ABSTRACT

PASSIVE BACK AND SHOULDER EXOSKELETONS FOR OCCUPATIONAL USE: A REVIEW

by
Erkan Ozan

Work-related musculoskeletal disorders (MSDs) account for a large portion of all work-related injuries according to OSHA. Back and shoulder-related disorders make the most of work-related MSDs according to the Bureau of Labor Statistics (BLS). Exoskeletons emerged in recent years with the potential to reduce the risks of work-related musculoskeletal disorders and injuries. Their use in occupational settings is increasing, and exoskeleton designs are rapidly evolving. This paper reviewed recent scientific articles (2015 and after) that evaluated back and shoulder-support passive industrial exoskeletons. The findings of these articles are summarized and analyzed to assess the benefits of passive upper-body exoskeletons by identifying agreements and disagreements through these articles. Seven BSEs (back support exoskeleton) through 16 articles and eight SSEs (shoulder support exoskeleton) through 14 articles are reviewed.

It is concluded through these articles that passive upper body exoskeletons can provide benefits with selected short-term manual handling tasks in industry settings. The benefits are more pronounced with quantitative assessments. Scientific studies aim to gather further data such as metabolic cost, oxygen consumption, and heart rate along with muscle load assessments to present clearer and more complete results. However, there is not enough data through the recent articles to make any clear conclusions about exoskeletons' benefits in real-

life working conditions for long term uses. Benefits can change with the design and task dramatically. However, none of these exoskeletons have presented a clear superiority to each other in these studies. Specifics of tasks and conditions should be considered to determine the most suitable exoskeleton.

BACK AND SHOULDER EXOSKELETONS FOR OCCUPATIONAL USE: A REVIEW

by
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APPROVAL PAGE

BACK AND SHOULDER EXOSKELETONS FOR OCCUPATIONAL USE: A REVIEW

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I dedicate this page to my wife, Berrin Ozan, who has encouraged me and kept me motivated and driven through the completion of my studies after not being a student for almost thirty years. I thank you for your words of encouragement and support to keep progressing when I needed it most.

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CHAPTER 1

INTRODUCTION

Musculoskeletal disorders (MSDs) are injuries or illnesses that result from overexertion or repetitive motion. They include soft-tissue injuries such as sprains, strains, tears, hernias, and carpal tunnel syndrome. Work-related musculoskeletal disorders (WRMSDs) that result in days away from work most commonly involve the back alone. In 2016, musculoskeletal disorders involving the back accounted for 38.5 percent of all work-related musculoskeletal disorders (134,550 back cases out of 349,050 total cases) which makes the largest portion. In the same year, musculoskeletal disorders involving the shoulder accounted for 14.9 percent of all work-related musculoskeletal disorders (52,008 shoulder cases out of 349,050 total cases) which makes the second largest portion (Bureau of Labor Statistics, 2018).

According to EU-OSHA, 58 percent of workers reported that they suffered from one or more musculoskeletal disorders in the past 12 months in 2015. This data includes 28-member states (EU-OSHA, 2019). OSHA estimates that work-related musculoskeletal disorders in the United States account for over 600,000 injuries and illnesses. These disorders now account for one out of every three dollars spent on workers' compensation. It is estimated that employers spend as much as $20 billion a year on direct costs for MSD-related workers' compensation and up to five times that much for indirect costs, such as those associated with hiring and training replacement workers. In addition to these monetary effects, MSDs often impose a substantial personal toll on affected workers who can no longer work or perform simple personal tasks like buttoning their clothes or brushing their hair (OSHA, 2000).

In recent years, wearable exoskeletons have been developed and used to reduce physical strain in demanding tasks in military, medical, and industrial settings. Industrial exoskeletons have emerged as a potential remedy to reduce work-related musculoskeletal disorders (WRMSDs) particularly with physically demanding jobs in industrial settings. According to American Society of Testing and Materials (ASTM), exoskeletons and exosuits are wearable technology designed to enable, augment, or assist with physical activities (ASTM F3323-19a, 2019).

Industrial exoskeletons are broadly classified as active and passive types. Active exoskeletons have actuators, e.g., motors and power sources such as battery packs, which provide energy for the actuators. An example of battery-operated full body exoskeleton, Sarcos Guardian XO Max (New Atlas 2022), is shown in Figure 1.1 The author claims that it offers wearers a 20 to 1 strength amplification, meaning around 100 pounds (45 kg) should feel as light as 5 pounds (2.2 kg).

Figure 1.1 Battery-powered full-body exoskeleton - Sarcos Guardian XO Max.

Source: https://www.sarcos.com/company/news/press-releases/power-performance-guardian-xo/, 2022

Passive exoskeletons do not have actuators. They store the energy, such as, when the user is bending down, and release this stored energy to support the user, such as when the user lifting and standing up. Gorsic et al. (2022) stated that although active exoskeletons provide more support than passive ones, they tend to be significantly more expensive and heavier than the passive exoskeletons. Passive exoskeletons may provide less assistance, but it can do so at a fraction of the cost, and it has much lighter weight than active ones. As a result, greater interest in the industry is found in passive exoskeletons.

Passive exoskeletons employ a variety of different mechanisms and materials for storing energy, including elastic bands, composites rods, torsional springs, gas springs, and coil springs and use various means to couple the forces from the exoskeleton to the body (Chang et al., 2020). There are devices that employ compressed air for storing energy (Ide et al., 2021). There are rigid and non-rigid exoskeletons. Rigid models are constructed with articulated rigid structure that may be heavier and create more restrictions on mobility (Toxiri et al., 2019). Non-rigid models are constructed with flexible materials such as textile fibers and elastic bands that may be lighter and more flexible. Another classification for industrial exoskeletons is based on the body part that they assist. There are full-body, lower, and upper-body exoskeletons. The upper body exoskeletons include back support exoskeletons (BSE) and shoulder support exoskeletons (SSE).

The objective of this study was to focus on passive industrial BSE and SSE due to the facts that back and shoulder injuries are number one and two, respectively, causes in all WRMSDs, and passive devices may be more beneficial in industrial settings. Systematic research of published scientific articles in electronic databases was conducted. Papers in the English language with recent dates (2015 and after), keywords such as “exoskeleton, upper body, passive, industrial, evaluation, occupational settings, etc.” and filtering through sources; 74 results were initially acquired. Articles were further selected that included laboratory and field testing of BSE and SSE and that employed quantitative physiological measurements, such as electromyography (EMG), muscle fatigue, heart rate (HR), oxygen consumption (VO2), and self-reported discomfort ratings, etc. to quantitatively evaluate the effectiveness of the exoskeletons. Several focus group qualitative studies were also included which seemed to be informative. Seven BSEs through 16 articles and eight SSEs through 14 articles are identified. Manufacturers’ websites and other related commercial websites were reviewed to gather data about these products.

The overall aim of this study was to evaluate the potential benefits of passive BSEs and SSE’s by identifying common and/or challenging findings from these articles. Previous exoskeleton review articles (de Looze et al. 2016; Toxiri et al., 2019; Ali et al. 2021) reviewed specifically BSEs. This study will present reviews of BSEs and SSE’s passive devices separately and include newer articles to present the newest trends and findings. This study will also identify any conflict of interests that can be beneficial when evaluating the findings. This was not done in the previous exoskeleton reviews.

CHAPTER 2

BACK-SUPPORT EXOSKELETONS (BSE) AND ASSOCIATED RECENT ARTICLES

The occupational low back pain has been directly associated with occupational risk factors including overexertion, manual material handling, bending, and prolonged/sustained non-neutral trunk postures (Punnett et al., 2005). Occupational tasks associated with these risk factors produce high back muscle and ligament strains, and spinal compression force in the lower back of the workers. BSEs assist back extension by providing supportive external forces on the upper body to reduce high muscle and ligament strain, and thereby they aim to reduce fatigue, pain in lower back and spinal forces.

Passive BSEs generate the back extension forces using various mechanical structures and force generation mechanisms. Laevo™ BSE (Koopman et al. 2018) employs bendable rods (1) and gas springs (2) with rigid structure (Figure 2.1 a). VT-Lowe's BSE (Alemi et al., 2019) employs flexible carbon fiber rods (3) with rigid structure (Figure 2.1 b). Herowear Apex (Moreno, 2020) employs elastic bands (4) with a non-rigid structure (Figure 2.1 c).

Direction of the supporting force delivered differs among the BSEs (Ali et al., 2021), which is illustrated in Figure 2.2. The elastic band in a soft BSE get stretched during the bending forward phase of lifting. It releases the assistive force during straightening up phase of the back (Figure 2.2 a). The direction of the supplemental force by the BSE is

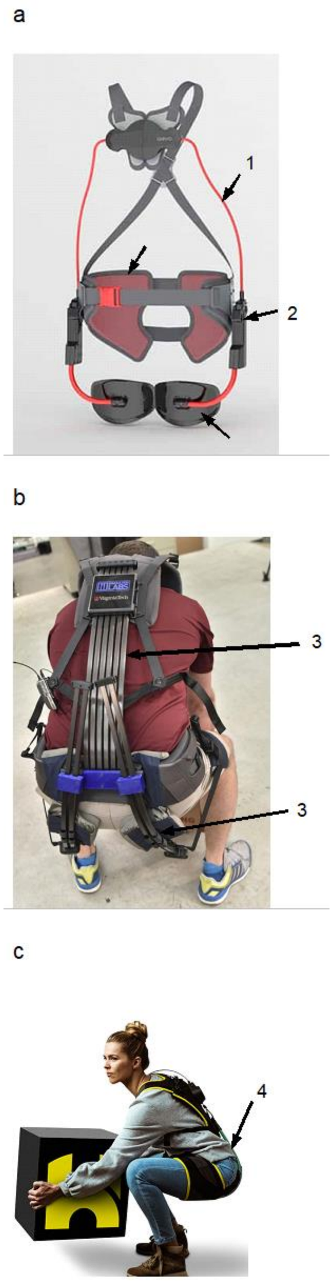

Figure 2.1 Passive back-support exoskeletons mechanical structures and force generation mechanisms.

Source: a) laevo-exoskeletons.com, 2022 b) vtx.vt.edu/articles/2017/05/eng-lowesexosuit.html, 2022 c) herowearexo.com, 2022

parallel to the spinal column. Contrarily, the rigid BSEs (Figure 2.1 b) produce the supporting force perpendicular to the spinal column during back extension. The perpendicular direction of force is beneficial, because it does not add to the spinal force.

Additionally, this supporting force has a greater moment arm to produce a balancing torque at the lower back.

More details about the structure and functions of the BSEs can be found from YouTube videos links provided in Appendix A. The following sections provide review of recent articles (2015 - 2022) related to laboratory and field testing of the BSEs for each commercially available BSEs.

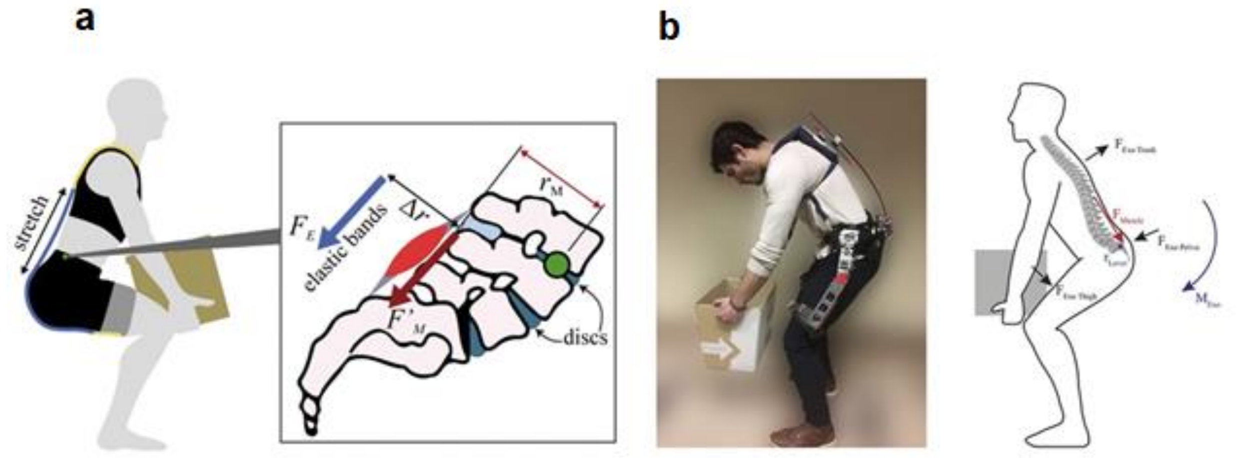

Figure 2. 2 Illustration of the direction of forces applied to the user while wearing (A) soft / non-rigid and (B) hard / rigid exoskeleton.

Source: Ali et al., 2021

Sixteen recent scientific articles (2015 and newer) for seven passive back-support exoskeletons are reviewed. The following sections provide brief descriptions of an individual BSEs followed by the summary of the studies that tested the BSE using a laboratory or field testing.

2.1. Laevo™

It is manufactured by a company named “Laevo” that is based in the Netherlands. It is a passive back-support exoskeleton that uses gas springs, flexible metal rods, and it has a rigid structure (Figure 2.1 a). The device produces a force that is perpendicular to the spinal column in assisting lifting.

Bosch's et al. (2016) study is done in laboratory settings by using an earlier version of Laevo™. Eighteen subjects performed two tasks: a simulated assembly task with the trunk in a forward-bended position and static holding of the same trunk position without any activity. The electromyography for muscles in the back, abdomen, and legs was measured. The perceived local discomfort was also measured. In the static holding task, endurance was defined as the time that people could continue without passing a specified discomfort threshold. In the assembly task, the study found lower muscle activity (by 35-38%) and lower discomfort in the low back when wearing the exoskeleton. Additionally, the hip extensor activity was also reduced. The exoskeleton led to more discomfort in the chest region. In the task of static holding, the team observed that exoskeleton use led to an increase in endurance time from 3.2 to 9.7 min, on average. The results illustrate the good potential of this passive exoskeleton to reduce the internal muscle forces and (reactive) spinal forces in the lumbar region.

Baltrusch et al. (2020) study had a goal to identify factors when developing an exoskeleton for low-back pain patients by exploring the perceptions and expectations of potential end users. The experiment used Laevo™ on two focus groups. The first group was 4 chronic low back pain patients and the second was 8 health care professionals specializing on low back pain patients. Important design characteristics were comfort, individual adjustability, independency in taking it on and off, and gradual adjustment of support. Patients raised concerns over loss of muscle strength. Health care professionals mentioned the risk of confirming disability of the user and increasing guarded movement in patients. The study concluded that implementation of a trunk exoskeleton to reduce low-back pain requires an adequate implementation strategy, including supervision and behavioral coaching.

Madinei et al. (May 2020) assessed the effects of two BSEs (BackX™ and Laevo™) with 18 participants in precision manual assembly tasks. Using both BSEs reduced metrics of trunk muscle activity in many task conditions (≤47% reductions when using BackX™ and ≤24% reductions when using Laevo™). Study findings suggest that using passive BSEs can be beneficial for quasi-static manual assembly tasks, yet their beneficial effects can be task-specific and specific to BSE design approaches.

Madinei et al. (June 2020), published another study with the same team focusing on symmetric and asymmetric repetitive lifting in terms of muscular activity, energy expenditure, joint kinematics, and subjective responses using the same two BSEs (BackX™ and Laevo™). Eighteen participants (gender-balanced) completed repetitive lifting tasks in nine different conditions, involving symmetric and asymmetric postures, lifting from floor or knee level and using two BSEs along with no BSE as a control condition (Figure 2.3). Wearing both BSEs significantly reduced peak levels of trunk extensor muscle activity (by ~9–20%) and reduced energy expenditure (by ~8–14%). Such reductions, though, were more pronounced in the symmetric conditions and differed between the two BSEs tested. Participants reported lower perceived exertion using either

BSE yet raised concerns regarding localized discomfort. Minimal changes in lifting behaviors were noticed when using either BSE. And use of both BSEs led to generally positive usability ratings. Results suggest that exoskeletons were particularly effective with lifting and lowering movements. However, there are statistically significant differences between the two such as between genders for the same tasks or with lifting or lowering.

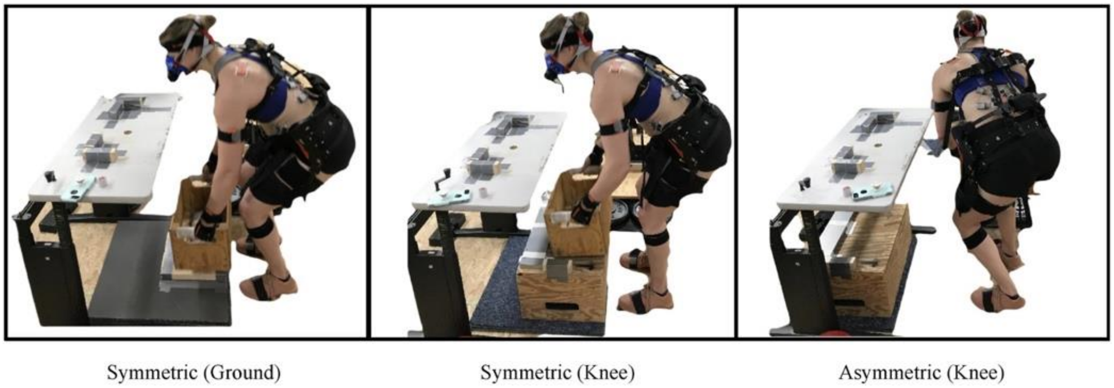
Symmetric (Ground)
Symmetric (Knee)
Asymmetric (Knee)

Figure. 2.3 Illustrations of the repetitive lowering/lifting task in each of the three experimental conditions. Source: Madinei et al. June 2020

Turja et al., 2022 used Laevo™ among Finnish nurses for analyzing the nurses' intention to use the exoskeleton in geriatric work. This was a qualitative study to assess users' overall reactions about using an exoskeleton when interacting with a patient. The study focused on five factors in specific: perceived usefulness and ease of use, trust toward the device, enjoyment of use, and anxiety toward the use. In the qualitative part of the analysis, the social environment's impact on the intention to use exoskeletons was investigated. In the first study, 16 nursing students, half of whom already had years of experience in nursing, were paired up and tasked with assisting a geriatric patient from a hospital bed into a wheelchair. The experiment was conducted in a controlled environment and proceeded in three stages. First, the nurses assisted the patient without exoskeletons; then, one of the nurses wore an exoskeleton; and last, both nurses wore an exoskeleton. Video, interview, and survey data were collected. In the second study, 7 nurses tested the Laevo™ in authentic care home environments where they had the exoskeleton in an individual use for a week. The nurses deployed the exoskeleton in tasks such as assisting a patient out and into a wheelchair, eating, and toileting. We interviewed the nurses before and after the trial period. The interviews were audio recorded, transcribed, and analyzed by content analysis. Some highlights from the article: In the first study, most nurses reported that the exoskeleton reduced lower back strain when assisting the patient. However, only half of the nurses reported intention to use exoskeletons in their work. They felt that wearing the Laevo™ made them stiffer and unable to react to sudden situations as they could without an exoskeleton. It was found in both studies that it would be important if the exoskeleton was inconspicuous for the patient. Patient feedback and feelings were significantly important to the nurses for the intention of use the device. The study concluded that the perceived usefulness and enjoyment of use increases and anxiety toward the use decreases nurses' exoskeleton acceptance. The results further imply that the best way to improve the perceived usefulness is to invest in the better ergonomics and pleasantness of the use. This would mean better fit for individual users. To lower the anxiety toward the exoskeleton use, then, the users would have to trust that the equipment is reliable and safe even in demanding and changing situations.

2.2. BackX™

It is manufactured by a company named SuitX that is based in the USA. It is a passive back-support exoskeleton that uses gas springs, and it has a rigid structure very similar to Laevo (Figure 2.4). The device provides supporting back extension force via a chest pad while lifting and the force is perpendicular to the spinal column.

Figure 2.4 BackX BSE.

Source: top3dshop.com/product/suitx-back, 2022

Poon et al. (2019) focuses on the effects of exoskeletons on muscular fatigue and oxygen consumption. It uses BackX™ on 12 male participants in a laboratory. Compared to the unassisted condition, the study concluded that wearing BackX™ reduced peak lumbar erector spinae activation by 16.5% for right lumbar erector spinae (RLES) and 21.8% for left lumbar erector spinae (LLES) ($p < 0.05$). The time subjects could hold a back-straining posture after the repetitive lifting session increased by 52% after wearing BackX™ during the lifting task. There was no significant negative change in oxygen consumption rate. This study confirms that wearing a BackX™ reduces muscle activation in the lower back for this specific dynamic lifting task. Additionally, the paper concluded that wearing a BackX™ may reduce the risk of low back injuries by reducing muscle activity and increasing endurance time to fatigue.

There are two more articles that experimented with BackX in section 2.1.

2.3. The Muscle Suit Stand Alone Model™

It is manufactured by a company named Innophys that is based in Japan. It is a passive back-support exoskeleton that uses compressed air, and it has a rigid structure. The device does not need external compressed air feed like the active models from this company. It opens feeding tubes when the user bends down which lets air to get in and closes them down when the user is lifting to support the lifting with compressed air.

Ide et al. (2021) had experimented with two different back-support from the same manufacturer (Innophys). Different than the other studies that are reviewed, this experiment used one active (the Muscle Suit – standard model) and one passive (the Muscle Suit – standalone model) back-support exoskeleton. Figure 2.5 illustrates the mechanisms for standard model (a) and standalone model (b). The study had four participants with multiple lifting tasks in a laboratory where muscle load and fatigue can be measured. The assistive effect in comparison with individual muscles was not always observed because the usage ratios of different muscles vary in different assist and load conditions. Hence, they proposed a metric: the sum of standardized IEMG (SS-IEMG-Imaging Electromyography) to measure overall muscle usage of all measurement muscles. The comparison of SS-IEMG showed a consistent effect of the Muscle Suit even in different conditions. As a result, the standard model of the Muscle Suit, which actively generates assistive force on the lumbar region, had the greatest reduction in muscle usage. Furthermore, the estimated passive assistive force of the standalone model was approximately 80% of that of the standard model. Hence, it is confirmed that the standalone model also provides a sufficient assistive effect.

Figure 2.5 Conceptual mechanism for lower back support with the Muscle Suit. (a) Standard model generating active assistive force. (b) Standalone model generating passive assistive force.

Source: Ide at al., 2021

It can be seen from this study that the passive device from the same manufacturer in the same task was as effective as 80% of the active device in reducing muscle load. The article also concluded that both devices were effective in reducing fatigue and states that since the standalone model (passive) has been marketed, nearly 100% of existing users have preferred it over the standard model (active).

2.4. Liftsuit™

It is manufactured by a company named Auxivo AG that is based in Switzerland. It is a passive back and hip support textile exoskeleton with a particular focus on lifting support. It uses elastic fibers, and it has a non-rigid (soft) structure. It has a very light weight compared to other passive BSEs (<0.9 kgs.).

Gorsic et al., 2022 presented a two-session evaluation of a commercial exosuit, the Auxivo LiftSuit 1.1. In session 1, 17 participants performed single repetitions of lifting and static leaning tasks with and without the exoskeleton. In session 2, 10 participants performed 50-box lifting repetitions with and without the LiftSuit. In session 1, where each task was only done twice, the exosuit reduced MT EMG (middle trapezius electromyography) when lifting and lowering a 15-lb box and during both leans. It also reduced ES (erector spinae) peak EMG when lifting and lowering a 30-lb box and during the 60-degree lean. The authors mentioned that they expected more consistent ES EMG reductions and no MT EMG reductions. The authors believed that the MT effect is due to the exosuit's elastic components being placed on the upper back, which is an uncommon choice in back support exoskeleton/ exosuit design. Nonetheless, the exosuit was perceived as mildly to moderately helpful in session 1. Reductions in MT EMG were also observed in session 2, but there were no ES EMG reductions, and the exosuit was not considered helpful. Instead, it appeared to encourage wearers to lift with their back, which may be detrimental in the long term. Thus, while the LiftSuit does have some short-term benefits, its design does not appear optimal for long-term use. Figure 2.6 shows a participant wearing the Liftsuit and other sensors for the assessment.

Figure 2.6 A participant wearing the Auxivo LiftSuit (Auxivo AG, Switzerland): front, back and side views. The participant is also wearing the sensors used in the study (e.g., wireless electromyography sensors under shirt, optical tracking markers on shirt, optical tracking markers on shoulders, hips and knees).

Source: Gorsic et al., 2022

Gorsic et al., 2022 also made a general conclusion by stating that the results had two implications for back support exosuits in general. First, placing exosuit elastic components on the upper back may lead to reductions in upper back muscle activation at the cost of less prominent reductions in lower back muscle activation. While intuitive, this has not been previously evaluated in back support exosuits, where MT EMG is not commonly measured. Second, beneficial effects during single task repetitions are not guaranteed to transfer to multiple repetitions, where device weaknesses not noticed on a single repetition (e.g., promoting a suboptimal lifting strategy) may become more apparent.

2.5 VT-Lowe's™

It is developed and manufactured by Lowe’s Inc with a cooperation from Virginia Tech University. It is a passive back-support exoskeleton that uses flexible beams (carbon fiber rods), and it has a rigid structure. Its carbon fiber rods act like a bow and an arrow to help user to lifting a load up with ease. The rods store energy when the user is bending down and release the energy when the user is lifting to support the lifting. Figure 2.7 presents front and rear views of the exoskeleton.

Figure 2.7 Front and back views of the VT-Lowe’s exoskeleton.

Source: Alemi et al., 2019

Alemi et al., 2019 assessed the effects of VT-Lowe’s exoskeleton, a novel passive lift-assistive device designed to offload the back muscles during repetitive lifting. The study was funded by Lowe’s, Inc. The study sponsors were not involved in the study design or the collection, analysis, and interpretation of the data, in the writing of the manuscript, or in the decision to submit the manuscript for publication. Three of the co-authors, S. E. Chang, J. Geissinger, and A. T. Asbeck are also co-authors on a patent for the exoskeleton which is currently licensed to Lowe’s Inc. In this study, the effect of the exoskeleton on electromyographic (EMG) signals was investigated in four different lifting types (stoop, squat, freestyle and asymmetric) and two box weights (0% and 20% of body weight). Four different lifting styles are illustrated in figure 2.8. Twelve young healthy adults ages 18–31 years were participants. The EMG signals for twelve muscles (iliocostalis erector spinae (IL), longissimus erector spinae (LT), multifidus (MF), bicep femoris (BF), vastus lateralis (VL) and abdominal external oblique (AEO) muscles) were measured.

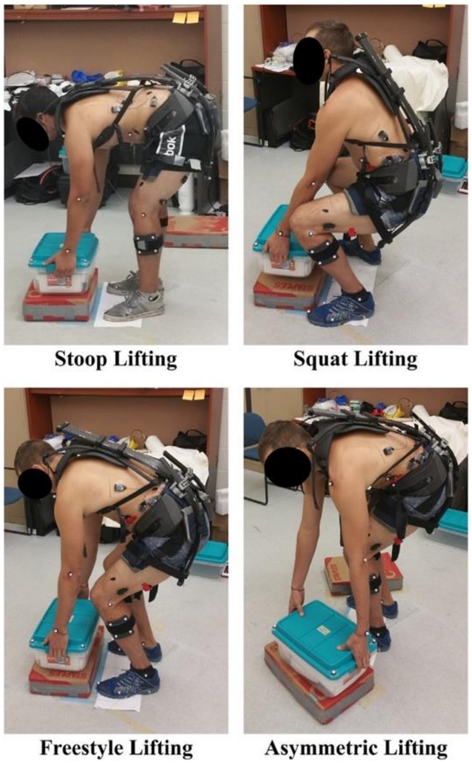

Figure 2.8 Photos of the four different lifting types in the experiment.

Source: Alemi et el., 2019

The exoskeleton significantly decreased the peak and mean activity of back muscles (IL and LT) by 31.5% and 29.3%, respectively, for symmetric lifts and by 28.2%

and 29.5%, respectively, for asymmetric lifts. The peak and mean EMG of leg muscles were significantly reduced by 19.1% and 14.1% during symmetric lifts, and 17.4% and 14.6% during asymmetric lifts. Although the exoskeleton reduced the activation of back and leg muscles, it slightly increased the activity of external oblique muscles, although this was not statistically significant. In conclusion, the effect of the VT-Lowe's exoskeleton on peak and mean muscle activation of 12 different muscles was fully examined. The EMG muscle activation was recorded and processed for four different lifting types at two box weights (0% and 20%). Results demonstrated that the exoskeleton could reduce the average peak and mean muscle activation of back and leg muscles regardless of different levels of box weights and lifting types. The exoskeleton had a significant effect on EMG reductions for all back (longissimus thoracis, iliocostalis lumborum and multifidus) and leg muscles (bicep femoris and vastus lateralis), but not for the external oblique muscles. For asymmetric lifts, back muscles (IL and LT) had smaller peak EMG reduction, but slightly higher mean EMG reduction compared to symmetric lifts (peak: 28.2% and mean: 29.5%). This was the same for leg muscles in asymmetric lifts where lower peak EMG reduction (17.4%) and higher mean EMG reductions (14.6%) were recorded. In addition to EMG results, the discomfort survey showed that except for the thigh which had an average discomfort of 0.94 in the Borg scale, participants experienced either no discomfort or an average discomfort of less than 0.3. The study concluded that the VT-Lowe's exoskeleton significantly reduced the peak and mean muscle activity of erector spinae, bicep femoris and vastus lateralis muscles for all different lifting types regardless of box weights, all without producing any significant discomfort.

Simon et al., 2021 used VT-Lowe's exoskeleton and focused on the kinematic differences between lifting with and without the exoskeleton over three different lifting styles (Freestyle, Squat, and Stoop) and two different box weights (0% and 20% of bodyweight). Twelve young and healthy males participated in laboratory settings for this study. Variables analyzed include the ankle and knee angles and angle between the Shoulder-Hip-Knee (SHK); the shoulder, elbow, and wrist heights; and the lifting speed and acceleration. On average, wearing the exoskeleton resulted in a 1.5 degree increase in ankle dorsiflexion, a 2.6 degree decrease in knee flexion, and a decrease of 2.3 degrees in SHK angle. Subjects' shoulder, elbow, and wrist heights were slightly higher while wearing the exoskeleton, and they lifted slightly more slowly while wearing the exoskeleton. Subjects moved more quickly while bending down as compared to standing up, and with the 0% bodyweight box as compared to the 20% bodyweight box. The values for freestyle lifts generally fell in between squat and stoop lift styles or were not significantly different from Squat. EMG data from the leg muscles had relationships with torso torque while the back and stomach muscles showed no significant relationships. The article concluded that results demonstrated an increase in the ankle dorsiflexion angle and decreases in the knee and waist flexion angles while wearing the exoskeleton. Future studies should investigate if this difference is maintained if individuals are fully adapted to the exoskeleton. The study also provided equations relating a person's torso angle, SHK angle, torso torque, COM height, and box height. Together, these provide a basis for analyzing the work and energy used during human motion and provide specifications for future exoskeletons for assisting with lifting. This study declares that it was funded by Lowe's, Inc. and the National Science Foundation (Grant # 1718801). The study sponsors did not have any involvement in the study design, data collection, analysis, or interpretation of data, the manuscript writing, or the decision to submit the manuscript for publication. And one of the co-authors, Asbeck, is a co-inventor of a patent on the exoskeleton that was used in this study.

Alemi et al., 2022 focused to quantify the metabolic savings resulting from the use of VT- Lowe's - a passive back- support exoskeleton (BSEs). The objectives of this study were to: 1) quantify the metabolic reductions due to the VT- Lowe's exoskeleton during lifting; and 2) provide a comprehensive model to estimate the metabolic reductions from using a passive BSE. In this study, 15 healthy adults (13 males, 2 females) performed repeated freestyle lifting and lowering of an empty box and a box with 20% of their bodyweight. Oxygen consumption and metabolic expenditure data were collected. A model for metabolic expenditure was developed and fitted with the experimental data of two prior studies and the without-exoskeleton experimental results. The metabolic cost model was then modified to reflect the effect of the exoskeleton. The experimental results revealed that VT-Lowe's exoskeleton significantly lowered the oxygen consumption by ~9% for an empty box and 8% for a 20% bodyweight box, which corresponds to a net metabolic cost reduction of ~12% and ~9%, respectively. The model developed in this study can be modified based on different study designs and can assist researchers in enhancing designs of future lifting exoskeletons. In general, reductions in both metabolic expenditure and oxygen consumption lower the possibility of the fatigue for manual material handling workers and consequently, the exoskeleton will reduce the risk of injuries especially for tasks involving heavy or repeated lifting. The article declared that while energy savings from metabolic reductions are important, a passive lifting exoskeleton's potential to reduce injuries (due to both reductions in muscle activity and metabolic fatigue) will likely be the most important benefit to the individuals wearing it. This study was also funded by Lowe's, Inc. The study sponsors were not involved in the experimental design or the collection, analysis, and interpretation of the data, in the writing of the manuscript, or in the decision to submit the manuscript for publication. Two of the co-authors in this study, A. Asbeck and J. Geissinger, are also co-authors on a patent for the exoskeleton.

2.6. Spexor™

It is developed as a European Union Research Project and funded by European Union Horizon 2020 to reduce work-related low back pain. It is a passive back-support exoskeleton that uses flexible beams (carbon fiber rods) like VT Lowe's, and it has a rigid structure. It has a relatively heavy weight (6.3 kgs.).

Baltrusch et al., 2019 set up an experiment with a passive exoskeleton (SPEXOR) that has been developed to reduce loading on the low back. The study aimed to assess the effect of this device on metabolic cost of repetitive lifting. Figure 2.9 presents how participants were set up for EMG measurements. Different than many other studies, this study recruited ten male employees working in the luggage handling department of an airline company with ample experience for lifting tasks at work. Metabolic cost, kinematics, mechanical joint work, and muscle activity were measured during a 5-min repetitive lifting task. Participants had to lift and lower a box of 10 kg from ankle height with and without the exoskeleton. The results showed that the metabolic cost was significantly reduced by 18% when wearing the exoskeleton. Kinematics did not change significantly, while muscle activity decreased by up to 16%. The exoskeleton took over 18–25% of joint work at the hip and L5S1 joints. However, the study did not find a significant reduction of joint work around the individual joints due to large variation in individual responses. The study concluded that wearing the SPEXOR exoskeleton decreased metabolic cost and might, therefore, reduce fatigue development and contribute to prevention of low-back pain during repetitive lifting tasks. Reduced metabolic cost can be explained by the exoskeleton substituting part of muscle work at the hip and L5S1 joints and consequently decreasing required back muscle activity.

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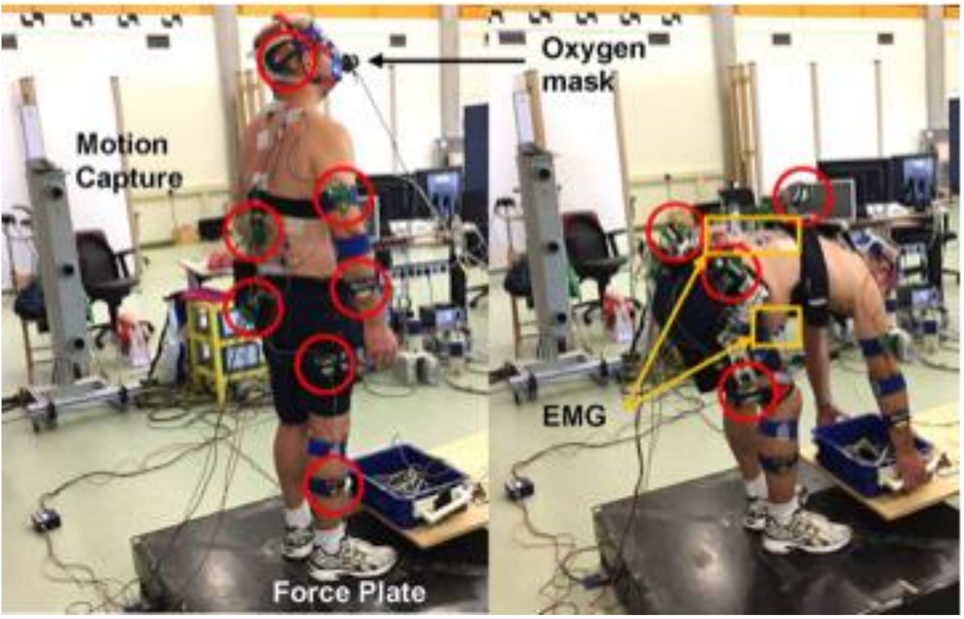

Figure 2.9 Experimental setup without (left) and with exoskeleton (right). Red circles show the cluster markers on the body (left) and on the exoskeleton (right). The yellow boxes show the EMG location.

Source: Baltrusch et al., 2019

Koopman et al., 2020 investigated the effect of the SPEXOR passive exoskeleton on compression forces, moments, muscle activity, and kinematics during static bending at six hand heights and during lifting of a box of 10 kg from around ankle height using three techniques: Free, Squat and Stoop. As different than most studies, ten healthy male luggage handlers (mean ± std, age: 46.4 ± 8.7 years, mass: 83.6 ± 16.2 kg, height: 1. 75 ± 0.07 m) from the Dutch airline company KLM, participated in the study after providing written informed consent. First, the exoskeleton was fitted to the participant and ten minutes were given to get familiarized with the device. The study mentioned a difference with regards to this exoskeleton by declaring that the most exoskeletons only have one joint at hip level, resulting in loss of range of motion and shifting of the exoskeleton relative to the body. To address these issues, a new exoskeleton design has been developed and tested. This exoskeleton was used in this study. The results showed that for static bending, the exoskeleton reduced the compression force by 13–21% depending on bending angle. Another effect of the exoskeleton was that participants substantially reduced lumbar flexion. While lifting, the exoskeleton reduced the peak compression force, on average, by 14%. Lifting technique did not modify the effect of the exoskeleton such that the reduction in compression force was similar. The article concluded that substantial reductions in compression forces were found as a result of the support generated by the exoskeleton and changes in behavior when wearing the exoskeleton. For static bending, lumbar flexion was reduced with the exoskeleton, indicating reduced passive tissue strain. In addition, the reduced peak compression force could reduce the risk of compression induced tissue failure during lifting. This suggest wearing the exoskeleton could reduce the risk of low back pain both during sagittal plane lifting and during static forward bending.

2.7. HeroWear Apex™

It is manufactured by a company named Herowear, LLC. It is a passive back-support exoskeleton that uses elastic bands and textile fibers, and it has a non-rigid (soft) structure. The device has “engage” and “disengage” modes for reducing restrictions when doing tasks other than lifting, carrying. Its weight is 3.4 lbs.

Moreno, 2020 is another study with a conflict of interest that has experimented with a prototype HeroWear Apex exosuit. Its author and some of the co-authors are also co-inventors on intellectual property related to the exosuit assessed in this study. The study was conducted at a workplace to evaluate user perceptions, acceptance, and muscle activity amongst logistics workers wearing an unmotorized, dual-mode, back-assist exosuit prototype (Figure 2.10). Eleven workers performed a lifting/lowering task with vs. without the exosuit, while back muscle activity was recorded. Figure 2.11 presents the results of the muscle activity. They then used the exosuit while performing their actual work tasks in a distribution center before completing a questionnaire about their user experience. Worker perceptions of the exosuit were overwhelmingly positive: 100% felt the exosuit could be useful and fit into their daily job without interfering, >90% felt assisted and that the exosuit made lifting easier, and >80% felt it was comfortable and that they were free to move naturally while wearing the exosuit. According to the study, average reductions in peak and total back muscle activity were ~10% across the full lifting/lowering task, and about two-thirds of workers exhibited reductions >15% during lifting or lowering.

Figure 2.10 Distribution center workers using an exosuit prototype on the job for a variety of logistics tasks: picking, palletizing, forklift driving.

Source: Moreno, 2020

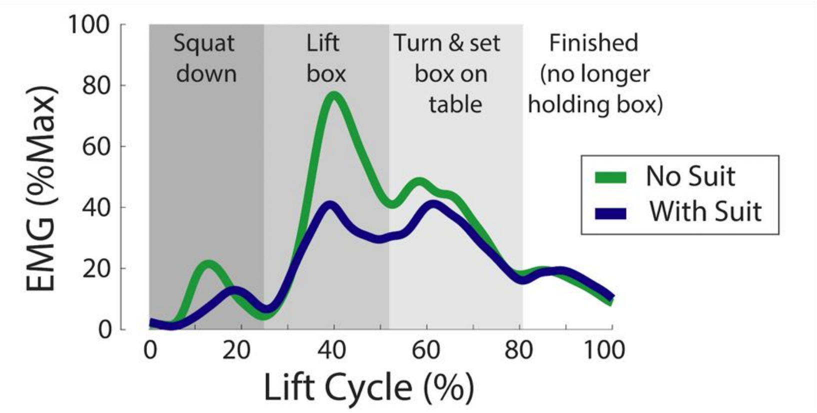

Figure 2.11 Results from representative workers showing reduced back muscle activity (EMG) when wearing the exosuit prototype.

Source: Moreno, 2020

Lamers and Zelik (2021) developed a prototype with an additional feature to an existing passive back-support exoskeleton and set up an experiment to assess its effects. The article declared the following statement: Authors E.P.L. and K.E.Z. are co-inventors on intellectual property related to the extensible exosuit discussed in this work. Author K.E.Z. is a co-founder of and has a financial interest in HeroWear, LLC, which has commercialized a different back-assist exosuit. HeroWear had no role in the research or development work reported in this manuscript, and no HeroWear products were used. This exoskeleton is not a rigid device. It is comprised of textile and elastic materials to reduce discomfort and limitation-on-movement related issues. The device has two modes (engaged and disengaged) that allow users to reduce its discomfort and restrictions while doing tasks other than lifting (like walking, carrying) which is illustrated in figure 2.12. The new prototype that was used in this study has an extension mechanism that increases the moment arm of the exosuit while in engaged mode, then collapses in disengaged mode to retain key benefits related to being lightweight, low-profile, and unobstructive. Figure 2.13 illustrates and explains the mechanism between two modes.

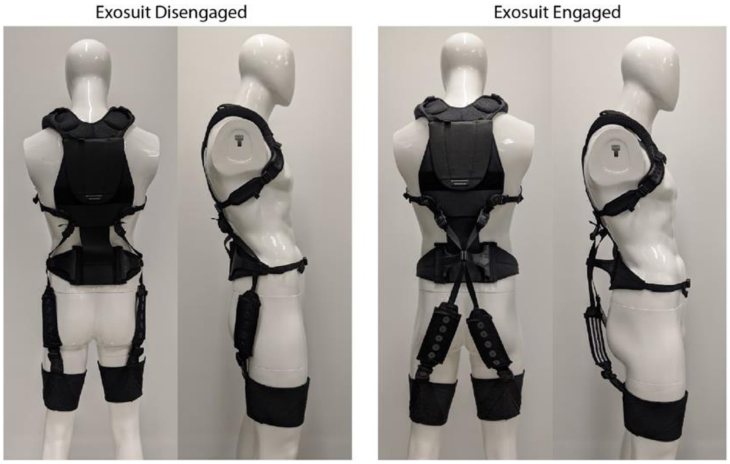

Figure 2.12 Photos of the extensible exosuit prototype in disengaged mode (two photos on the left), and in engaged mode (two photos on the right).

Source: Lamers and Zelik (2021)

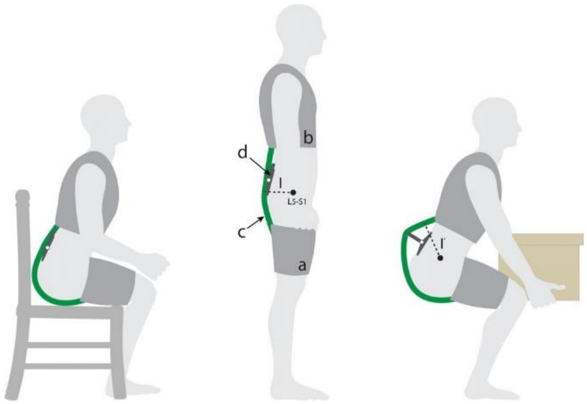

Figure 2.13 Conceptual depiction of the extensible exosuit. This concept is shown in disengaged (collapsed) mode during seated and standing postures, and in engaged (extended) mode during lifting. The extensible exosuit is composed of a leg (a) and trunk (b) interface, an elastic band (c), and a mechanism (d) that can switch between an extended (larger moment arm) and collapsed state (smaller moment arm). The elastic band (green) runs along the user's posterior, over the moment arm mechanism, and connects the leg interface to the trunk interface. In engaged mode, as the user bends forward or crouches down, the elastic band stretches, applying tension forces to the leg and trunk interfaces. The addition of the extension mechanism redirects the path of the elastic band, increasing the exosuit moment arm (from l to l^0) relative to the lumbosacral (L5-S1) joint. This simplified image is only intended to introduce the basic concept.

Source: Lamers and Zelik (2021)

Lamers and Zelik (2021) (continued) performed a single subject study to assess whether the extensible exosuit in engaged mode could provide the same torque assistance but with reduced device-to-body forces (shoulders and legs) compared to the previous model exosuit during a manual lifting task. The second part was to test to confirm that the user could perform common movements and postures (e.g., walking, carrying, leaning, twisting, sitting) without feeling restricted while wearing the extensible exosuit in disengaged mode. The subject provided written consent prior to testing according to the approved Vanderbilt University Institutional Review Board protocol. A single subject (female, 64 kg, 1.74 m, 26 years) performed a lifting and lowering task while wearing the extensible exosuit vs. the form-fitting exosuit. User and exosuit kinematics and elastic band tension data were collected. The subject performed eight lifting and eight lowering movements with a 13 kg box, paced at 15 lifting/lowering movements per minute. Next, the subject performed a series of common movement tasks while wearing the extensible exosuit in disengaged mode. The subject performed the following tasks: level treadmill walking, walking while carrying a 13 kg box, stair ascent/descent, sitting, sit-to-stand, twisting at the torso in the coronal plane, leaning left and right in the frontal plane, leaning forward and backward in the sagittal plane. Immediately after completing each movement the subject filled out a questionnaire in which she rated how much she felt that the extensible exosuit interfered with the task on a five-point Likert scale. According to the results of the study, the extensible exosuit prototype could provide the same low back assistance torque as a form-fitting exosuit, but with reduced device-to-body forces on the shoulders and legs (reduced by 36% in the case study, but the model provides insight on how to adjust design parameters to increase or decrease this magnitude as desired). One-user feedback confirmed that the extensible exosuit successfully aided during lifting, reduced device-to-body forces on the shoulders and legs, improved perceived comfort, and allowed for full freedom of movement and posture (including sitting) when disengaged.

Gorsic et al., 2021 stated that while most trunk exoskeletons are rigid devices, more lightweight soft exoskeletons (exosuits) have recently been developed. One such exosuit is the HeroWear Apex, which achieved promising results in the developers' own work but has not been independently evaluated. This study thus presented an evaluation of the Apex with 20 adult participants (5 women and 15 men with no history of chronic back pain or back injury) during multiple brief tasks: standing up from a stool with a symmetric or asymmetric load, lifting a unilateral or bilateral load from the floor to waist level, lifting the same bilateral load with a 90-degree turn to the right, lowering a bilateral load from waist level to floor, and walking while carrying a bilateral load. The tasks were performed with first with exosuit assistance disengaged, then with it engaged, then disengaged again. Four measurement types were taken: electromyography (of the erector spinae, rectus abdominis, and middle trapezius), trunk kinematics, self-report ratings, and heart rate. The study concluded that engaging the exosuit decreased ES (erector spinae) EMG during lifting and lowering tasks by approximately 15% on average (with decreases ranging from 5% to 30% between tasks), which may in the long term reduce fatigue and allow wearers to work safely for longer periods of time. Furthermore, a decrease in MT (middle trapezius) EMG was noted in one task. No EMG increases were observed when the exosuit was engaged, suggesting no adverse effects on other measured muscles or tasks. Mean HR measurements did not show any difference with or without the exoskeleton. Finally, participants rated the exosuit as mildly to moderately helpful. Results may transfer to similar exosuits, and may inform experts working with other wearable devices, who could use this information to improve their own designs.

2.8. Analysis of Benefits and Shortcomings from Wearing Back-Support Exoskeletons

Sixteen recent scientific articles (2015 and newer) for seven passive back-support exoskeletons are reviewed and their findings are presented in the Table 2.1. A total of 215 participants were used in these experiments (137 males, 50 females, and 28 not gender specified). Majority of the articles employed quantitative methods to evaluate BSEs, with six articles had both qualitative and quantitative and two articles had only qualitative methods.

Among the quantitative methods, muscle loading with EMG use was the most employed. Eleven studies measured EMG of one or more muscle groups to quantify the change in muscle activation while comparing with or without BSE or while comparing with two or more BSE's. All EMG measurements except one (Gorsic et al., 2022) reported reductions of muscle load while using BSE compared to not wearing BSE. The reduction in EMG ranging from 9% to 47%.

Decreased muscle activity in the body also decreases oxygen consumption, which indicates overall reduction of physiological cost from a physical exercise. One study (Alemi et al., 2022) reported 9% reduction of oxygen consumption from wearing BSE.

Table 2.1 Passive Back-Support Exoskeleton Studies

Study	Device	Method	Findings
Bosch et al., 2016	Laevo™	Participants: -9 male / 9 female healthy participants in a laboratory Procedure: -Quantitative measurement with EMG on back, abdomen, leg muscles and perceived local discomfort -1st assembly task with a forward bending position -2nd static holding with the same trunk position	-1st assembly task: lower muscle activity (by 35-38%) and lower discomfort in the low back. Reduction in hip extensor activity. Discomfort in chest region. -2nd static holding task: endurance time increased from 3.2 to 9.7 min, on average.
Baltrusch et al., 2020	Laevo™	Participants: -4 patients and 8 healthcare workers as focus groups Procedure: - Qualitative measurement	-Important design characteristics for patients were comfort, individual adjustability, independency in taking it on and off, and gradual adjustment of support. -Implementation of a trunk exoskeleton to reduce low-back pain requires an adequate implementation strategy.
Turja et al., 2022	Laevo™	Participants: -16 nursing students with experience Procedure: -Qualitative measurement -1st task of moving a patient -2nd having exoskeleton for individual use	-Most nurses reported reduction in lower back strain when assisting a patient. -Only half of nurses reported intention of using the exoskeleton due to feeling of being stiffer, unable to react to sudden situations, and negative patient reactions.
Madinei et al. (May 2020)	BackX™ and Laevo™	Participants: -9 male / 9 female healthy participants in a laboratory Procedure: - Quantitative measurement with EMG -Precision manual assembly tasks with both BSEs and without	- Reduced trunk muscle activity (≤47% reductions when using BackX™ and ≤24% reductions when using Laevo™). -Findings suggest that using passive BSEs can be beneficial for quasi-static manual assembly tasks, yet their beneficial effects can be task-specific and specific to BSE design approaches.

Madinei et al. (June 2020)	BackX™ and Laevo™	Participants: -18 healthy gender balanced participants in a laboratory Procedure: - Quantitative measurement with EMG -Lifting tasks involving symmetric and asymmetric postures with 2 exoskeletons and without.	-Reduced peak levels of trunk extensor muscle activity (by ~9–20%). -Reduced energy expenditure (by ~8–14%). -Reductions were more pronounced in the symmetric conditions and differed between the two BSEs tested. -Minimal changes in lifting behavior using either exoskeleton.
Poon et al., 2019	BackX™	Participants: -11 males in a laboratory Procedure: - Quantitative measurement with EMG and oxygen consumption -Repetitive dynamic lifting task	- Reduced peak lumbar erector spinae (LES) activation by 16.5% for right LES and 21.8% for left LES ($p < 0.05$). - The time subjects could hold a back-straining posture after the repetitive lifting session increased by 52% with exoskeleton during the lifting task. - No significant change in oxygen consumption rate.
Ide et al. (2021)	The Muscle Suit™ - Standard (Active) and Stand Alone (Passive) Models	Participants: - 3 male / 1 female participants in a laboratory Procedure: -Multiple lifting tasks with active and passive devices from the same manufacturer -Quantitative - Muscle load and fatigue are measured.	-Passive exoskeleton was as effective as 80% of the active device in reducing muscle load. -Both devices were effective in reducing fatigue and nearly 100% of existing users have preferred the passive exoskeleton over the standard model (active).
Gorsic et al., 2022	Auxivo LiftSuit 1.1.	Participants: -17 (8M / 9F) and 10 (5M / 5F) participants Procedure: -Session 1: 17 participants performed repetitions of lifting 15 and 30 lbs. boxes and static leaning tasks	-Mildly to moderately helpful in session 1. -Not considered helpful in session 2. -May be - due to elastic fibers in upper back, reduced MT EMG but not enough ES EMG reductions.

		-Session 2: 10 participants performed 50 lbs. box lifting repetitions -Quantitative - EMG measurements	- Beneficial effects of single lifting are not guaranteed to transfer to multiple liftings.
Alemi et al., 2019*	VT-Lowe's	Participants: -12 healthy male adults in a laboratory Procedure: -4 lifting types (stoop, squat, freestyle and asymmetric) and two box weights (0% and 20% of body weight) -Quantitative - EMG on 12 muscles -Qualitative – survey for discomfort	- Reduced peak and mean activity of back muscles (IL and LT) by 31.5% and 29.3%, respectively, for symmetric lifts by 28.2% and for asymmetric lifts by 29.5%. -Reduced peak and mean EMG leg muscles by 19.1% and 14.1%, for symmetric lifts by 17.4% and for asymmetric lifts by 14.6%. - Slight increase on activity of external oblique muscles. -Slight discomfort for thigh on survey.
Simon et al., 2021*	VT-Lowe's	Participants: -12 healthy males in a laboratory Procedure: -Quantitative - Measured kinematic differences for 3 lifting styles (Freestyle, Squat, and Stoop) and two different box weights (0% and 20% of bodyweight)	- On average, exoskeleton caused 1.5-degree increase in ankle dorsiflexion, 2.6 degree decrease in knee flexion, and a decrease of 2.3 degrees in SHK angle. -Shoulder, elbow, and wrist heights were slightly higher, and they lifted slightly more slowly with exoskeleton. -Future studies should investigate if this difference is maintained when individuals are fully adapted to the exoskeleton.
Alemi et al., 2022*	VT-Lowe's	Participants: -15 healthy adults (13 males / 2 females) Procedure: -Quantitative - Repeated freestyle lifting and lowering of an empty box and a box with 20% of bodyweight. Oxygen consumption and metabolic expenditure data were collected. A model for metabolic expenditure was developed and fitted with the experimental data of two prior studies	- The experimental results: Device reduced oxygen consumption by ~9% for an empty box and 8% for a 20% bodyweight box, which corresponds to a net metabolic cost reduction of ~12% and ~9%, respectively. - The article concluded that the exoskeleton's potential to reduce injuries (due to both reductions in muscle activity and metabolic fatigue) will likely be the most important benefit.

Baltrusch et al. (2019)	Spexor	Participants: -10 experienced male luggage handlers at airlines company Procedure: - Quantitative - Metabolic cost, kinematics, mechanical joint work, and muscle activity was measured during a 5-min repetitive lifting task with 10 kgs. load	-18% reduction on metabolic cost. -Kinematics did not change significantly while muscle activity decreased by up to 16%. -Exoskeleton took over 18–25% of joint work at the hip and L5S1 joints. However, no significant reduction of joint work around the individual joints due to large variation in individual responses. -Exoskeleton decreased metabolic cost and might, therefore, reduce fatigue development and contribute to prevention of low-back pain during repetitive lifting tasks.
Koopman et al. (2020	Spexor	Participants: -10 experienced male luggage handlers at airlines company Procedure: -Quantitative - Compression forces, moments, muscle activity, and kinematics are measured -Static bending and lifting of 10 kgs load from ankle height using three techniques: Free, Squat and Stoop	-For static bending: 13–21% reduced compression force depending on bending angle. Another effect was that participants substantially reduced lumbar flexion. -For lifting: 14% reduced peak compression force on average. Lifting technique did not modify the effect of the exoskeleton. -Wearing the exoskeleton could reduce the risk of low back pain both during sagittal plane lifting and during static forward bending.
Moreno, 2020*	Apex Herowear	Participants: -11 male logistics workers at workplace Procedure: -Quantitative - Back muscle activity was recorded during Lifting/lowering tasks. -Qualitative – Performed actual work tasks in distribution center with exoskeleton and completed a questionnaire.	-Quantitative: 10% average reduction in peak and total muscle activity during lifting / lowering. -Qualitative: 100% felt the exosuit could be useful and fit into their daily job without interfering, >90% felt assisted and that the exosuit made lifting easier, and >80% felt it was comfortable and that they were free to move naturally while wearing the exosuit.

Lamers and Zelik (2021)*	Apex Herowear	Participants: -One young female Procedure: -Assess the new prototype with qualitative and quantitative measurements -Quantitative - Performed 8 lifting and lowering movements with a 13 kg box, paced at 15 lifting/lowering movements per minute -Qualitative - Performed a series of common movement tasks while wearing the extensible exosuit in disengaged mode	-Prototype provides the same low back assistance torque as a form-fitting exosuit, with reduced device-to-body forces on the shoulders and legs (reduced by 36% in the case study). -One-user feedback confirmed that the extensible exosuit successfully aided during lifting, reduced device-to-body forces on the shoulders and legs, improved perceived comfort, and allowed for full freedom of movement and posture (including sitting) when disengaged.
Gorsic et al., 2021	Apex Herowear	Participants: -5 females, 15 males Procedure: -Series of lifting / carrying / lowering tasks with symmetric or asymmetric loads, and unilateral or bilateral loads -Quantitative & Qualitative -Electromyography (of the erector spinae, rectus abdominis, and middle trapezius), trunk kinematics, self-report ratings, and heart rate.	-Decreased ES EMG during lifting and lowering tasks by approximately 15% on average (with decreases ranging from 5% to 30% between tasks). Decrease in MT EMG was noted in one task. No EMG increases were observed on measured muscles. -Participants rated the exosuit as mildly to moderately helpful.

* Study may have a conflict of interest or received funding or been conducted with involvement of the BSE manufacturer.

Metabolic cost measurements in two studies (Baltrusch et al., 2019 and Alemi et al., 2022) reported 9% and 18% reductions, further indicates effectiveness of BSE in reducing physical strain. One study (Poon et al., 2019) reported no significant change for oxygen consumption.

Five articles made kinematic assessments, and none reported negative results. Koopman et al., 2020 reported that BSE substantially reduced lumbar flexion during static bending, indicating reduced passive tissue strain. The study also reported reduced compression force for static bending (13-21%) and for lifting (14%) which could reduce the risk of compression induced tissue failure during lifting. This suggest wearing the exoskeleton could reduce the risk of low back pain both during sagittal plane lifting and during static forward bending.

Poon et al., 2019 stated 52% increase in endurance, Bosch et al., 2016 stated that static holding time increased from 3.2 to 9.7 minutes on average. Energy expenditure was measured by Madinei et al., June 2020 with 8 to 14% reductions. Ide et al., 2021 reported reductions in fatigue both with active and passive BSEs from the same manufacturer. Majority of these results support the fact that BSE is effective in reducing physical strain.

There were some findings that may be considered as negative. Two articles (Bosch et al., 2016 / Alemi et al., 2019) reported slight to moderate discomfort in chest, back, and thigh areas. One article (Gorsic et al., 2022) reported that the exoskeleton was not helpful in one of the tasks in the experiment. Another article (Turja et al., 2022) reported that even though most nurses reported that the exoskeleton reduced lower back strain when assisting the patient, only half of the nurses reported the intention of using the exoskeleton due to feeling of being stiffer, feeling of being unable to react to sudden situations, and negative patient reactions.

There were also interesting findings that are worth mentioning in here. One article (Ide et al., 2021) experimented with active and passive back-support exoskeletons from the same manufacturer for the same tasks. The study reported that the passive exoskeleton was as 80% effective as the active exoskeleton. The article added that most existing users of the active exoskeleton preferred the passive exoskeleton once they tried the passive one. Another article (Madinei et al., May 2020) stated that passive back-support exoskeletons can be beneficial for quasi-static manual assembly tasks, yet their beneficial effects can be task-specific and specific to exoskeleton design approaches.

CHAPTER 3

SHOULDER-SUPPORT EXOSKELETONS (SSE) AND ASSOCIATED RECENT ARTICLES

There are many occupations that require workers to maintain extended or overhead arm positions for prolonged periods. Supporting the weight of the extended arm, along with any handheld tool for a period, require substantial shoulder muscle activation and muscles fatigue over time. For shoulder injuries specifically, overhead work has been defined as a risk factor because of the exposure to complex and concurrent stresses and strains on tissues in the upper extremity (De Bock et al., 2021). Assembly line workers, painters, welders, and surgeons in medical profession are examples of occupations that involve fatigue in shoulder joint and carry risk of shoulder musculoskeletal disease (MSD). Majority of the shoulder-support exoskeletons (SSE) reduce shoulder muscle activation by providing a flexible support under the extended upper arm via a mechanical linkage system which transmits the supporting load to the pelvic structure of the worker. Few of the SSEs are designed for using with very heavy handheld tools, such as a video camera. These SSEs support the whole weight of the hand tool by directly supporting them on a waist belt and do not provide any support the upper arms. The SSEs found from the literature survey and discussed below.

The following sections provide brief descriptions of eight commercially available SSEs followed by review of recent articles (2015 - 2022) discussing laboratory and field testing of the SSE's. More details about the SSEs can be found in the list of links for YouTube videos of SSEs that are provided in Appendix B.

3.1 Levitate Airframe™

It is manufactured by a USA based company named Levitate Technologies. It is a passive, shoulder-support exoskeleton that uses gas springs to store energy when the upper arm is moving downward and utilizes a rigid mechanical link structure to transfers the supporting load to the pelvic belt (Figure 3.1). It provides progressively more support to the upper arm when it is lifted upward.

Figure 3.1 Structure of Levitate Airframe (2022).

Source: https://www.levitatetech.com/airframe/, 2022

An earlier study, Butler and Wisner (2017), conducted a 5-day field test of the exoskeleton device from Levitate Technologies that was specifically designed to prove or disprove whether such a device has a place in a real-world work environment. The two experienced welders and the two experienced painters were selected and fitted with the device. One painter's productivity improved by 26.79% and the other by 53.13% while performing a dynamitic, moderate to severe ergonomic, repetitive job. The welders' performance with an exoskeleton device showed that productivity improved 86%. Job quality was managed at a certain level with a utilization of simulators during the experiment. The study concluded that although the exoskeleton testing proves welders and painters can perform at a higher quality level for longer periods (improved productivity) with the aid of an exoskeleton device, eventually humans will reach a level of fatigue at which they need to stop and rest. The perceived benefit is that with regularly scheduled breaks and lunch, welders and painters may not reach a level of fatigue that could be considered dangerous to their safety and health with the use of an exoskeleton device.

Spada et al. (2017) conducted a study at an automotive plant with 29 participants. Qualitative and quantitative results showed a positive effect of the exoskeleton for those activities that involve a posture with raised arms. Workers increased their performance (average improvement 30%) when wearing the exoskeleton and perceived less fatigue. Encouraging data also emerged from the workers' interviews. Still, during the focus group, workers affirmed that the use of the exoskeleton should be on a voluntary base.

Liu et al. (2018) experimented with an earlier version of Levitate exoskeleton on laparoscopic surgeons as the widespread adoption of laparoscopic surgery has put new physical demands on them and it is leading to increased musculoskeletal disorders and injuries. Shoulder, back, and neck pains are among the most common complaints experienced by laparoscopic surgeons. The study used three phases of testing. In each phase, general surgery residents or attendings were randomized to wearing the exosuit at the beginning or at the crossover point. The first phase tests for surgeon manual dexterity wearing the device using the Minnesota Dexterity test, the Purdue Pegboard test, and the Fundamentals of Laparoscopic Surgery (FLS) modules. The second phase tests the effect of the device on shoulder pain and fatigue while operating the laparoscopic camera. The third phase rates surgeon experience in the operating room between case-matched operating days. Twenty subjects were recruited for this study. Exosuit surgeons experienced significantly less fatigue at all time periods and arm pain (3.11 vs 5.88, $p = 0.019$) at 10 min. Surgeons wearing the exosuit during an operation experienced significant decrease in shoulder pain and 85% of surgeons reported some form of pain reduction at the end of the operative day. The study concluded that the exosuit can be a minimally intrusive device that laparoscopic surgeons can wear to reduce pain and fatigue of surgery without significantly interfering with operative skills or manual dexterity.

Iranzo et al. (2020) performed a study that uses Airframe® for tasks in an automotive assembly line. The operators (n=12) performed continuous cycles of dynamic overhead work consisting of the assembly of the car body at the underside of the car making use of pneumatic screwdrivers. The EMGs (anterior part of deltoid, trapezius, latissimus dorsi, and erector spinae) were measured for the muscle activity analysis on the one hand, and the ergonomics study on the other hand. The latter consisted of an approach based on Jonsson’s work, that establishes acceptance thresholds of cumulative percentage of maximum voluntary contraction (%MVC) of muscle activity in a work cycle. The joint angles motion capture was carried out by measuring the angles of the neck, back, and arms joints. All measurements were performed during experimental sessions with and without an exoskeleton. The key findings show reductions of 34% and 18% of the deltoid and the trapezius muscular activities, respectively, which in turn could lead to a reduction of discomfort and fatigue. The erector spinae and latissimus dorsi muscles were not significantly affected by the exoskeleton. The values of muscular activity were also represented over Jonsson’s acceptance areas. Referring to the posture, some differences were found in the range of movement of the back, neck, and arms owing to the use of the exoskeleton; however, the differences were smaller than 5% in all cases. The study concludes that the use of an exoskeleton provokes a clear reduction of the low and medium muscular activity in the muscles in charge of arms flexion. This can lead to lesser discomfort and fatigue but does not reveal a reduction of risk of injury for overload efforts. No differences were found in the activity of the potentially adversely affected muscles: the erector spinae and the latissimus dorsii. Consistently, agreeing results were reflected in the data drawn over the ergonomic curves. Despite the topics on the impact of exoskeleton constraining the natural movements, the exoskeleton was found to reduce the range of back movements in a very small percentage, and minor modifications in the pattern of workers' mobility were observed. These results agree with the workers' feedback, who reported this slight loss of mobility. The study concludes that despite the observed advantages of exoskeletons, there is still plenty of room for improvement. Some of the participants reported after using the exoskeleton, pain in the areas in contact with the arm supports and suggested a more flexible and adaptive design of the exoskeleton structure. These shortcomings should be considered in further designs. Finally, another design aspect to be carefully considered is the fixations to the body to avoid misalignments that might lead to inadequate load distribution and reduce the efficiency of the system or even have negative effects.

Cha et al. (2020) worked with 14 surgical team members who completed a 10-min simulated laparoscopic surgical task with an exoskeleton from Levitate (Figure 3.2). The participants completed a usability questionnaire afterwards. The study focused on four themes: (1) characteristics of individuals, (2) perceived benefits, (3) environmental/societal factors, and (4) intervention characteristics. Participants noted that exoskeletons would benefit workers who stand in prolonged, static postures (e.g., holding instruments for visualization) and indicated that they could foresee a long-term decrease in MS symptoms with the intervention. Specifically, raising awareness of exoskeletons for early-career workers and obtaining buy-in from team members may increase future adoption of this technology. Mean participant responses from the System Usability Scale were 81.3 out of 100 (*SD* = 8.1), which was in the acceptable range of usability. In its conclusion, the study suggests acceptable usability for surgical tasks in operating rooms. The paper concluded that exoskeletons as an intervention received positive comments, especially from individuals in the nursing role. Thus, exoskeleton technology has the potential in this work environment to improve workforce retention and decrease MS symptoms for all team members. Although adoption of arm-support exoskeletons can be valuable, a key contribution of this initial work is the identification of unique aspects of the surgical environment and barriers and facilitators such as cost and team member buy-in that need to be addressed to help guide future translation of exoskeletons into practice.

Figure 3.2 Experimental setups for simulated Laparoscopic Surgery task in Cha et al., 2020.

Source: Cha et al., 2020

3.2 ShoulderX™

It is manufactured by a company named SuitX that is based in the USA. It is a passive, shoulder-support exoskeleton that is designed to support workers with overhead tasks. It uses gas springs and has rigid mechanical linkages to transmit supporting forces to the waist (Figure 3.3).

Figure 3.3 ShoulderX™ Configuration.

Source: https://www.suitx.com/shoulderx, 2022

Alabdulkarim and Nussbaum (2019) experimented with three different passive exoskeletons, Fortis™-full body exoskeleton, ShoulderX™ - shoulder-support exoskeleton, The Fawcett Exsovest™ with zero-G mechanical arm (Figure 3.4). 16 gender-balanced participants simulated drilling for 15 minutes and additional 3 minutes while the remaining outcome measures were obtained. The study compared different passive exoskeletal designs in terms of physical demands (maximum acceptable frequency = MAF, perceived discomfort, and muscular loading) and quality in a simulated overhead drilling task, and the moderating influence of tool mass (~2 and ~5 kg).

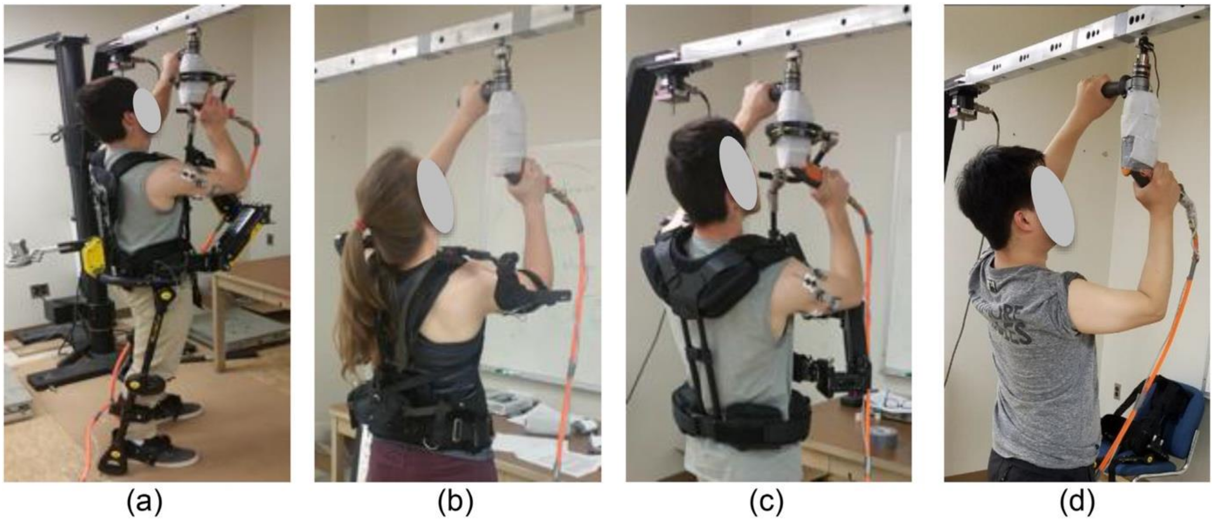

Figure 3.4 Illustrations of participants using: (a) the FORTIS™ Exoskeleton (Full); (b) the SuitX™ ShoulderX™ (Shoulder); (c) the Fawcett Exsovest™ with a zeroG mechanical arm; and (d) in the control condition (No support).

Source: Alabdulkarim and Nussbaum (2019)

Alabdulkarim and Nussbaum (2019) summarized that the exoskeleton designs included mechanical arms appeared to increase loading on the low back (Fortis™-full body exoskeleton and The Fawcett Exsovest™ with zero-G mechanical arm), though this effect was partially alleviated when the design allowed counterbalancing the load and transferring it to the ground (i.e., the Full device). When the tool was connected to a mechanical arm, lower quality was observed. The exoskeleton design that mainly supported the shoulder (ShoulderX™) reduced shoulder peak loading, but it also increased median loading of the dominant upper arm (i.e., TB-R muscle) and did not appear to impact quality. To facilitate the successful implementation of exoskeletons in occupational settings, this study highlights the need to consider at least three dimensions of potential outcomes – specifically physical demands, task performance, and usability – all of which may be influential in determining the potential effectiveness of exoskeletons in the workplace. Three distinct designs were tested, and which led to varied outcomes in these dimensions, with no one design found obviously superior across all dimensions. Given the evident potential of such technology, however, future research is needed to address some of the challenges that were identified, and to compare exoskeleton design approaches under more diverse and realistic conditions.

Van Engelhoven et al. (2019) used an earlier version of ShoulderX™ on 18 male participants in laboratory settings. The article concluded that ShoulderX™ significantly reduced overall median and PTA (peak torque amplitude) during static and repetitive overhead tasks using light and heavier tools. The magnitude of PTA preferred by participants varied, and excessive PTA increased antagonist muscle activity for some participants. Therefore, selecting the PTA level is likely an important factor in maximizing reductions in shoulder flexor muscle activity while avoiding negative impacts to preference or antagonist muscle activity. There was a note for a conflict of interest for one or more authors on this article.

De Bock et al. (2021) published a study that points out potential differences in laboratory and in-field experiments with exoskeletons. The article states to their best knowledge that it was the first study to thoroughly evaluate two commercially available passive shoulder exoskeletons during both isolated (laboratory conditions) and in-field tasks. Four healthy industrial workers performed controlled and in-field evaluations without and with two exoskeletons, ShoulderX™ and Skelex™ in a randomized order. The study has found reduced trapezius muscle (TR) activities up to 46% with ShoulderX™ and 30% with Skelex™ compared to No Exo during isolated tasks. These differences were less pronounced during in-field work, where reductions up to 8% and 26% were observed with ShoulderX™ and Skelex™, respectively. Subjective data demonstrated that the operators experienced a reduced temporal workload but scored the usability moderate when working with a passive shoulder exoskeleton. Additionally, increased upper body discomfort and frustration were present, especially with ShoulderX. Beneficial effects in the field were more pronounced when wearing Skelex™ while better assistance of the ShoulderX™ was reported during isolated tasks. Despite reduced muscle activity and heart rate when wearing an exoskeleton, the rating of perceived exertion was not always altered. According to the article, this is probably due to the combination of the exoskeleton support and negative subjective feelings such as discomfort, frustration, and limited usability. The study emphasized that caution is needed when interpreting laboratory- based exoskeleton evaluations because these results cannot be transferred to all in-field conditions.

3.3 Skelex™

It is manufactured by a company named Skelex that is based in Netherlands. It is a passive shoulder-support exoskeleton that is designed to support workers with overhead tasks. It uses gas springs and flexible frames (Figure 3.5). The exoskeleton has a semi-rigid structure. The article studied with Skelex is reviewed in the ShoulderX section.

Figure 3.5 Skelex Exoskeleton.

Source: https://www.skelex.com/skelex-360-xfr/, 2022

3.4 Ekso Vest™ – It is manufactured by a company named EksoBionics, Inc. that is based in the USA. The company has several exoskeletons for medical support that are extensively studied. It is a passive, shoulder-support exoskeleton that is designed to support workers with overhead tasks. It uses a series of compact gas springs and has a rigid structure.

Kim et al. (2018) Part 1 used EksoVest™ (an earlier version of Ekso Evo™) to assess its expected effects in terms of perceived discomfort, shoulder muscle activity, and task performance. 12 gender-balanced healthy participants completed the study in laboratory settings (Figure 3.6). The article suggests that using the exoskeleton did not substantially influence perceived discomfort but did decrease normalized shoulder muscle activity levels (e.g., ≤ 45% reduction in peak activity). Drilling task completion time decreased by nearly 20% with the vest, but the number of errors increased. The study declares that there was no conflict of interest, but it was supported by a grant from EksoBionics, Inc. and The Boeing Company. The former loaned the prototype exoskeleton, and employees of both companies provided information that contributed to the design of the current study. However, these individuals were not involved in data analysis/interpretation or the decision for publication.

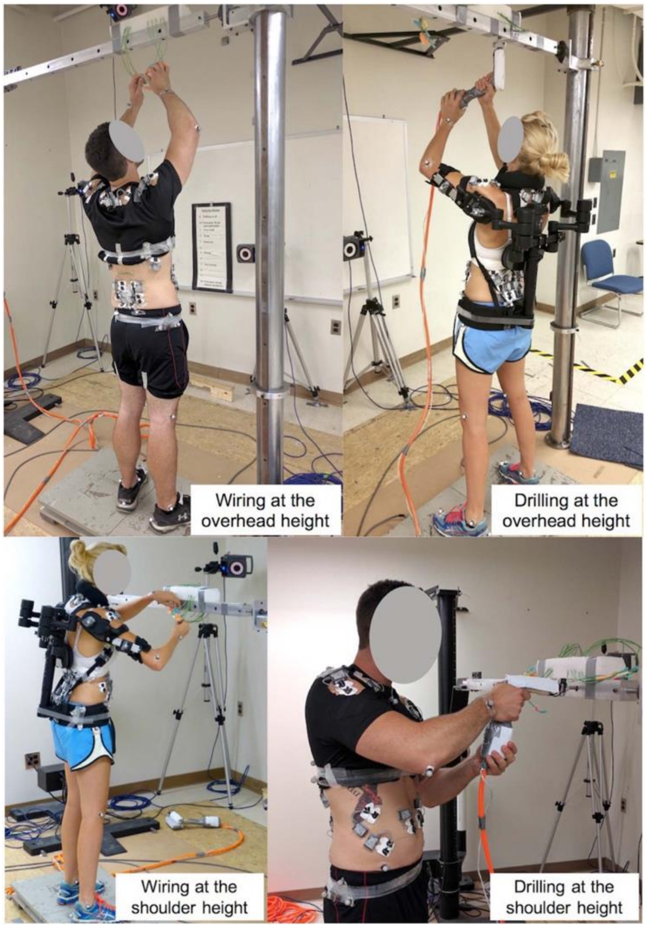

Figure 3.6 Height adjustable workpiece and example of drilling and wiring tasks at two different work heights (i.e., shoulder and overhead).

Source: Kim et al., 2018 – Part 1

Kim et al. (2018) Part 2 used EksoVest™ to assess its unexpected effects in terms of usability, shoulder range of motion limitations, postural control, slip and trip hazards, and spine loading during overhead tasks. 27 healthy participants (14 males and 13 females) completed one or more evaluation tests and were recruited from the local university and community. Donning/doffing the vest was easily done by a wearer alone. The vest reduced the max. shoulder abduction ROM by ~10% and increased the mean center of pressure velocity in the anteroposterior direction by ~12%. However, its use had minimal influences on trip-/slip-related fall risks during level walking and significantly reduced spine loadings (up to ∼30%), especially during the drilling task. Although the study declares that there was no conflict of interest, it was supported by a grant from EksoBionics, Inc. and The Boeing Company. The former loaned the prototype exoskeleton, and employees of both companies provided information that contributed to the design of the current study. However, these individuals were not involved in data analysis/interpretation or the decision for publication.

3.5 MATE™ (Muscular Aid Technology Exoskeleton)

It is manufactured by a company named Comau that is based in Italy. It is a passive, shoulder-support exoskeleton that is designed to support workers with overhead tasks. MATE's spring-loaded actuation box stores energy through an advanced mechanism during the extension phase, and then returns it to the user during the flexion phase. It has a rigid structure.

Pacifico et al. (2022) designed a study with a passive shoulder-support exoskeleton called MATE™ (Muscular Aid Technology Exoskeleton). The study investigated the effects of the device on 7 experienced workers during their regular work shifts in an enclosures production site. Experimental activities included three sessions, two of which were conducted *in-field* (namely, at two workstations of the painting line, where panels were mounted and dismounted from the line; each session involved three participants), and one session was carried out in a realistic *simulated* environment (namely, the workstations were recreated in a laboratory; this session involved four participants). Figure 3.7 illustrates "in-field" and "simulated" sessions. The effect of the exoskeleton was evaluated through electromyographic activity and perceived effort. After *in-field* sessions, device usability and user acceptance were also assessed. Data were reported individually for each participant. Results showed that the use of the exoskeleton reduced the total shoulder muscular activity compared to normal working conditions, in all subjects and experimental sessions. Similarly, the use of the exoskeleton resulted in reductions of the perceived effort in the shoulder, arm, and lower back. The article stressed that all participants indicated high usability and acceptance of the device. The study also declared the limitations of the experiment that the effects were observed only in a short amount of time and within isolated tasks. The authors of this study declared a financial interest / personal relationship with the manufacturing company.

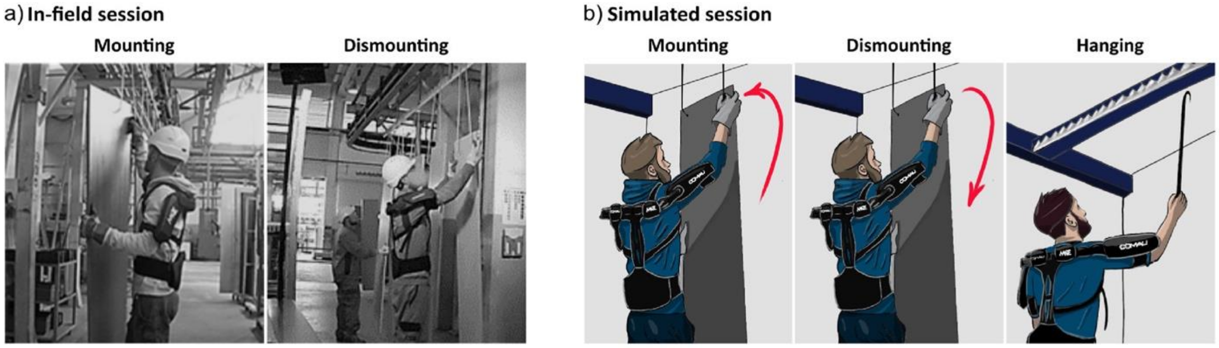

Figure 3.7 Illustration of participants during in-field (a) and simulated (b) sessions. In the in-field session, the exoskeleton was tested in the mounting and dismounting station. The simulated session included three tasks: the mounting, dismounting tasks, and the hanging task.

Source: Pacifico et al., 2022

3.6 Paexo™

It is manufactured by a company named Ottobock that is based in Germany. It is a passive, shoulder-support exoskeleton that is designed to support workers with overhead tasks. Paexo Shoulder uses springs and has a rigid structure (Figure 3.8). It is a light-weight shoulder exoskeleton that weighs less than 3.9 pounds (1.9 kgs.).

Figure 3.8 Configuration of Paexo Shoulder support exoskeleton.

Source: https://www.ottobock.com/en-us/Home, 2022

Maurice et al., 2019 assessed a passive shoulder-support PAEXO exoskeleton for over-head drilling tasks. Twelve healthy college students performed an over- head pointing task with a portable tool, with and without wearing PAEXO. The participants' physical and physiological state was monitored with whole-body inertial motion capture (Xsens Awinda system), ground reaction force (Kistler force plates), EMG on shoulder and back muscles (right anterior deltoid and right erector spinae longissimus), oxygen consumption, and heart rate. The tool motion was recorded with optical motion capture to evaluate task completion time. The perceived workload was assessed with the NASA Task Load Index. Following the experiment, participants answered a questionnaire, and a semi-directed interview was conducted to evaluate technology acceptance. Following validation with the lab study, PAEXO was tested with industrial workers in an automotive assembly factory. Four workers wore PAEXO during 20 consecutive workdays. Data were collected for 15 minutes at the beginning and end of each shift, during one week before starting using PAEXO (baseline), and during the first and last week of use. A simpler set of sensors was used to comply with the work requirements. Movements of workers were recorded with a regular camera, and body pose will be extracted using an image-processing library. Heart rate was also recorded during their shift. At the end of the shift, workers answered a technology acceptance questionnaire. According to the results of the lab study, muscle activation of anterior deltoid, oxygen consumption and heart rate were significantly reduced when using the exoskeleton, respectively by 55%, 33% and 19%. These results suggest that PAEXO efficiently reduces physical strain and fatigue. Conversely, task performance –assessed by movement duration–, activation of erector spinae and center of pressure movements remained unaffected. Hence PAEXO has no negative side effects neither on the user nor on productivity. Importantly, NASA-TLX scores indicated that the reduction in workload observed with objective measurements was perceived as such by participants (21% reduction in perceived workload with PAEXO). A modification of the arm movement was observed, with the arm being more abducted when using PAEXO. This modified posture however seems to come from a free choice of participants related to not having to sustain the arm weight anymore, rather than being imposed by the exoskeleton. Participants mentioned that they did not feel constrained in their movements. Eventually, acceptance score was high, and participants all said that they would choose to use the exoskeleton again for such a task. The article stated that the data collected during field-testing with industrial workers were currently analyzed to evaluate the impact of PAEXO on real end-users. So, no results were included regarding the field-testing.

Fritzsche et al., 2021 presented a different approach by extending laboratory and field research with biomechanical simulations using the AnyBody Modeling System to assess a passive shoulder-support exoskeleton called Paxeo Shoulder. Based on a dataset recorded in a laboratory experiment with 12 participants using the exoskeleton Paexo Shoulder in an overhead task, the same situation was reproduced in a virtual environment and analyzed with biomechanical simulation (Figure 3.9).

Figure 3.9 Experimental set up for data recording at the laboratory experiment.

Source: Fritzsche et al., 2021

Fritzsche et al., 2021 stated that according to the simulation results, the exoskeleton substantially reduces muscle activity and joint reaction forces in relevant body areas. Deltoid muscle activity and glenohumeral joint forces in the shoulder were decreased between 54 and 87%. Simultaneously, no increases of muscle activity and forces in other body areas were observed. Biomechanical simulation results widely agree with experimental measurements in the previous laboratory experiment and supplement such by providing an insight into effects on the human musculoskeletal system. The study concludes that Paexo Shoulder is an effective device to reduce physical strain in overhead tasks. The framework can be extended with further parameters, allowing investigations for product design and evaluation.

Latella et al., 2021 experimented with a commercially available PAEXO passive shoulder-support exoskeleton for overhead tasks. Twelve novice participants have been equipped with inertial and force/torque sensors to simultaneously estimate the whole-body kinematics and the joint torques by means of a probabilistic estimator, while performing an overhead task with a pointing tool. An evaluation has been performed to analyze the effect at the whole-body level by considering the conditions of wearing and not-wearing PAEXO during overhead work. Results indicated that PAEXO provides a reduction of the whole-body joint effort across the experimental task blocks (from 66% to 86%). Moreover, the analysis along with five different body areas shows that 1) the exoskeleton provides support at the human shoulders by reducing the joint effort at the targeted limbs, and 2) that part of the internal wrenches is intuitively transferred from the upper body to the thighs and legs, which is shown with an increment of the torques at the leg's joints. The study stated that the probabilistic estimation algorithm can be used as a validation metric to quantitatively assess PAEXO performances, paving thus the way for the next challenging milestone, such as the optimization of the human joint torques via adaptive exoskeleton control.

3.7 Fortis™

It is manufactured by a company named Lockheed Martin that is based in the USA. It is a passive, full-body exoskeleton that is designed to act as a third arm to support the weight of tools and other loads with over waist or over shoulder tasks (Figure 3.10). It uses gas springs and has a rigid structure from foot to shoulders. Most of the load is transferred to the ground via the foot linkage. It does not provide any support directly to arms or shoulders. The article studied with Fortis exoskeleton is in the ShoulderX section.

Figure 3.10 Demonstration of Fortis Exoskeleton (Full-Body).

Source: lockheedmartin.com/en-us/products/exoskeleton-technologies/industrial.html, 2022

3.8 Fawcett Exovest with Zero G2 Mechanical Arm™

It is manufactured by a company named Tiffen that is based in the USA. It is a passive, upper-body exoskeleton that is designed to act as a third arm to support the weight of tools and particularly for holding cameras (Figure 3.11). Like Fortis, this device does not directly provide any support to arms or shoulders. It has a semi-rigid structure. It uses pads and waist band to transform the weight. The article studied with Fawcett Exovest is reviewed in the ShoulderX section.

Figure 3.11 Steadicam Fawcett Exoskeleton.

Source: tiffen.com/products/steadicam-fawcett-exovest, 2022

3.9. Analysis of Benefits and Shortcomings from Wearing Shoulder-Support Exoskeletons

Fourteen recent scientific articles (2015 and newer) for eight passive SSEs are reviewed and their findings are presented in the Table 3.1. A total of 219 participants were used in these experiments (117 males, 36 females, and 66 not gender specified). Except for one article (Cha et al., 2020), all studies used quantitative methods. Five articles had only quantitative methods, and eight articles had both qualitative and quantitative methods.

Among the quantitative methods, muscle loading with EMG use was the most employed. Nine studies measured EMG of one or more muscle groups to quantify the change in muscle activation while comparing with or without SSE or while comparing with two or more SSE's. All EMG measurements reported reductions of muscle load in performed tasks ranging from 8% to 87%.

Decreased muscle activity in the body also decreases oxygen consumption, which indicates overall reduction of physiological cost from a physical exercise. One study (Maurice et al., 2019) reported 33% reduction of oxygen consumption and 19% reduction of heart rate from wearing SSE. Six articles measured performance and reported increases in performance when wearing SSE between 26.79 to 86%. However, two of these studies stated lower quality in tasks. Four studies assessed kinematics and none of them reported negative effects. One article (Iranzo et al., 2020) reported some differences in the range of movement of the back, neck, and arms owing to the use of the exoskeleton; however, the differences were smaller than 5% in all cases. The article stated that this translates as a slight loss of mobility. Two articles (Spada et al., 2017 and Liu et al., 2018) reported reductions in fatigue and increase in endurance.

Table 3.1 Passive Shoulder-Support Exoskeleton Studies

Study	Device	Method	Findings
Butler and Wisner (2017)	Levitate Airframe	Participants: -2 welders and 2 painters (most experienced) Procedure: -Quantitative - 5-day field test performing a dynamitic, moderate to severe ergonomic, repetitive tasks. - Job quality was managed at a certain level.	- Painters' productivity improved by 26.79% and 53.13%. The welders' performance with an exoskeleton device showed that productivity improved 86%. -With regularly scheduled breaks and lunch, welders and painters may not reach a level of fatigue that could be considered dangerous to their safety and health with the use of an exoskeleton device.
Spada et al. (2017)	Levitate Airframe	Participants: -29 male employees in an automotive plant Procedure: - Qualitative and quantitative assessments of activities that involve a posture with raised arms.	-Workers increased their performance by 30% on average and perceived less fatigue. -Encouraging data also emerged from the workers' interviews. Still, during the focus group, workers affirmed that the use of the exoskeleton should be on a voluntary base.
Liu et al. (2018)	Levitate Airframe	Participants: -20 general surgery residents Procedure: -Qualitative and quantitative - 1st phase tests for manual dexterity using the Minnesota Dexterity test, the Purdue Pegboard test, and the Fundamentals of Laparoscopic Surgery (FLS) modules -2nd phase tests the effect of the device on shoulder pain and fatigue while operating the laparoscopic camera	- Significantly less fatigue at all time periods and arm pain (3.11 vs 5.88, p = 0.019) at 10 min. -Significant decrease in shoulder pain and 85% of surgeons reported some form of pain reduction at the end of the operative day. -Minimally intrusive device that laparoscopic surgeons can wear to reduce pain and fatigue of surgery without significantly interfering with operative skills or manual dexterity.

		-3rd phase rates surgeon experience in the operating room between case-matched operating days.	
Iranzo et al. (2020)	Levitate Airframe	Participants: -11 male / 1 female employees in an automotive plant Procedure: -Continuous dynamic overhead work was performed -Quantitative - EMGs (anterior part of deltoid, trapezius, latissimus dorsi, and erector spinae) were measured -Cumulative percentage of maximum voluntary contraction (%MVC) of muscle activity in a work cycle were assessed -The joint angles motion capture was carried out by measuring the angles of the neck, back, and arms joints.	-Clear reduction of low and medium muscular activity (34% and 18%) in charge of arms flexion. -Does not reveal a reduction of risk of injury for overload efforts. -No differences were found in the activity of the potentially adversely affected muscles: the erector spinae and the latissimus dorsii. -Slight loss of mobility. -Some reported pain in the areas in contact with the arm supports.
Cha et al. (2020)	Levitate Airframe	Participants: -14 surgical team members Procedure: -Qualitative -Participants performed a 10-min simulated laparoscopic surgical task and completed a usability questionnaire afterwards.	- Mean participant responses from the System Usability Scale were 81.3 out of 100 (*SD* = 8.1), which was in the acceptable range of usability. -Received positive comments, especially from individuals in the nursing role but adaptation of exoskeleton would depend on factors such as cost and team member buy-in programs.
Alabdulkarim and Nussbaum (2019)	Fortis, ShoulderX, Fawcett Exsovest with Zero G Arm	Participants: -16 gender-balanced participants in a laboratory Procedure:	-Mechanical arms increased loading on the low back (Fortis and The Fawcett Exsovest™ with zero-G mechanical arm), though this effect was partially alleviated when the design allowed counterbalancing the load and transferring it to the ground.

		- Drilling for 15 minutes and additional 3 minutes with two different tools (2 and 5 kgs) -Quantitative and qualitative - 3 different exoskeletal designs are assessed for maximum acceptable frequency = MAF, perceived discomfort, and muscular loading -Quality of drilling task is also assessed	-When the tool was connected to a mechanical arm, lower quality was observed. -ShoulderX reduced shoulder peak loading, but increased median loading of the dominant upper arm, and did not appear to impact quality. -Physical demands, task performance, and usability – all of which may be influential in determining the potential effectiveness of exoskeletons in the workplace. -None of the devices were found obviously superior across all dimensions.
Van Engelhoven et al. (2019) *	ShoulderX	Participants: -18 male participants in laboratory Procedure: -Quantitative - static and repetitive overhead tasks using light and heavier tools	-Significantly reduced overall median and PTA (peak torque amplitude). -The magnitude of PTA preferred by participants varied, and excessive PTA increased antagonist muscle activity for some participants.
De Bock et al. (2021)	ShoulderX, Skelex	Participants: -4 healthy male industrial workers in laboratory and industrial settings Procedure: -Qualitative and quantitative -2 different exoskeletons assessed during both isolated (laboratory conditions) and in-field tasks	-Reduced trapezius muscle (TR) activities up to 46% (ShoulderX) and 30% (Skelex) in isolated tasks. -Reductions up to 8% (ShoulderX) and 26% (Skelex) in-field work. -Operators experienced a reduced temporal workload but scored the usability moderate. -Increased upper body discomfort and frustration especially with ShoulderX. -Beneficial effects in the field were more pronounced when wearing Skelex while better assistance of the ShoulderX was reported during isolated tasks. -Despite reduced muscle activity and heart rate when wearing an exoskeleton, the rating of perceived exertion was not always altered. -

			The study emphasized that caution is needed when interpreting laboratory- based exoskeleton evaluations because these results cannot be transferred to all in-field conditions.
Kim et al. (2018) Part 1 *	Ekso Vest	Participants: -12 gender-balanced healthy participants in a laboratory Procedure: -Quantitative and qualitative -Drilling and wiring tasks at shoulder and overhead heights -Perceived discomfort, shoulder muscle activity, and task performance were assessed.	- No significant influence perceived discomfort. -Decrease in normalized shoulder muscle activity levels (e.g., ≤ 45% reduction in peak activity). -Drilling task completion time decreased by nearly 20% with the vest, but the number of errors increased.
Kim et al. (2018) Part 2 *	Ekso Vest	Participants: -27 healthy participants (14 males and 13 females) Procedure: -Qualitative and quantitative -Assessed usability, shoulder range of motion limitations, postural control, slip and trip hazards, and spine loading during overhead tasks	-Donning/doffing the vest was easily done by a wearer alone. The vest reduced the max. shoulder abduction by ~10% and increased the mean center of pressure velocity in the anteroposterior direction by ~12%. -Minimal influences on trip-/slip-related fall risks during level walking. -Reduced spine loadings (up to ~30%), especially during the drilling task.
Pacifico et al. (2022) *	MATE™ (Muscular Aid Technology Exoskeleton)	Participants: -7 male experienced employees in plant and laboratory -Procedure: -2 sessions were conducted in-field (mounting / dismounting) and 1 session was carried out in a laboratory (mounting / dismounting / hanging)	- Reduced the total shoulder muscular activity in all subjects and sessions. -Reductions of the perceived effort in the shoulder, arm, and lower back. -All participants indicated high usability and acceptance of the device. -The study also declared that the effects were observed only in a short amount of time and within isolated tasks.

		-Quantitative and qualitative -Electromyographic activity, perceived effort, device usability, and user acceptance were assessed.	
Maurice et al., 2019	PAEXO	Participants: -12 healthy college students -4 workers Procedure: -Qualitative and quantitative -Physiological state, EMG on shoulder and back muscles (right anterior deltoid and right erector spinae longissimus), oxygen consumption, heart rate, and task completion time were measured. -The perceived workload was assessed. A questionnaire was conducted for acceptance. -Workers in an automotive assembly factory used PAEXO for 20 consecutive workdays.	-Reduction in muscle activation of anterior deltoid, oxygen consumption and heart rate respectively by 55%, 33% and 19%. -Activation of erector spinae and center of pressure movements remained unaffected. So, no negative side effects. -21% reduction in perceived workload. -Arms were being more abducted which seems to come from having to sustain less arm weight anymore. -Acceptance score was high, and participants all said that they would choose to use the exoskeleton again for such a task.
Fritzsche et al., 2021	PAEXO	Participants: -12 healthy college students (simulation in a laboratory) Procedure: -. Quantitative - Based on a dataset recorded in a laboratory experiment (above study) the same situation was reproduced in a virtual environment and analyzed with biomechanical simulation using AnyBody Modeling System.	-Deltoid muscle activity and glenohumeral joint forces in the shoulder were decreased between 54 and 87%. -No increases of muscle activity and forces in other body areas. Biomechanical simulation results widely agree with experimental measurements in the previous laboratory experiment. -The study concludes that Paexo Shoulder is an effective device to reduce physical strain in overhead tasks.

Latella et al., 2021	PAEXO	Participants: -12 novice male participants Procedure: -Quantitative - Performed an overhead task with a pointing tool. -Whole-body kinematics and the joint torque by mean of a probabilistic estimator were assessed.	- Reduction of the whole-body joint effort across the experimental task blocks (from 66% to 86%). -The exoskeleton provides support at the human shoulders by reducing the joint effort at the targeted limbs, and that part of the internal wrenches is intuitively transferred from the upper body to the thighs and legs, which is shown with an increment of the torques at the leg's joints. -The study stated that the probabilistic estimation algorithm can be used as a validation metric to quantitatively assess PAEXO performances, paving thus the way for the next challenging milestone, such as the optimization of the human joint torques via adaptive exoskeleton control.

* Study may have a conflict of interest or received funding or been conducted with involvement of the BSE manufacturer.

Regarding qualitative assessments, four out of five articles reported high rates of acceptability and two (not all but some participants reported discomfort in these two articles) out of five articles reported increased perceived discomfort. Majority of these results support the fact that SSEs are effective in reducing physical strain.

There were some findings that may be considered as negative. Alabdulkarim and Nussbaum (2019) assessed three exoskeletons and reported that two devices increased loading on the low back. Third device reduced shoulder peak loading but increased median loading of the dominant upper arm. Iranzo et al., 2020 reported that the exoskeleton use does not reveal a reduction of risk of injury for overload efforts. Participants in that study reported a slight loss of mobility and some reported pain in the areas in contact with the arm supports. De Bock et al., 2021 reported that participants experienced a reduced temporal workload but scored the usability moderate. They also reported increased upper body discomfort and frustration. The article stated that despite reduced muscle activity and heart rate when wearing an exoskeleton, the rating of perceived exertion was not always altered.

There were also interesting findings that are worth mentioning in here. De Bock et al., 2021 assessed two different passive shoulder-support exoskeletons in laboratory and in-field tasks. Reductions in trapezius muscle (TR) activities in laboratory (46% and 30%) and in-field (8% and 26%) were significantly different. More interestingly, the exoskeleton that provided the most reduction in laboratory (46%), provided lesser reduction in-field (8%) tasks. The same exoskeleton offered better assistance in isolated tasks (in laboratory) but the other device’s beneficial effects were more pronounced in-field. Alabdulkarim and Nussbaum (2019) assessed three exoskeleton and concluded that none of these devices had an obvious superiority in all aspects. Spada et al., 2017 reported that despite encouraging data from interviews regarding exoskeleton acceptability, workers mentioned that exoskeleton use should be on voluntary basis. Cha et al., 2020 received positive comments, especially from individuals in the nursing role but adaptation of an exoskeleton would depend on factors such as cost and team member buy-in programs.

CHAPTER 4

RESULTS AND CONCLUSION

4.1 Results

This literature review presented an analysis of thirty recent scientific articles (2015 and newer) that evaluated fifteen passive upper body exoskeletons in total. Sixteen scientific articles for seven passive back-support exoskeletons and fourteen scientific articles for eight passive shoulder-support exoskeletons were reviewed. A total of 434 participants were used in these thirty articles. Only 86 of them were females and 254 of them were males (94 participants were not gender specified).

90% of these studies (27 out of 30) had quantitative assessments. Twenty studies out of twenty-seven had EMG measurements. 95% of these EMG assessments (19 out of 20) reported reductions of muscle load in performed tasks ranging from 8% to 87%. Two out of three articles measured oxygen consumption reported 9% and 33% reductions. Two articles measured metabolic cost reported 9% and 18% reductions. One article reported 19% reduction in heart rate.

Two scientific studies (Gorsic et al., 2022; and Alabdulkarim and Nussbaum (2019)) with quantitative assessments had reported negative results. Other negative results or feedbacks came from qualitative assessments such as discomfort, less mobility, feeling of less mobility, overall acceptance, and cost.

Compared to back-support exoskeletons, the benefits of shoulder-support exoskeletons through EMG assessments were more pronounced. All EMG results reported reductions, but reductions had bigger percentages with SSEs (8% to 87% for shoulders compared to 9% to 47%).

4.2 Conclusion

Most of the reviewed scientific articles present benefits with isolated, short-term tasks. The benefits are more pronounced with quantitative assessments. According to few studies with field tests, the benefits of exoskeletons are less pronounced in-field tasks. Scientific studies aim to gather further data such as metabolic cost, oxygen consumption, heart rate along with muscle load assessments to present clearer and more complete results. Studies also focus on more complex tasks involving twisting, asymmetric lifts, etc. to simulate more real-life conditions. There is still a need for assessments that include real-work life conditions with mid to long-term experiments.

It is concluded through these articles that passive upper body exoskeletons can provide benefits with selected manual handling tasks in industry settings. However, there is not enough data through the recent articles to make any clear conclusions about exoskeletons' benefits in real-life working conditions within long term uses. It is not clear whether beneficial effects are only for specific tasks. Long term effects on muscles and lifting habits are not clear, either. Benefits can also change with the design and task dramatically. However, none of these exoskeletons have presented a clear superiority to each other in these studies.

Primary and secondary tasks, conditions, weight, sexes of users, specific requirements such as waterproof or fire-resistant capabilities, etc. should be considered to find the best exoskeleton for the job.

Most of the exoskeleton manufacturers are frequently upgrading and improving their existing products. Exoskeleton manufacturers address discomfort, mobility, and acceptance related feedback. Relatively newer exoskeletons have non-rigid design that are made of textile fibers can offer more flexibility, less discomfort, and lighter products. As of today, non-rigid designs are not able to offer the same average muscle load reductions according to the EMG assessments in the reviewed papers.

Female participants are considerably less used in these studies (254 males vs. 86 females). Increasing female participants and distinguishing their feedback particularly with regards to comfort may be useful due to physical differences. Manufacturers also improve their designs for female users in this regard.

Passive upper-body exoskeletons are still considerably expensive compared to many other PPEs (personal protection equipment) such as work shoes or filtered masks. However, as their users and manufacturers increase, cheaper exoskeleton models are becoming available. Large automobile and other manufacturers have been using exoskeletons. The data from these companies may be very useful to analyze exoskeletons' benefits further which may speed up the process of making exoskeletons cheaper as insurance companies may apply reductions in workers compensation rates. Thus, independent scientific studies with such companies are needed to assess their benefits in real-work environments.

APPENDIX A

YOUTUBE VIDEOS OF SELECTED BACK SUPPORT EXOSKELETONS

Laevo: https://www.youtube.com/watch?v=Ug1AqMYdEUM&t=3s

BackX: https://www.youtube.com/watch?v=cRnlXnTFb3k

Musclesuit: https://www.youtube.com/watch?v=QB5KKcnwFt8

Auxivo: https://www.youtube.com/watch?v=JY9VQhkThYI

VT Lowe’s: https://www.youtube.com/watch?v=zpLU04A9ySQ

Spexor: https://www.youtube.com/watch?v=rI6m5PxMEsI

Apex Herowear: https://www.youtube.com/watch?v=VWrXd-YGCTk

APPENDIX B

YOUTUBE VIDEOS OF SELECTED SHOULDER SUPPORT EXOSKELETONS

Levitate: https://www.youtube.com/watch?v=OCZzlUHLKAI

ShoulderX: https://www.youtube.com/watch?v=FHMFv8-0GLM

Skelex: https://www.youtube.com/watch?v=c5RUDua3owA

Eksovest: https://www.youtube.com/watch?v=lWmFEoDjUc4

MATE: https://www.youtube.com/watch?v=3peRrsu82Lg

Paexo: https://www.youtube.com/watch?v=Z3P3_4ZugLE&t=28s

Fortis: https://www.youtube.com/watch?v=eQeLVY22PMk

Fawcett Exovest with Zero G^2 Mechanical Arm:

https://www.youtube.com/watch?v=6rmRkX3lX_Y

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