INITIAL INVESTIGATION INTO THE EFFECT OF POWERED LUMBAR-SUPPORT INDUSTRIAL EXOSKELETONS

Prof. Dr. med. Herbert Schuster
Private Practice Genetics & Preventative Medicine, Berlin, Germany
Scientific Committee, Association of the Exoskeleton Industry e.V.
March 2020

Key Findings:

1. Active lumbar support exoskeletons reduce the propensity of MSDs as they effectively relieve muscular strain and decrease levels of fatigue – It is estimated that the total cost of lost productivity attributable to MSDs among people of working age in the EU could be as high as 2% of gross domestic product (GDP), or around EUR 300 billion annually.

2. Electromyography results show a mean reduction in muscular strain of Δ48-50% in the lumbar erector spinae muscles and a maximum amplitude of up to Δ66%

3. Ergospirometry testing confirmed that active exoskeleton wearers reduced their average O2 consumption by more than 15%

4. Study participants recorded a 15% lower maximum heart rate during periods of exertion

5. The benefits provided by the active exoskeleton were most pronounced during activities requiring participants to complete a strict quota of lifting and mental tasks within a set timeframe (i.e. similar to in a work situation)

INITIAL INVESTIGATION INTO THE EFFECT OF POWERED LUMBAR-SUPPORT INDUSTRIAL EXOSKELETONS

Prof. Dr. med. Herbert Schuster
Private Practice Genetics & Preventative Medicine, Berlin, Germany
Scientific Committee, Association of the Exoskeleton Industry e.V.

Musculoskeletal disorders (MSDs) are the leading cause of disability in the workplace, and the most commonly cited reasons for worker absenteeism after cold & flu. Recent estimates have placed the total cost of MSDs in terms of productivity loss at around 2% of GDP in the European Union (EU) (Bevan: 2015), or around EUR 300 billion each year. MSDs are especially prevalent in working environments where prolonged and repetitive manual lifting tasks cause strain on certain muscle groups. Employers often seek to mitigate MSDs through cognitive ergonomic training & risk assessment, the optimization of administrative work processes, and physical workplace modifications. A wide range of bionic exoskeletons are now being deployed throughout EU member states as a novel approach to remedy the issue. They are either purely mechanical *passive* systems, or battery-powered *active* systems. Their introduction has prompted occupational safety & health (OSH) agencies and trade unions to raise questions as to their effectiveness. This study utilizes surface electromyography and spirometry tools to analyze the effectiveness of *active* lumbar-support exoskeletons in reducing the risk factors which contribute to lower back MSDs, as well as investigating their effect on general fatigue and how these metabolic parameters relate to overall performance.

Introduction

Musculoskeletal Disorders (MSDs)

According to the World Health Organization (WHO), Musculoskeletal conditions are the leading contributor to disability worldwide, with lower back pain being the single leading cause of disability globally. The problem is prevalent across all age groups and is a leading cause of absenteeism and reduced output in the workplace. Currently, between one-in-three and one-in-five people live with a musculoskeletal pain condition (WHO 2019).

It has been estimated that the annual costs arising from these occupational illnesses amount to around 2% of the gross domestic product of the European Union (EU) (Bevan: 2015), or around EUR 300 billion each year.

Lower back MSDs are the most common in the industrial and logistics sectors, as well as in other areas of work, such as the healthcare field, where nurses and caregivers are required to lift immobile patients from their beds.

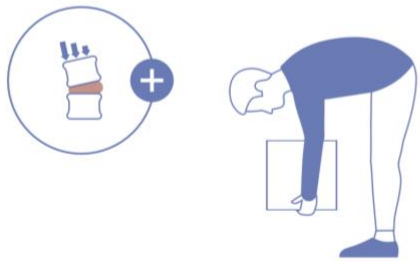
This study will seek to simulate various activities in a laboratory setting to investigate the leading causes contributing to lower back MSDs, and the potential for using active lumbar support exoskeletons as a preventative measure.

The Problem: Back pain & Spinal Loading

The pathology of lower back pain is dependent on many factors that are often idiosyncratic of the individual and the life they lead. However, repetitive manual labour tasks – specifically those that include compressive forces and prolonged loading – do put a large portion of the working population at a higher risk than most.

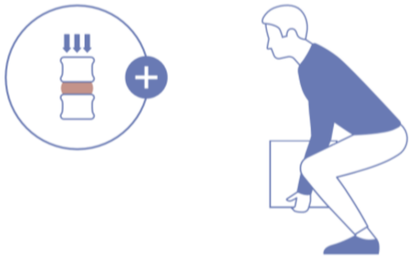
Motions such as bending, lifting and carrying weights cause the viscoelastic characteristics of the intervertebral disc (IVD) to decrease when exposed to sustained loading, and therefore to degenerate in form and function, essentially causing the load to transfer to surrounding structures. Repetitive actions of this kind act to inflict damage on nerve endings, thereby causing pain. Due to localization, most often the lumbar spine is affected since it is prone to higher biomechanical stress.

It has been posited that the most common cause of back pain, neck stiffness and problems with joints, is repetitive physical exertion exacerbated by awkward motions. Modern everyday life is predominantly filled by sedentary activities, especially those that neglect the hip and the back extensors.



Poor lifting form places uneven pressure on spinal discs

Such actions shorten muscles and ligaments, resulting in reduced mobility, poor posture and incorrect loads with irreversible damage to the anatomical structures of the musculoskeletal system. Improper lifting and carrying and the associated overstraining of the intervertebral discs are the main causes of functional and structural back problems, especially in the lower back region.



Repetitive lifting motions a leading cause of lower back pain

Current preventative solutions are grounded in occupational safety & health education to teach workers to lift with correct form, keeping a straight back and taking the weight with the whole of the back, and the leg muscles.

Education and Ergonomics

The current approach favored by most governmental bodies, worker's unions, and occupational health & safety agencies, is to provide a robust educational framework to teach all workers and employers of the dangers of musculoskeletal disorders, and preventative measures that can be taken in the form of best practice guidelines for ergonomic work environments (Nielsen et al. 2018).

In spite of these efforts, surveys conducted by Eurofound show that a significant number of workers in Europe report working conditions that require carrying or moving heavy loads and furthermore report being required to work at very high speed (European Foundation for the Improvement of Living and Working Conditions 2020).

Moreover, evidence suggests that the workers at highest risk of suffering from MSDs are those who perform repetitive tasks under time pressure and with little leeway (Roquelaure 2018).

Exoskeletons

Bionic exoskeletons are now being deployed throughout EU member states as a novel approach to improving musculoskeletal health in scenarios such as overhead work, to reduce load on the neck-shoulder area during prolonged elevation of the upper arms, as well as rapid repetitive lifting, carrying, and bent-forward tasks, such as tire changing (Grävemeyer 2020).

Exoskeletons are defined as on-body external mechanical structures. They can either be passive or active systems. 'Passive exoskeletons use the restoring forces of springs, dampers or other materials to support human movement, where the energy stored is generated exclusively by the movement of the user' (de Looze et al. 2016).

Active exoskeletons, on the other hand, 'utilize external energy sources, such as electrical motors to power the actuators to support the user with lifting activities' (Gopura and Kiguchi 2009).

Lumbar-support exoskeletons are designed to prevent lower back pain and permanent musculoskeletal damage. They assist the user by generating an extension moment which supports the back-extensor muscles and relieves the lower back while lifting or setting down heavy weights, as well as supporting the lower back muscles when in a forward bent posture.

There are numerous studies which use electromyography (EMG) readings to show reductions in lower-back muscle activity, indicating that lumbar-support exoskeletons can reduce physical stress in the lower spine (Toussaint et al. 1995; Barrett and Fathallah 2001; Abdoli-E. et al. 2006; Abdoli-E and Stevenson 2008; Frost et al. 2009; Godwin et al. 2009; Graham et al. 2009; Lotz et al. 2009; Wehner et al. 2009; Sadler et al. 2011; Ulrey and Fathallah 2013a, 2013b; Whitfield et al. 2014; Bosch et al. 2016; de Looze et al. 2016; INRS & Corfor 2017; Huysamen et al. 2018; Näf, M. B. 2018; Kazerooni, H. et al. 2019; Koopman et al. 2019; Motmans et al. 2019; Theurel and Desbrosses 2019).

Fewer studies have been conducted to show how lower-back exoskeletons affect metabolic parameters which indicate fatigue (Whitfield et al. 2014; Baltrusch et al. 2019).

Previous studies on the evaluation of exoskeletons almost exclusively focus on passive exoskeletons or body worn assistive devices. Although these experimental studies showed a reduction in the loading of the lower back during lifting, bending and static holding tasks (Abdoli-E and Stevenson 2008; Graham et al. 2009; Wehner et al. 2009; Ulrey and Fathallah 2013a; Bosch et al. 2016; Koopman et al. 2019; Yong, X. et al. 2019), they also revealed some major limitations regarding versatility, comfort and user acceptance, highlighting that although assistive devices can reduce the mechanical loading when performing one specific task, they might restrain performance in others. Baltrusch et al. (2019) assessed the effect of a passive lower back exoskeleton on functional performance for various work-related tasks.

Apart from objective time measurements they also gained subjective data of perceived task difficulty and discomfort via a visual-analog scale. Although they found an increase in objective performance in static forward bending, they found no increase in lifting performance. Additionally, the results showed a decrease in performance in tasks, such as walking, carrying and ladder climbing (Baltrusch et al. 2019).

Thus, it needs to be distinguished between solely performing static holding of a forward bending trunk posture or the necessity of a combination of many different tasks other than lifting, like carrying, walking and working in different postures.

Significance was found for the decrease in *perceived* task difficulty and local discomfort in the back during static forward bending, but also for perceived difficulty in various other tasks such as walking, squatting and wide standing. Tasks where hip flexion was involved felt more difficult when wearing the exoskeleton. They concluded that a full range of motion of the hips and trunk is required to increase versatility and user acceptance.

However, these studies were chiefly conducted under strictly controlled environments, which did not sufficiently analyze the relationship between time pressure, fatigue and the consequences for posture, resulting in increased muscular strain. It is hypothesized that under these conditions, the reductions achieved through the support of exoskeletons for both metabolic parameters and electromyography should be significantly higher than under strictly controlled conditions.

Active exoskeletons offer the potential to support the sensitive lower back region, as well as reducing general user fatigue, by ensuring that the wearer maintains a healthy posture, whilst offering Lift Assist support from an external power source.

Device ensures user maintains healthy stance when lifting & active force assist (25kgf) supports lumbar muscles

The Exoskeleton Device

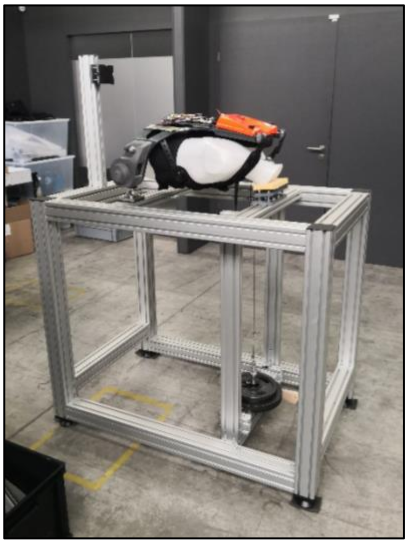
The device used was the Cray X which has been developed by German Bionic Systems. The Cray X is a battery-powered active exoskeleton which, according to the manufacturer and depending on the configuration, weighs less than 8kg and has a Lift Assist of 25kgf.

The device has a user interface to enable functionality customization based on body type and user preference, such as the sensitivity of the motors, and strength of additional support provided by the actuators.

For the purposes of control in scientific evaluation, test subjects were asked not to set these customizable parameters to less than 60% support.

Lift Assist

In the context of active exoskeletons, Lift Assist is defined as the degree of potential support provided by the device. For this study, Lift Assist has been measured by attaching the Cray X to a test dummy which was then bent forward to simulate lifting. A number of weights were attached to the dummy at increasing weights to determine how much the exoskeleton is able to lift by itself, without a human participant.



The tool used to measure Lift Assist potential with Cray X attached to test dummy which lifts incrementally increasing weights.

The Cray X device lifted a 25kg weight by itself without a human participant.

The U.S. National Institute for Occupational Safety and Health (NIOSH) guidelines establish a load constant of 23kg (51lbs) as a maximum recommended weight for lifting at the standard lifting location under optimal conditions (Waters et al. 1993; National Institute for Occupational Safety and Health 2019).

Methodology

Measuring Equipment

Electromyography (EMG)

Electromyography is an electrodiagnostic technique for evaluating and recording the electrical activity produced by skeletal muscles. The electromyograph utilizes electrodes that are placed on skin to detect the electrical potential generated by muscle cells.

The tool used to capture electromyography was FreeEMG from the BTS Bioengineering.

In the context of exoskeletons, a significant reduction on musculoskeletal strain is expected when the subject is wearing the supportive exoskeleton, as measured against results gathered without exoskeleton.

Electromyography signals were taken from the lumbar erector spinae and thoracic erector spinae muscles, to measure relief of the lower back, as well as on the upper back and the quad and hamstring muscles in the legs, to investigate whether the relief gained in the lower back from using the exoskeleton device leads to extra exertion in other parts of the body, shifting the problem from one location to another.

Ergospirometry

Ergospirometry is a common clinical approach used to assess cardiopulmonary function and maximum performance potential. Cardiopulmonary Exercise Testing (CPET) is a non-invasive method to assess heart and lung function during exertion. In a typical setting, patients would exert themselves physically on a treadmill or exercise bike.

By measuring factors such as max VO_2/kg consumption, max VCO_2/kg production, the respiratory exchange ratio (RER), and max heart rate (bpm) during periods of physical exertion, it is possible to evaluate the rate of general fatigue, and make certain assumptions about metabolic fatigue.

During the course of this study, metabolic parameters were analyzed with and without the exoskeleton to determine what effect the device had on the general fatigue of the participants.

The tool used for metabolic analysis was the Smart Analyzer from DYNOSTICS.

Reduction of O_2 consumption and CO_2 production was expected when the exoskeleton is used, as opposed to when task is performed without bionic assistance.

Participants

In total, an even distribution of 16 healthy men and women were chosen for the investigation with an average age of 30 ± 4 years, average height of 172 ± 10cm, and average weight of 65 ± 15kg.

Each participant demonstrated no known existing medical disorders before the test beginning.

Set Up

At first, height, weight, and trunk height of the participants were measured. The subjects where informed about the testing protocol. EMG electrodes were placed on their lower Er. Spinae muscle and surrounding muscles for control. The exoskeleton was then fitted and adjusted to the participant, where relevant. Finally, a spirometry mask was fitted over the nose and mouth.

Testing Procedure

To become habituated with the exoskeleton device and the EMG and spirometry equipment, the subjects were asked to walk around and bend and squat for a period of 5 minutes at leisure before signaling that they were comfortable and ready to begin testing.

Control Variables

Controlled variables vary with each activity dependent on the hypothesis. A total of four activities were chosen to test the assumptions that active exoskeletons:

- Provide a significant strain reduction on the lower back
- Contribute towards a significant reduction in overall fatigue of the user
- Enable the user to exert themselves for a longer duration of time under stress
- Lead to a reduction in error rate when exerting themselves under stress, due to a reduction in overall general fatigue

Strain Reduction – Activity 1

Static lifting task where participants were asked to lift and set down weights of 10kg & 20kg with and without the use of the Cray X device for 20 repetitions.

This experiment simulates work that requires lifting, but where there are no time constraints. Thus, participants were able to focus on lifting the weights while maintaining a healthy posture.

The results should indicate how the Cray X supports with reduction in muscular strain when a healthy posture in maintained.

Fatigue Reduction – Activity 2

Participants were asked to lift weights of 10kg & 20kg with and without the use of the Cray X device for 20 repetitions and shift the weight to a location distanced 20 meters away, and then return each weight to the original location.

Extending the distance needed to travel to transport the weights is designed to increase the level of fatigue.

Time Trial – Activity 3

Participants were asked to lift weights of 10kg & 20kg with and without the use of the exoskeleton device for as many repetitions as possible within the time limit of 1 hour, shifting the weight to a location distanced 20 meters away.

Mental Fatigue – Activity 4

Participants were asked to lift weights of 10kg & 20kg with and without the use of the Cray X device for as many repetitions as possible within the time limit of 1 hour, shifting the weight to one of five locations, each distanced 20m apart, where the end location is dictated by the solution to a simple mathematical problem written on a note in the contents.

Activity 4 is expected to most closely simulate the kind of activities that workers would face under real-life conditions.

The goal of this experiment is to determine the extent to which the device can reduce general fatigue, and therefore reduce the propensity for error when conducting everyday activities.

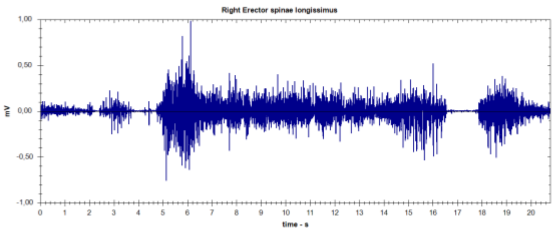
Data Processing

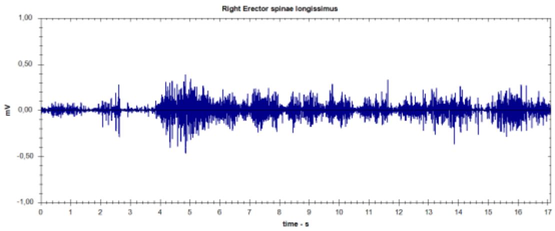
After the participants had completed the tasks and the data was collected, it was pseudonymized for processing to hide any identifying parameters, such as name, age, gender, height, and weight, to ensure that data analysis was conducted without bias.

Results

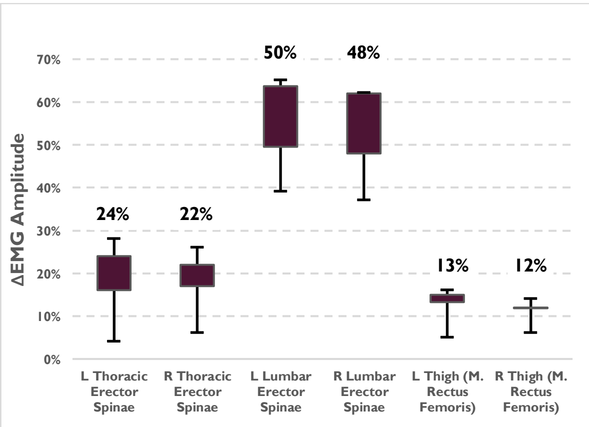
Electromyography

Across all activities, the delta from completing the tasks without, to completing tasks with, the exoskeleton device, derived from the mean across all participants resulted in a significant reduction in the lumbar erector spinae muscles.





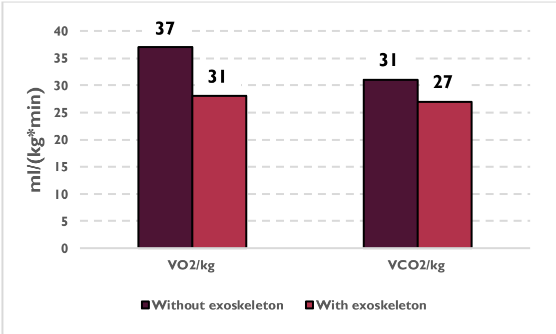
Electromyography results show a mean reduction in muscular strain of Δ48-50% in the lumbar erector spinae muscles and a maximum amplitude of up to Δ66%, and a reduction of 22-24% on the thoracic erector spinae muscles.



The M. Rectus Femoris also showed a mean reduction of 12-13%, indicating that the relief gained in the lower back region did not shift the problem by causing additional strain in the participants' thigh muscles.

Spirometry

Ergospirometry testing confirmed that active exoskeleton wearers reduced their average O2 consumption by more than 15%, compared to when participants completed the tasks without support.



The most significant results were recorded during the time trial and mental fatigue activities, where participants were asked to exert themselves for an extended period of time with high energy.

Heart Rate

Test subjects showed negligible difference in heart rate during rest periods with and without the device. In periods of exertion, a significant reduction of maximum heart rate of 15% was recorded whilst wearing the device.

Time Trial

Due to the general fitness levels of the test participants, results varied greatly. However, the number of repetitions did increase for all participants across the board.

Participant engaged in high intensity Time Trial – Activity 3.

Additionally, of all the tests, the Time Trial – Activity 3 and Mental Fatigue – Activity 4, produced the highest reductions in mean EMG readings when compared to other activities, as well as oxygen consumption.

The mean number of repetitions within the specified time period also increased by 23%.

Mental Fatigue

Participants again showed a distinct improvement in lifting and transporting a higher number of repetitions to the correct locations, whilst displaying the highest overall mean reductions in metabolic and muscular parameters.

Discussion

The rate of fatigue has been shown to directly correlate with the ability to maintain a healthy posture, as participants focus their efforts on increasing the number of lifting repetitions, rather than remaining attentive to the educational efforts designed to encourage proper ergonomic movements.

A significant reduction in oxygen consumption was observed when participants were using the exoskeleton in comparison to without support. Lower oxygen consumption is a sign of lower workload as the consumption is proportional to the energy expenditure.

Increasing CO_2 production is a sign of fatigue. At low levels, energy is provided by fatty acid metabolism, whereas at high levels and with high tension in the skeletal muscles, blood flow is not sufficient to provide enough oxygen to the muscle cells. Subsequently muscle cells change the substrate for energy production from fatty acid to glucose. As a consequence of this, anaerobic metabolism of glucose leads to an increase of the production of CO_2, which can be measured in the breath. If CO_2 production in liter per time unit is greater than oxygen uptake, this is a sign of exhaustion.

During the *Time Trial – Activity 3*, it was observed that participants generally began to increasingly neglect their lifting posture (lifting with a straight back and bent legs) when put under more stressful conditions, which yielded higher mean EMG results showing an increased strain of the lumbar erector spinae muscles when not wearing the exoskeleton device.

Furthermore, despite the relative heterogeneity of the study population (in terms of age, weight, length, body composition, and physical fitness etc.), the results showed a surprisingly consistent pattern of reductions. It should furthermore be noted that the participant with the lowest body mass (the shortest and lightest in the group) also showed significant reductions in levels of fatigue, despite the higher proportional weight of the device.

Although this study does not make a direct comparison between active and passive systems, the results are compelling and show that there is a place for active lumbar support exoskeletons in high intensity working environments that require lifting, carrying, shifting, bending, and other awkward positionings.

Due to the external power source, users are supported with a high support in the lower back (relative to *Force Assist*), as well as being compensated in terms of their overall *balance of energy,* because the body does not need to produce the energy itself.

The result is overall fatigue reduction, where the weight of the exoskeleton device is offset by the added external energy it provides to help when repetitively lifting other much heavier weights.

An analogous example is the difference between riding uphill with an electric bicycle vs. riding uphill with a manual bicycle; the electric bike is slightly heavier, but still allows the rider to get to the peak quicker and with less energy expended than their counterpart.

Regarding the test methodology, although the study was designed with a range of different testing procedures to mimic a broad range of working scenarios, there is still need for long term study in real-world scenarios.

Conclusion

In conclusion, the study has indicated that *active* lumbar-support exoskeletons could be used as a very effective tool to support workers that are forced to adopt awkward positionings over long periods of time and in high intensity environments by relieving muscular strain and reducing levels of general fatigue.

References

Abdoli-E, Mohammad; Stevenson, Joan M. (2008): The effect of on-body lift assistive device on the lumbar 3D dynamic moments and EMG during asymmetric freestyle lifting. In Clinical biomechanics (Bristol, Avon) 23 (3), pp. 372–380. DOI: 10.1016/j.clinbiomech.2007.10.012.

Abdoli-E., Mohammad; Agnew, Michael J.; Stevenson, Joan M. (2006): An on-body personal lift augmentation device (PLAD) reduces EMG amplitude of Erector Spina during lifting tasks. In Clinical Biomechanics 21 (5), pp. 456–465.

Baltrusch, S. J.; van Dieën, J. H.; Bruijn, S. M.; Koopman, A. S.; van Bennekom, C. A. M.; Houdijk, H. (2019): The effect of a passive trunk exoskeleton on metabolic costs during lifting and walking. In Ergonomics 62 (7), pp. 903–916. DOI: 10.1080/00140139.2019.1602288.

Bevan, S. (2015): Economic impact of musculoskeletal disorders (MSDs) on work in Europe. In Best Pract Res Clin Rheumatol. 2015 Jun;29(3):356-73. DOI: 10.1016/j.berh.2015.08.002.

Barrett, A.; Fathallah, F. (Eds.) (2001): Evaluation of four weight transfer devices for reducing loads on the lower back during agricultural stoop labor. Annual International Meeting of the American Society of Agricultural Engineers (ASAE). Sacramento, USA, July 29 - August 1 (Paper No. 01-8056).

Bosch, Tim; van Eck, Jennifer; Knitel, Karlijn; Looze, Michiel de (2016): The effects of a passive exoskeleton on muscle activity, discomfort and endurance time in forward bending work. In Applied ergonomics 54, pp. 212–217. DOI: 10.1016/j.apergo.2015.12.003.

de Looze, Michiel P.; Bosch, Tim; Krause, Frank; Stadler, Konrad S.; O'Sullivan, Leonard W. (2016): Exoskeletons for industrial application and their potential effects on physical work load. In Ergonomics 59 (5), pp. 671–681. DOI: 10.1080/00140139.2015.1081988.

European Foundation for the Improvement of Living and Working Conditions (2020): European Working Conditions Survey.

Frost, David M.; Abdoli-E, Mohammad; Stevenson, Joan M. (2009): PLAD (personal lift assistive device) stiffness affects the lumbar flexion/extension moment and the posterior chain EMG during symmetrical lifting tasks. In Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology 19 (6), e403-12. DOI: 10.1016/j.jelekin.2008.12.002.

Godwin, Alison A.; Stevenson, Joan M.; Agnew, Michael J.; Twiddy, Alexis L.; Abdoli-Eramaki, Mohammad; Lotz, Christy A. (2009): Testing the efficacy of an ergonomic lifting aid at diminishing muscular fatigue in women over a prolonged period of lifting. In International Journal of Industrial Ergonomics 39 (1), pp. 121–126. DOI: 10.1016/j.ergon.2008.05.008.

Gopura, R. A. R. C.; Kiguchi, K. (Eds.) (2009): Mechanical designs of active upper-limb exoskeleton robots: State-of-the-art and design difficulties. IEEE International Conference on Rehabilitation Robotics. Kyoto, 23 -26 June.

Graham, Ryan B.; Agnew, Michael J.; Stevenson, Joan M. (2009): Effectiveness of an on-body lifting aid at reducing low back physical demands during an automotive assembly task: assessment of EMG response and user acceptability. In Applied ergonomics 40 (5), pp. 936–942. DOI: 10.1016/j.apergo.2009.01.006.

Grävemeyer, Arne (2020): Zusatzmuskeln zum Umschnallen. Exoskelette beugen körperlicher Überlastung vor. In CT Magazin für computer technik 2020, 1/4/2020 (2), pp. 124–127. Available online at https://www.heise.de/select/ct/2020/2/157832788715095 9.

Huysamen, Kirsten; Looze, Michiel de; Bosch, Tim; Ortiz, Jesus; Toxiri, Stefano; O'Sullivan, Leonard W. (2018): Assessment of an active industrial exoskeleton to aid dynamic lifting and lowering manual handling tasks. In Applied ergonomics 68, pp. 125–131. DOI: 10.1016/j.apergo.2017.11.004.

Kazerooni, H. & Tung, Wayne & Pillai, Minerva. (2019). Evaluation of Trunk-Supporting Exoskeleton. Proceedings of the Human Factors and Ergonomics Society Annual Meeting. 63. 1080-1083. 10.1177/1071181319631261.

Koopman, Axel S.; Kingma, Idsart; Faber, Gert S.; Looze, Michiel P. de; van Dieën, Jaap H. (2019): Effects of a passive exoskeleton on the mechanical loading of the low back in static holding tasks. In Journal of biomechanics 83, pp. 97–103. DOI: 10.1016/j.jbiomech.2018.11.033.

Lotz, Christy A.; Agnew, Michael J.; Godwin, Alison A.; Stevenson, Joan M. (2009): The effect of an on-body personal lift assist device (PLAD) on fatigue during a repetitive lifting task. In Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology 19 (2), pp. 331–340. DOI: 10.1016/j.jelekin.2007.08.006.

Motmans, R.; Debaets, T.; Chrispeels, S. (2019): Effect of a Passive Exoskeleton on Muscle Activity and Posture During Order Picking. In Sebastiano Bagnara, Riccardo Tartaglia, Sara Albolino, Thomas Alexander, Yushi Fujita (Eds.): Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018). Volume III: Musculoskeletal Disorders, vol. 820. Cham: Springer International Publishing (Advances in Intelligent Systems and Computing, 820), pp. 338–346.

Näf, M. B., Koopman, A. S., Baltrusch, S., Rodriguez-Guerrero, C., Vanderborght, B., Lefeber, D. (2018).

Passive Back Support Exoskeleton Improves Range of Motion Using Flexible Beams. Frontiers in Robotics and AI, 5, 456–16. http://doi.org/10.3389/frobt.2018.00072.

National Institute for Occupational Safety and Health (2019): Ergonomics and Musculoskeletal Disorders | NIOSH | CDC. Available online at https://www.cdc.gov/niosh/topics/ergonomics/, updated on 1/1/2019, checked on 1/15/2020.

Nielsen, Karina; Jørgensen, Marie Birk; Milczarek, Malgorzata; Munar, Lorenzo (2018): Healthy workers, thriving companies – a practical guide to wellbeing at work.

Roquelaure, Yves (2018): Musculoskeletal disorders and psychosocial factors at work. Brussels: ETUI aisbl (Report / European Trade Union Institute, 142).

Sadler, Erin M.; Graham, Ryan B.; Stevenson, Joan M. (2011): The personal lift-assist device and lifting technique: a principal component analysis. In Ergonomics 54 (4), pp. 392–402. DOI: 10.1080/00140139.2011.556259.

Theurel, Jean; Desbrosses, Kevin (2019): Occupational Exoskeletons: Overview of Their Benefits and Limitations in Preventing Work-Related Musculoskeletal Disorders. In IISE Transactions on Occupational Ergonomics and Human Factors 24 (8), pp. 1–17. DOI: 10.1080/24725838.2019.1638331.

Toussaint, Huub M.; Winter, Andrea F. de; Haas, Yvonne de; Looze, Michiel P. de; van Dieën, Jaap H.; Kingma, Idsart (1995): Flexion relaxation during lifting: Implications for torque production by muscle activity and tissue strain at the lumbo-sacral joint. In Journal of biomechanics 28 (2), pp. 199–210. DOI: 10.1016/0021-9290(94)00051-5.

Ulrey, Brent L.; Fathallah, Fadi A. (2013a): Effect of a personal weight transfer device on muscle activities and joint flexions in the stooped posture. In Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology 23 (1), pp. 195–205. DOI: 10.1016/j.jelekin.2012.08.014.

Ulrey, Brent L.; Fathallah, Fadi A. (2013b): Subject-specific, whole-body models of the stooped posture with a personal weight transfer device. In Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology 23 (1), pp. 206–215. DOI: 10.1016/j.jelekin.2012.08.016.

Waters, T. R.; Putz-Anderson, V.; Garg, A.; Fine, L. J. (1993): Revised NIOSH equation for the design and evaluation of manual lifting tasks. In Ergonomics 36 (7), pp. 749–776. DOI: 10.1080/00140139308967940.

Wehner, Michael; Rempel, David; Kazerooni, Homayoon (2009): Lower Extremity Exoskeleton Reduces Back Forces in Lifting. In : ASME 2009 Dynamic Systems and Control Conference. October 12-14, 2009, Hollywood, California, USA. ASME 2009 Dynamic Systems and Control Conference. Hollywood, California, USA, 10/12/2009 - 10/14/2009. [New York]: ASME, pp. 49–56.

Whitfield, Brett H.; Costigan, Patrick A.; Stevenson, Joan M.; Smallman, Catherine L. (2014): Effect of an on-body ergonomic aid on oxygen consumption during a repetitive lifting task. In International Journal of Industrial Ergonomics 44 (1), pp. 39–44. DOI: 10.1016/j.ergon.2013.10.002.

WHO (2019): Musculoskeletal conditions. World Health Organization. Available online at www.who.int/news-room/fact-sheets/detail/musculoskeletal-conditions, updated on 11/26/2019.

Yong, X., Yan, Z., Wang, C., Wang, C., Li, N., & Wu, X. (2019) Ergonomic Mechanical Design and Assessment of a Waist Assist Exoskeleton for Reducing Lumbar Loads During Lifting Task. Micromachines 2019, 10, 463; DOI: 10.3390/mi10070463.