: 10-point scale (0 - worst, 10 - best); – Users' impression: Overall usability: Continuous 0-100 scale (0 - not helpful at all, 100 - absolutely helpful); Perceived fit, comfort, RoM constraints: 7-point Likert scale.	Independent: Exoskeleton: none, BackX™, Laevo™; Posture: standing, kneeling; Load starting/target position: symmetric - SY (front), asymmetric - ASY (right-to-left, left-to-right) Sex: female – ♀, male - ♂ Dependent: Changes in peak EMG activity: – Trunk extensor muscle - TEM (bilateral ES-T, ESI-L); – Abdominal muscle - AM (bilateral OEA, RA); – Shoulder muscle - SM (bilateral TD, DA); – Neck muscle - NM (bilateral ES-C); – Leg muscle - LM (bilateral VL). Changes in metabolic cost; Changes in perceived discomfort at chest, waist, thighs; Changes in perceived balance; Changes in perceived exertion at shoulders, lower back, legs; Changes in perceived overall usability; Changes in perceived fit; Changes in perceived comfort; Changes in perceived movement constraints; Preferred exoskeleton selection.	EMG: ▼ TEM: SY (Laevo™ 17%, BackX™ 24%) > ASY (Laevo™ 15%, BackX™ 13%); ♀ (Laevo™ 23%, BackX™ 21%) > ♂ (Laevo™ 9%, BackX™ 15%); ▲ AM Laevo™ (4.1%); ▼ AM BackX™ (8.7%); ▼ SM BackX™-standing (13%); Metabolic cost: ▼ Laevo™ ASY standing (5.5%), SY kneeling (10.8%); ▼ BackX™ SY standing (12.6%), ASY kneeling (6.2%). Chest discomfort: Laevo™ > BackX™ (38%); Waist discomfort: BackX™ > Laevo™; Thigh discomfort: ♀: BackX™ > Laevo™; ♂: Laevo™ > BackX™; Perceived balance:▲ (13%) with Laevo™ in SY kneeling. Perceived exertion: ▼ Shoulder in ♀ with Laevo™; ▼ Lower-back (♂ > ♀); ▼ Leg in ♀ with Laevo™. Usability: Standing: moderate-very (Laevo™ & BackX™); Kneeling: slight-moderate (Laevo™ & BackX™). Fit: BackX™ (4.7) > Laevo™ (3.5) Preferred exoskeleton: BackX™ > Laevo™

(Madinei et al., 2020b)	9♀, 9♂ Healthy ♀ 25.1 ± 3.1 yrs ♂ 26.8 ± 3.9 yrs	**Laboratory study** 4 min. of repetitive symmetric/asymmetric lifting/lowering of load (10% body mass) at 10 cycles/min., using preferred technique, with/without exoskeleton at preferred settings: A) Symmetric – SY: lowering from waist height to mid-shank/knee level, 25 cm horizontal distance, lifting back to waist height; B) Asymmetric – ASY: lowering from waist height to knee level, 90° right of midline, 50 cm horizontal distance, lifting back to waist height; 5 min. inter-trial rest. **Measurements** Objective: – EMG: DA, ES-T, ESI-L, OEA, RA; – Metabolic cost; – Motion capture. Subjective: – Perceived exertion: Borg CR-10 scale; – Perceived local discomfort: 7-point Likert scale (0 - no discomfort, 6 - extreme discomfort); – Users' impression: Overall usability: Continuous 0-100 scale (0 - not helpful at all, 100 - absolutely helpful); Perceived fit, comfort, RoM constraints: 7-point Likert scale.	Independent: Exoskeleton: none, BackX™, Laevo™; Load target position: midline mid-shank level, midline knee level, 90° right of midline knee level; Cycle phase: lifting (↑), lowering (↓) Sex: female – ♀, male - ♂ Dependent: Changes in peak EMG activity: – Trunk extensor muscle - TEM (ES-T, ESI-L); – Total trunk muscle - TTM (bilateral ES-T, ESI-L, OEA, RA); – Shoulder muscle - SM (bilateral DA); Changes in metabolic cost; Changes in trunk and lumbar spine angular velocity; Changes in trunk and lumbar spine RoM; Changes in perceived discomfort at chest, waist, thighs; Changes in perceived exertion at shoulders, arms, lower back, abdominal region, legs; Changes in perceived overall usability; Changes in perceived fit; Changes in perceived comfort; Changes in perceived movement constraints; Preferred exoskeleton selection.	EMG: ▼ TEM-right ↓ (Laevo™ 8.7%, BackX™ 18.3%) ▼ TEM-left ↓ (Laevo™ 9.3%, BackX™ 20.0%) ♀: Laevo™ (11.5%), BackX™ (22.4%) ♂: BackX™ (16.5%) ▼ TTM ↓ (Laevo™ 7.8%, BackX™ 17.3%) ▼ TEM-right ↑ (BackX™ 11.9%) ▼ TEM-left ↑ (BackX™ 11.9%) ▼ TTM ↑ (BackX™ 10.4%) ▼ Metabolic cost: ♀: Laevo™ (8.9%), BackX™ (13.2%) ♂: Laevo™ (6.4%) SY-mid-shank: Laevo™ (9.5%), BackX™ (13.6%) SY-knee: Laevo™ (10.2%), BackX™ (8.1%) Trunk flexion/extension angular velocity: ▼ ↓ (Laevo™ 7.1%) ▼ ↑ mid-shank (Laevo™ 12%) Local discomfort: Chest: Laevo™ > BackX™; Waist: ♀ BackX™ > Laevo™; Thigh: ♀ BackX™ > Laevo™. Perceived exertion: ▼ shoulder: Laevo™ 22.8%, BackX™ 29.8%; ▼ arm: Laevo™ 23.5%, BackX™ 17.6%; ▼ lower-back: Laevo™ 32.7%, BackX™ 40.2%; ▼ abdomen: Laevo™ 36.9%, BackX™ 34.9%; ▼ leg: Laevo™ 24.9%, BackX™ 24.5%. Usability: moderate-very Fit: BackX™ (5.0 ± 1.1) > Laevo™ (3.4 ± 1.4) Preferred exoskeleton: BackX™ > Laevo™

(Madinei et al., 2020a)	9♀, 9♂ Healthy ♀ 24.0 ± 2.4 yrs ♂ 25.3 ± 4.8 yrs	**Laboratory study** Picking up pegs with one hand and inserting them with the other into 2×5 grooved holes on a pegboard as quickly as possible, with/without exoskeleton at preferred settings: A) Unsupported - UNSUP (no chair): 26 pegboard locations (4 working heights, 7 locations at waist/knee, 3 locations at ankle/below-floor). B) Supported - SUP (backless chair): 6 pegboard locations (2 working heights, 3 locations: 0 cm, 20 cm in front of knees; 20 cm from knees at 45° right of midline). 1-3 min. inter-trial rest. **Measurements** Objective: – EMG: ES-T, ESI-L, OEA, RA; – Completion time. Subjective: – Perceived exertion: Borg CR-10 scale.	Independent: Exoskeleton: none, BackX™, Laevo™; Pegboard location: A) Working height: waist - 90 cm, knee - 48 cm, ankle - 6 cm above floor, 20 cm below floor; Waist/knee location: 0 cm, 20 cm, 40 cm in front of feet, 20 cm, 40 cm from feet at 45°, 90° right of midline; Ankle/below-floor location: 0 cm, 20 cm in front of feet, 20 cm from feet at 45° right of midline. B) Working height: knee height, 20 cm below knee; Location: 0 cm, 20 cm in front of knees, 20 cm from knees at 45° right of midline. Sex: female (♀), male (♂) Dependent: Changes in peak EMG activity: – Trunk extensor muscle - TEM (ES-T, ESI-L); – Total trunk muscle - TTM (bilateral ES-T, ESI-L, OEA, RA); Changes in completion time; Changes in perceived lower-back exertion.	EMG: A)▼ TEM-right (Laevo™ 2 conditions 24%, BackX™ 12 conditions 38%): BackX™: ♀ > ♂; Laevo™: ♀ only. ▲ TEM-right (Laevo™ 2 conditions 64%); ▼ TEM-left (Laevo™ 1 condition 22%, BackX™ 8 conditions 38%): BackX™: ♀ > ♂; Laevo™: ♀ only. ▲ TEM-left (Laevo™ 2 conditions 44%); ▼ TTM (Laevo™ 1 condition 16%, BackX™ 10 conditions 31%): BackX™: ♀ > ♂; Laevo™: ♀ only; ▲ TTM (Laevo™ 2 conditions 32%). B)▼ TEM-right (Laevo™ 2 conditions 24%, BackX™ 6 conditions 47%); ▼ TEM-left (Laevo™ 2 conditions 21%, BackX™ 6 conditions 45%); ▼ TTM (Laevo™ 2 conditions 13%, BackX™ 6 conditions 35%). Completion time: A)▲ ♀ (Laevo™ 3%, BackX™ 4.1%), ♂ (BackX™ 3.5%); B)▲ ♀ (Laevo™ 6.9%, BackX™ 7.6%). Perceived lower-back exertion: A)▼ ♀ (50-80%). B)▲ ♂ (75%).

(Kim et al., 2020)	9♀, 9♂ Healthy ♀ 24.0 ± 2.4 yrs ♂ 25.3 ± 4.8 yrs	**Laboratory study** Picking up pegs with one hand and inserting them with the other into 2×5 grooved holes on a pegboard as quickly as possible, with/without exoskeleton at preferred settings: A) Unsupported - UNSUP (no chair): 26 pegboard locations (4 working heights, 7 locations at waist/knee, 3 locations at ankle/below-floor). B) Supported - SUP (backless chair): 6 pegboard locations (2 working heights, 3 locations: 0 cm, 20 cm in front of knees; 20 cm from knees at 45° right of midline). 1-3 min. inter-trial rest. **Measurements** Objective: – EMG: DA, TD, TC, VL; – Joint angle: lumbar spine, hip, knee. Subjective: – Perceived balance: 0-10 scale (0 – worst, 10 – best) – Perceived localized discomfort (chest, waist, thighs): 7-point scale (0 - no discomfort, 3 - high discomfort, 6 - extreme discomfort); – Perceived fit, comfort, body movement constraints: 7-point scale; – Overall helpfulness of exoskeleton: 0-100 scale (0 - not helpful at all, 100 - absolutely helpful).	Independent: Exoskeleton: none, BackX™, Laevo™; Pegboard location: A) Working height: waist - 90 cm, knee - 48 cm, ankle - 6 cm above floor, 20 cm below floor; Waist/knee location: 0 cm, 20 cm, 40 cm in front of feet, 20 cm, 40 cm from feet at 45°, 90° right of midline; Ankle/below-floor location: 0 cm, 20 cm in front of feet, 20 cm from feet at 45° right of midline. B) Working height: knee height, 20 cm below knee; Location: 0 cm, 20 cm in front of knees, 20 cm from knees at 45° right of midline. Sex: female (♀), male (♂) Dependent: Changes in median EMG activity; Changes in median joint angle; Changes in perceived balance; Changes in perceived discomfort; Perceived fit, comfort, body movement constraints; Overall helpfulness of exoskeleton.	Lumbar lateral bend angle at Below Floor level: A)▼ ♀ (Laevo™ 1.8-1.9°, BackX™ 1.7-3.0°), ♂ (Laevo™ 0.8-2.3°, BackX™ 2.0-2.8°); Perceived discomfort: A) Waist at Ankle level: BackX™ > Laevo™; Chest at Knee level: Laevo™ > BackX™; Waist at Below Floor level with BackX™: ♂ > ♀; Chest at Knee level, extreme locations: Laevo™ > BackX™; B) Chest at Knee level, extreme pegboard locations: ♂ > ♀; Perceived body movement constraints: BackX™ > Laevo™; Overall helpfulness of exoskeleton: Laevo™: 60 (♂) - 63 (♀); BackX™: 53 (♂) - 55 (♀).

▼Significant decrease, ▲ Significant increase, NMV – No mean value provided; BB – m. Biceps Brachii, BF – m. Biceps Femoris, DA - m. Deltoideus Anterior, ES – m. Erector Spinae, ES-C – m. Erector Spinae - Cervical, ES-L – m. Erector Spinae - Lumbar, ES-T – m. Erector Spinae - Thoracic, ESI – m. Erector Spinae - Iliocostalis, ESI-L – m. Iliocostalis Lumborum, ESL – m. Erector Spinae - Longissimus, ESL-L – m. Longissimus Lumborum, ESL-T – m. Longissimus Thoracis, GM – m. Gluteus Maximus, LD – m. Latissimus Dorsi, MS – m. Multifidus spinae, OEA – m. Obliquus Externus Abdominis, OIA – m. Obliquus Internus Abdominis, RA – m. Rectus Abdominis, TA – m. Trapezius pars Ascendens, TC - mid-cervical m. Trapezius, TD – m. Trapezius pars Descendens, VL – m. Vastus Lateralis, VM – m. Vastus Medialis; CoM – Centre of Mass, EMG – Electromyography, LBP – low back pain, LPD – Local Perceived Discomfort Scale, LPP – Local Perceived Pressure Scale, M-SFS – Modified Spinal Function Sort, VAS – Visual Analog Scale, RoM – Range of Motion, yrs – years of ag

Table 3: Measurements for objective evaluation of exoskeletons.

Measurement		Number of studies
BACK LOADING	**Back EMG activity:** ES (26), MS (1), LD (2)	**27**
	Joint angle: trunk/lumbar spine/L5/S1 (7), hip (2)	**8**
	RoM: lumbar spine (2), trunk (2), hip (1)	**2**
	Time of awkward back/shoulder position	**1**
	Deflection: trunk	**2**
	Angular velocity: trunk (4), lumbar spine (2), hip (2)	**6**
	Extension time: trunk	**1**
	Moment: L5/S1/low back	**6**
	Compression forces: L5/S1/spine	**5**
	Shear: spine	**1**
	Contact pressure	**1**
ENERGETIC LOADING	**Power:** hip (1), knee (1), L5/S1 (1)	**3**
	Work: exoskeleton (1), participant (1)	**2**
	Metabolic cost	**6**
	Heart rate and blood pressure	**1**
PERFORMANCE	**Performance time:** carrying (3), ladder-climbing (3), stair-climbing (3), sit-to-stand (3), task completion (1)	**4**
	Endurance time: static bending (4), 3-point kneeling (3), shoveling (1)	**5**
	Maximal number of lifting cycles/scoops	**5**
	Distance: fingertip-to-floor (3), wide-stance (3), walking (3), shoveling (1)	**4**
	Stride length	**1**
SIDE EFFECTS	**Abdominal EMG activity:** RA (14), OA (12)	**15**
	Lower-limb EMG activity: BF (7), GM (2), RF (2), VL (3), VM (1)	**10**
	Upper-limb EMG activity: T (5), DA (3), BB (1)	**7**
	Joint angle: knee	**3**
	RoM: overall (3), CoM (3), knee (1)	**5**
	Angular velocity: knee (1)	**1**

BB – m. Biceps Brachii, BF – m. Biceps Femoris, CoM – Center of Mass, DA - m. Deltoideus Anterior, ES – m. Erector Spinae, GM – m. Gluteus Maximus, LD – m. Latissimus Dorsi, MS – m. Multifidus Spinae, OA – m. Obliquus Abdominis (Internus and Externus), RA – m. Rectus Abdominis, RF – m. Rectus Femoris, RoM – Range of Motion, T – m. Trapezius (pars Ascendens and Descendens), VL – m. Vastus Lateralis, VM – m. Vastus Medialis.

Table 4: Scales used for quantitative subjective evaluation of exoskeletons.

Measurement	Number of studies
General discomfort: VAS	3
Local discomfort: VAS (3), 7-point Likert scale (3), 10-point Likert-scale (1), Borg CR-10 scale (1), LPD (1)	9
Comfort of exoskeleton: 7-point Likert scale (3), 5-point scale (1)	4
Fit of exoskeleton: 7-point Likert scale	3
Back posture with exoskeleton: 5-point scale	1
Perceived fatigue: VAS (2), 5-point scale (1)	3
Perceived exertion: Borg CR-10 scale	4
Perceived task difficulty: VAS	3
Self-estimation of physical capacity: M-SFS (5-point Likert scale)	1
Perceived back-load reduction by exoskeleton: 5-point scale	1
Perceived balance: 10-point scale	2
Ease of donning/doffing exoskeleton: 5-point scale	1
Adjustability of exoskeleton: VAS	3
Efficacy of exoskeleton: VAS	3
Efficiency of exoskeleton (fast, organized): 7-point scale	1
RoM constraints by exoskeleton: VAS (3), 7-point Likert scale (3)	6
Interference of exoskeleton with work tasks: VAS	1
Ease of walking, handling loads, stepping on/off pallet jack with exoskeleton: 5-point scale	1
Perspicuity, dependability of exoskeleton: 7-point scale	1
Stimulation by, attractiveness, novelty of exoskeleton: 7-point scale	1
Overall usability of exoskeleton: Continuous 0-100 scale (3), SUS (1)	4
Probability of exoskeleton use at work: VAS	2
Preferred exoskeleton	2

LPD – Local Perceived Discomfort Scale, LPP – Local Perceived Pressure Scale, M-SFS – Modified Spinal Function Sort, SUS – System Usability Scale, VAS – Visual Analog Scale.