Aus dem

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Back-support exoskeletons in industrial tasks ─ Effects and side-effects on physical stress and strain

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Chapter 1

Introduction

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1.1 Musculoskeletal disorders in the working population

Work-related musculoskeletal disorders (WMSDs), such as impairments of muscles, joints, tendons, and ligaments, have been reported to be the most frequent occupational health problem in industrial countries. According to the European Agency for Safety and Health at Work, 60% of all self-reported health problems of employees in the European Union (EU) belong to the musculoskeletal system (DeKok et al., 2019). The consequences are often limitations in their daily life, such as physical function in daily activities and quality of life. Further repercussions are impairments in their working activities, such as efficiency and productivity loss and sick leave (Duenas et al., 2016; Eurostat, 2010). Musculoskeletal disorders (MSDs) are the most frequently reported reasons for sick leave. In Germany, for example, 25.2% of the total registered sick leave days (17.4 days/year/person) was related to MSDs in 2016. This resulted in production cost losses of 17.2 billion euros for the economy in that year, representing 0.5% of the German gross domestic product (Dauber & Isusi, 2019).

The most affected area of MSDs is the back, often resulting in lower back pain (LBP; de Kok et al., 2019; Eurostat, 2010; Hartvigsen et al., 2018), which has been registered to be the leading cause of disability worldwide (Hartvigsen et al., 2018). In the EU, 12-month prevalence rates for overall back pain have recently been reported to be 43% for employees in general (Dauber & Isusi, 2019) and 55–60% for blue-collar workers, with the lower back most commonly affected (DeKok et al., 2019; Govaerts et al., 2021). In certain professional groups, the prevalence rates might even exceed these rates. For example, cross-sectional surveys identified a 12-month prevalence of 70% in flight baggage handlers for back pain (Bergsten et al., 2015) and 89% in wind farmers for LBP (Jia et al., 2016).

The cause of LBP is multifactorial, including physical or biomechanical (e.g., exposure to physical load), psychosocial (e.g., job satisfaction), and personal or individual (e.g., socio-economic status) factors (da Costa & Vieira, 2010; de Kok et al., 2019; Dick et al., 2020; Hartvigsen et al., 2018). The strongest association for LBP was shown for physical exposures (Dick et al., 2020), such as repetitive movements, dynamic or static work in awkward postures, carrying or moving heavy loads, and lifting (da Costa & Vieira, 2010; de Kok et al., 2019; Dick et al., 2020).

1.2 Prevention of work-related musculoskeletal disorders

Various prevention strategies for WMSDs are available at work in industrial countries. For example, the European Agency for Safety and Health reports that 91% of European employees work in companies that provide equipment for lifting and moving assistance, 83% work in companies that provide ergonomic equipment, 75% work in companies that include regular work breaks for awkward postures, 63% work in companies that include task rotation for reducing repetitive movements, 87% of the employees have access to training on working techniques, and 73% have access to equipment for reducing their workload (Dauber & Isusi, 2019). In this respect, three past (systematic) reviews (one including a meta-analysis) focusing on workplace interventions regarding LBP concluded that most interventions were either ineffective or had unclear benefits due to low quality of evidence (Gatty et al., 2003; Maher, 2000; Steffens et al., 2016). On the contrary, a recent review with meta-analyses found positive effects on LBP, quality of life, and related parameters when evaluating workplace interventions (Russo et al., 2021). However, despite access to workplace interventions, the impact of WMSDs, including symptoms like LBP, remains significant (Di Tecco et al., 2022; EU-OSHA, 2023; Govaerts et al., 2021) and their prevention is challenging as a result of their multifactorial nature (Di Tecco et al., 2022). This indicates that ongoing treatments and prevention may be insufficient or inappropriate and provides support for the need of innovative approaches to manage WMSDs. Exoskeletons have recently been introduced to prevent WMSDs, including the back area, and have gained a growing interest in both industry and research (Steinhilber et al., 2020; Toxiri et al., 2019), offering a unique opportunity to reduce biomechanical loads via a user-robotic interface (Govaerts et al., 2021; Lee et al., 2012).

1.3 Exoskeletons

Exoskeletons are wearable mechanical structures that aim to support the musculoskeletal system in motion (e.g., in physical work tasks) by generating forces/torques on human joints (de Looze et al., 2016; Steinhilber et al., 2020; Toxiri et al., 2019). Their innovation has been described to be the combination of human intelligence and robot power (Lee et al., 2012). Their field of application can be medical, occupational, or military. Most exoskeletons have been designed for medical reasons such as rehabilitation or daily living movement assistance, e.g., supporting gait and the general functionality of the locomotor system. Military exoskeletons mainly aim to support walking and carrying loads. Occupational exoskeletons, also described as work-related or industrial exoskeletons, aim to reduce the physical workload in defined body areas during the performance of certain work tasks (ExR). Technically, they have been classified according to (1) the type of actuation (active vs passive), (2) structures and attachments (rigid vs soft), and (3) joint alignment. First, active exoskeletons are powered through actuators such as electrical motors or hydraulic cylinders, while passive exoskeletons—which account for the majority of commercially available exoskeletons—use components such as springs, dampers, or straps for storing energy (Howard et al., 2020; Lee et al., 2012; Toxiri et al., 2019). Second, the structures that transfer the supportive torques from one area to another can be either rigid or soft, inducing a load perpendicular or parallel to the respective body segment (Toxiri et al., 2019). Third, anthropomorphic exoskeletons are designed to align the rotation axis of the exoskeleton to the rotation axis of the human joint and therefore allow it to move in accordance with the wearer. Quasi-anthropomorphic exoskeletons allow similar movements but without exact alignments of the joints. Non-anthropomorphic exoskeletons have more simple builds and allow specific movements for performing specific tasks (de Looze et al., 2016; Lee et al., 2012). Further, exoskeletons can be grouped according to the supported body area, e.g., the upper limbs, lower limbs, back, combinations of several areas, or single joints (de Looze et al., 2016; Lee et al., 2012; Toxiri et al., 2019). This dissertation focuses on exoskeletons with an occupational purpose and will mainly discuss passive, anthropomorphic devices that support the lower back.

Classification within the context of occupational safety and health

There is ongoing debate about whether a qualification of occupational exoskeletons for personal protective equipment (PPE) is justifiable (BGHW, 2022; DGUV, 2019; Lowe et al., 2019), as the objectives of occupational exoskeletons and PPEs to prevent WMSDs or work-related injury coincide (Howard et al., 2020). Using PPE is one solution within the application of personal protective measures. It is the last of four options in the so-called STOP principle, recommended by the Federal Institute for Occupational Safety and Health in Germany to maintain employees' work-related physical and psychosocial health. The application of the measures follows a hierarchical order. First, the

"**S**ubstitution" or avoidance of health hazards must be implemented with priority. If not possible, "**T**echnical" protection measures should be applied, including the technical equipment of the workplace, in order to avert any health hazards. The third option is "**O**rganizational" protection measures, e.g., the reorganization of work processes. Fourth, if the previously described principles are not sufficient, the use of "**P**ersonal" protective measures is an option, including PPE (BAuA, 2022). Although occupational exoskeletons are not yet classified as PPE, they are already used in some companies with the aim to prevent the risk for WMSDs and manufacturers promote their preventive effects (Howard et al., 2020; Steinhilber et al., 2020).

Laevo® V2.56 exoskeleton

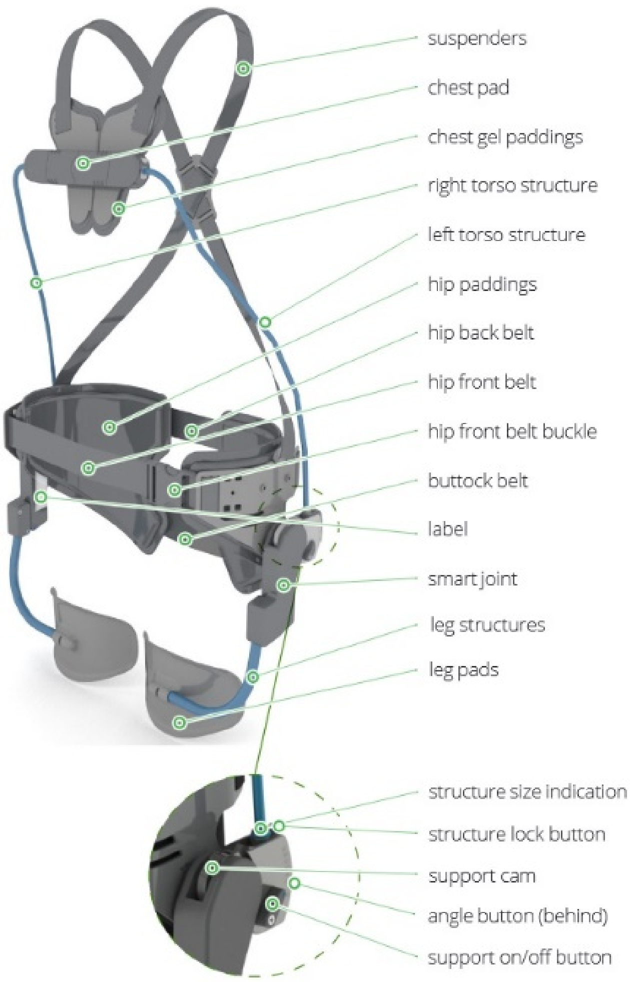

Figure 1: The passive exoskeleton Laevo® V2.56 (Laevo B.V., Delft, The Netherlands) (user manual, 2018; *Laevo B.V., Delft, The Netherlands; https://laevo-exoskeletons.com/ Manuals*).

One exemplary exoskeleton that has already been tested by industrial companies is the passive back-support exoskeleton (BSE) Laevo® (V2.56, Laevo B.V., Delft, the

Netherlands; 2.8kg). The Laevo® exoskeletons aim to "prevent back injuries and improve quality of life" by reducing back strain in occupational settings (Laevo). It works via an energy-storing gas spring system located outside the hip joint pivot point ("smart joint"). The smart joint is connected by rigid bars to a chest pad on the lower sternum level and a leg pad on the front of the thighs. When bending the trunk, energy is stored and emitted by trunk extension movement (Laevo). Structures responsible for trunk or hip extension are relieved by the trunk extension torque applied, which is supported by a force pushing perpendicular onto the thighs (Toxiri et al., 2019).

1.4 Back-support exoskeletons in industrial tasks—State of the evidence

Recently, researchers have increasingly evaluated the effects of using BSEs on physical stress and strain parameters (De Bock et al., 2022; Kermavnar et al., 2021; Theurel & Desbrosses, 2019). Herein, physical stress is the quantitative action of a load, for example, induced due to physical exposure. Physical strain is the individual physical response to the stressor, depending on an individual's characteristics and capabilities (e.g., muscle activity, heart rate, perceived exposure; Rohmert, 1986). In some exoskeleton evaluations, physical stress was detected, mostly via force measurements. However, the evaluation of physical strain parameters, such as muscle activity, heart rate, and perceived exertion or discomfort were more popular measures. Herein, muscle activity was the most frequently used objective strain parameter (de Looze et al., 2016; Kermavnar et al., 2021; Theurel & Desbrosses, 2019), reflecting the amount of muscle activity provided for performing a certain physical task (Burden, 2010). Reductions in stress and strain parameters are considered positive in terms of musculoskeletal health, however, evidence for the positive effect is still lacking. Most studies thus far were conducted under laboratory conditions, evaluated acute effects, included highly controlled simulated work tasks, and focused on the intentionally supported area (target area), e.g., the back (de Looze et al., 2016; Kermavnar et al., 2021; Theurel & Desbrosses, 2019).

There are some (systematic) reviews that provide an informative overview of the effects of using BSEs (de Looze et al., 2016; Kermavnar et al., 2021; Theurel & Desbrosses, 2019), upper limb-support exoskeletons (ULEs) (de Looze et al., 2016; McFarland & Fischer, 2019; Theurel & Desbrosses, 2019), or the technical aspects of BSEs (Toxiri et al., 2019). However, despite the existing reviews, and because of very rapid development and frequently newly published papers in recent years, a current and straightforward overview of the topic is lacking. In this respect, no quantitative analyses (e.g., via meta-analyses) have been performed across aspects such as exoskeleton types, body areas, or outcome parameters. A systematic review, including meta-analyses will provide a broad and general overview of the effects and side-effects that potentially occur when using exoskeletons. The knowledge gained will be used as a basis for further research and will help in decision making in terms of the implementation of the devices in the field.

Effects of using back-support exoskeletons

Some studies have shown promising results in terms of reducing the muscular activity in the back when using a BSE in lifting tasks or when performing static trunk forward bent postures. For example, reductions of acute muscle activity ranging between 8–24% when using a BSE in frontal oriented lifting tasks (Abdoli-Eramaki & Stevenson, 2008; Alemi et al., 2020; Baltrusch et al., 2020a; Koopman, et al., 2020a) and 11–61% when using a BSE in static holding tasks (Agnew, 2008; Bosch et al., 2016; Graham et al., 2009; Koopman et al., 2019; Madinei et al., 2020b; Wei et al., 2020) were identified in several studies. However, these findings were not supported by other investigators, as they did not find significant changes (Baltrusch et al., 2019; Ulrey & Fathallah, 2013a) or reported an increase in back muscle activity in some of the various performed task executions (Koopman et al., 2019; Madinei et al., 2020b).

Side-effects of using back-support exoskeletons

Exoskeletons incorporate the mechanism of relieving one body area but possibly redistributing load to other body areas (Toxiri et al., 2019). Consequently, these newly loaded areas might be exposed to increased biomechanical stress and strain. For safe applications of exoskeletons in the work field, it is crucial that any potential health hazards to the musculoskeletal system when using the devices can be excluded. Hints for side-effects can be found in the literature (e.g., Bosch et al., 2016; Kim et al., 2020), and in one evaluation of two distinct BSEs[1], possible side-effects of using the devices in various assembly task executions were intensively focused. Although they did not find

[1] backX™ AC (US Bionics Inc., Berkeley, CA) and Laevo™ V2.5 (Laevo, Delft, The Netherlands)

main effects for the majority of the investigated parameters (e.g., muscle activity, body posture), using either BSE, created side-effects in some task executions (Kim et al., 2020). Nevertheless, there is a lack of evidence and limited consensus on the effect of work-related BSEs on body areas other than the target areas (non-target areas).

Some rigid passive BSEs (including the Laevo®) provide a supportive trunk extension torque with the support of a force pushing perpendicular onto the thighs via leg-pads (Toxiri et al., 2019). Therefore, special attention should be paid to the knee joints as they may be exposed to an increased load. After the back and the upper limbs, the knee joint belongs to the most affected areas by WMSDs. A 33% prevalence of work-related knee disorders in industrial workers in Europe was reported in a systematic review (with meta-analysis) by Govaerts et al. (2021). Similar risk factors as those for back pain were reported, such as awkward postures, lifting, and repetitive movements (da Costa & Vieira, 2010; de Kok et al., 2019). As BSEs are intended to be used during work tasks, it seems crucial to focus intensively on knee joint loading when evaluating BSEs. However, no study investigating BSEs has focused on forces or moments in the knee joint or other non-target areas.

Body posture

As a result of the exoskeleton acting mechanically on the human body—e.g., the exoskeleton's structures pushing against certain body segments—the body posture of the exoskeleton user may change (Ulrey & Fathallah, 2013b). Joint posture may determine joint loading and thus be related to musculoskeletal health. The knee flexion angle in lifting, for example, was related to knee force magnitudes and further influences spine loading (Kingma et al., 2010). For the lumbar spine, prolonged (hyper-) flexion was related to increased spinal forces (Gallahager, 2010; Fatallah, 2004; Ulrey & Fatallah, 2013a), overstretching of spinal ligaments (Ulrey & Fatallah, 2013a), and thus an increased risk for intervertebral disc and ligament injuries (Burgess-Limerick, 2001; Gallahager, 2005; Adams, 1982; Ulrey & Fatallah, 2013a). An excess of spinal flexion might be prevented by using a BSE[2] (Ulrey & Fathallah, 2013a, 2013b). Summarizing the existing literature of effects when using BSEs: lumbar or kyphotic spinal flexions were reported to be substantially reduced (Koopman, et al., 2020b; Sadler et al., 2011),

[2] BNDR (Limbic Systems Inc., Ventura, CA)

slightly reduced (Ulrey & Fathallah, 2013a), not substantially altered (Abdoli-Eramaki et al., 2006; Baltrusch et al., 2020a; Kim et al., 2020; Koopman et al., 2019; Ulrey & Fathallah, 2013a), or increased (Koopman et al., 2020a); trunk flexions were shown to either trend towards or were significantly increased (Bosch et al., 2016) or did not change (Baltrusch et al., 2020a); hip flexions increased (Luger et al., 2021a; Sadler et al., 2011), decreased (Koopman et al., 2019; Simon et al., 2021), or did not change (Ulrey & Fathallah, 2013a); and knee flexions increased (Luger et al., 2021a), decreased (Simon et al., 2021), did not substantially change (Abdoli-Eramaki et al., 2006; Baltrusch et al., 2020a; Ulrey & Fathallah, 2013a), or were overextended (observed but not evaluated) (Bosch et al., 2016). Drawing clear consent or presuming a direction of how wearing a BSE may affect body posture is not possible from these findings. Despite the presumed importance of monitoring body posture in BSE evaluations, the number of investigations including such parameters is still limited.

1.5 Influencing factors—Work tasks and their execution technique

In exoskeletons whose function is based on a pivot joint, the joint's flexion angle determines the assistive torque the device provides to the user (e.g., the Laevo®) (Koopman et al., 2019). Therefore, the exoskeleton's support likely depends on the trunk and lower limb postures. Depending on the workplace, a movement amplitude might be restricted, e.g., no possibility to bend the knees when lifting or lowering an object. In realistic work scenarios, movements are usually not performed in only the sagittal plane (symmetric trunk orientation). Additional trunk rotations may be required to perform a certain task (asymmetric trunk orientation), resulting in different flexion angles between the left and the right side of the exoskeleton structures. Therefore, the effects of using a BSE are designed to be dependent on the body posture in the respective work tasks. However, to date, the influence of varying body postures within a certain task (e.g., lifting style or asymmetric trunk orientation) has been rarely investigated. One workgroup focusing on asymmetric trunk orientation found less pronounced effects of using two distinct BSEs[3] when performing lifting and lowering tasks asymmetrically compared to symmetrical trunk orientation (Alemi et al., 2020; Madinei et al., 2020a). They further reported varying effects when comparing different trunk orientations in assembly tasks

[3] backX™ AC (US Bionics Inc., Berkeley, CA) and Laevo™ V2.5 (Laevo, Delft, The Netherlands)

(Madinei et al., 2020b). The influence of lifting style has been scarcely investigated in the context of exoskeletons, and no clear consensus can be drawn from the findings of those existing investigations (Abdoli-Eramaki et al., 2006; Alemi et al., 2019; Frost et al., 2009).

In summary, the evidence for the advantages or disadvantages of using occupational BSEs is both limited and conflicting. Their effectiveness concerning workers' health has not yet been demonstrated, e.g., the prevention of (lower) back WMSDs (Howard et al., 2020; Steinhilber et al., 2020; Theurel & Desbrosses, 2019). Furthermore, possible side-effects that may negatively affect the human body cannot be excluded from existing literature. Despite the lack of evidence, manufacturers promote their various beneficial effects, such as significant stress and strain reductions[4], fatigue, and/or injury prevention[5], and reductions of sick absence and work turnover[6] (Auxivo; Bionics; ExoAtlant; Laevo; Ottobock).

[4] Laevo exoskeletons (Laevo, Delft, The Netherlands), CrayX (German Bionic, Augsburg, Germany), ExoAtlant (ExoAtlet, Luxembourg), LiftSuit (Auxivo AG, Schwerzenbach, Switherland), Ottobock back exoskeletons (Ottobock, Duderstadt, Germany)
[5] Laevo exoskeletons, CrayX, ExoAtlant, LiftSuit, Ottobock back exoskeletons
[6] CrayX, Ottobock back exoskeleton

1.6 Aims of the thesis

Indeed, before implementing exoskeletons in the field, their scientific evaluation is crucial to ensure an advantageous as well as a safe application. More specifically, it needs to be determined whether the exoskeleton has the potential to relieve the musculoskeletal structures in the target area in the absence of side-effects (which may increase stress and strain in other body areas). Therefore, the main research question of this doctoral thesis is:

- *What are the effects of using a back-support exoskeleton in industrial tasks on physical stress or strain?*

Further sub-questions of this doctoral thesis include:

- *Does using a back-support exoskeleton relieve strain on the musculoskeletal system of the back?*
- *What are the side-effects in non-target areas when using a back-support exoskeleton?*

To answer these questions, the following research objectives will be addressed:

1. To determine what is currently known about the influence of using occupational exoskeletons during work tasks on acute physical stress and strain. *(Chapter 2).*
2. To determine the influence of using a passive back-support exoskeleton (the Laevo® V2.56) on muscle activity, posture, and heart rate during simulated industrial tasks, including distinct lower limb postures and symmetric and asymmetric trunk orientations. *(Chapters 3 & 4)*
3. To determine the effects of using a passive back-support exoskeleton (the Laevo® V2.56) on tibiofemoral joint loading during simulated industrial tasks, including distinct lower limb postures and symmetric and asymmetric trunk orientations. *(Chapter 5)*

1.7 Outline of the thesis

In *Chapter 2*, a systematic review with meta-analyses is presented. The review focuses on the influence of using occupational exoskeletons on several physical stress and strain parameters. Biomechanical, physiological, and subjectively perceived parameters regarding the exoskeleton's target area, but also the non-target areas, are evaluated. Here, exoskeletons that were developed and investigated for an occupational setting are included. However, in this dissertation, the focus is primarily on passive devices trunk orientation trunk orientation—which aim to support the lower back.

In *Chapters 3–5*, various results of a physiological and biomechanical evaluation of the back-support exoskeleton Laevo® V2.56 are presented. Therefore, a laboratory study investigating the device in simulated occupational tasks was conducted. *Chapters 3 and 4* present the effects of using the exoskeleton on muscle activity of the back but also of other possibly influenced body areas (e.g., legs, abdomen, shoulder/neck). Further, they include monitoring of spine and lower limb postures and heart rate, which may be influenced by wearing and using the device. Specifically, in *Chapter 3*, the results of a manual assembly task (sorting screws and pins), holding a forward bent trunk posture statically (with and without additional trunk rotation) are described. In *Chapter 4*, a dynamic task of repetitive lifting and lowering a load is presented. The task was performed with two different knee postures (stoop and squat), each one with and without an additional trunk rotation. Due to the load-transferring mechanism of the Laevo® exoskeleton inducing a load perpendicular to the front part of the thighs, it was assumed that using the device may affect the knee joint loading. In *Chapter 5*, therefore, the focus lies on the influence of using the exoskeleton on forces acting on the tibiofemoral joint in vertical and horizontal (anteroposterior) directions. These parameters were investigated during the same experimental work tasks described in Chapters 3 and 4.

In *Chapter 6*, the findings presented in Chapters 3–5 are summarized and discussed concerning the questions of this thesis and in a broader context of the current state of exoskeleton research and application. To this concern, remaining questions are highlighted. Finally, recommendations for future research as well as for the practical implementation of exoskeletons are presented.

Chapter 2

The influence of using exoskeletons during occupational tasks on acute physical stress and strain compared to no exoskeleton - A systematic review and meta-analysis.

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Review article

The influence of using exoskeletons during occupational tasks on acute physical stress and strain compared to no exoskeleton – A systematic review and meta-analysis

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ABSTRACT

Objectives: This systematic review and meta-analysis determined the effects of using an exoskeleton during occupational tasks on physical stress and strain compared to not using an exoskeleton.
Methods: Systematic electronic database searches were performed and the review was prepared according to the PRISMA guidelines. Treatment effects on the predefined outcomes were calculated using standardized mean differences for continuous outcomes in several meta-analyses using Review Manager 5.3. Registration: PROSPERO (CRD42020168701).
Results: 63 articles were included in qualitative syntheses and 52 in quantitative, but most of them did not extensively evaluate musculoskeletal stress and strain and the risk of bias was rated high for all included studies. Statistically significant effects of using back, upper-limb, or lower-limb exoskeletons have been observed in the supported body areas (e.g. reduced muscle activity, joint moments and perceived strain). Studies which did not exclusively focus on the supported body area also showed statistically significant effects in the non-supported areas (e.g. changed muscle activity and perceived strain) and in physiological outcomes (e.g. reduced energy expenditure).
Conclusions: Using an exoskeleton during occupational tasks seems to reduce user's acute physical stress and strain in the exoskeleton's target area. However, impact on workers' health is still unknown, primarily because of missing long-term evaluations under real working conditions. Furthermore, this systematic review highlights a lack of studies (1) following high quality methodological criteria, (2) evaluating various inter-related stress and strain parameters instead of only focusing on one specific, and (3) evaluating non-target body areas instead of only the directly supported body area.

1. Introduction

Work-related musculoskeletal disorders (WMSD) have a high impact on workers' wellbeing, health care systems and economy. Around 60% of all self-reported work-related health problems in the European Union correspond to the musculoskeletal system (DeKok et al., 2019). The consequences of these health problems are often limitations in daily life for the person concerned as well as constraints in working activities (Eurostat, 2010) leading to a remarkable amount of sick leave days from work (Burton and Kendall, 2014; da Costa and Vieira, 2010; Eurostat, 2010). Specific working conditions are known to contribute to an elevated risk of WMSD; heavy physical work, lifting tasks, repetitive movements, awkward static and dynamic working postures are some of the most prevalent reported risk factors (da Costa and Vieira, 2010; Eurofound, 2012; Eurostat, 2010).

Strategies to avoid physically demanding exposure at work have been implemented, such as the modification of workplaces and automation of work processes; however, this is not always feasible because of economic reasons or workplace characteristics that require the full competences of a human (de Looze et al., 2016). Recently, there has been a growing interest in exoskeletons for supporting movements and postures in an occupational context and thereby reducing the physical workload (de Looze et al., 2016; Toxiri et al., 2019). By using an exoskeleton, human power can be increased due to the support of the

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addressed musculoskeletal structures (de Looze et al., 2016), whereas physical and cognitive human competences remain almost unaffected. Exoskeletons can be classified according to their functionality, either as passive or active depending on the energy sources used. Passive exoskeletons use load-bearing elements (e.g., springs) that are able to store and release energy that is gained by the user's movements. Active exoskeletons use additional external actuators, such as electric motors or pneumatic muscles (Gopura and Kiguchi, 2009) to provide extra energy (de Looze et al., 2016; Toxiri, 2018). According to the respective work tasks given, different exoskeletons have been developed to support the upper limbs for working with elevated arms, the lower limbs for prolonged standing work, or the back for lifting or prolonged forward bending. Full-body-exoskeletons assist several of the mentioned areas and some exoskeletons only support single joints like the elbow, wrist, knee or ankle.

Several exoskeletons have been evaluated in a (simulated) occupational context to identify their potential impact on parameters associated with WMSD (Steinhilber et al., 2020b) which refer to physical stress (e.g. joint load) or physical strain (e.g. muscle activity, perceived discomfort or fatigue.), (de Looze et al., 2016; McFarland and Fischer, 2019; Theurel and Desbrosses, 2019; Toxiri, 2018). Stress is the quantitative amount of a stressor (work-related exposure) and strain the individual's response to this stressor (Rohmert, 1986).

Although work-related physical stress and strain reflect different concepts, epidemiological studies consistently demonstrate that both physical strain parameters like elevated muscle activity (Hanvold et al., 2013; Luttmann et al., 2010; Westgaard, 1999) and peak and cumulative discomfort at work (Reenen et al., 2008), together with physical stress parameters like high peak (Norman et al., 1998) and cumulative (Coenen et al., 2013, 2014) mechanical loadings at the lumbar spine estimated by shear forces and joint moments are associated with WMSD.

The potential of reducing the level of muscle activity in the supported body region by using an exoskeleton was shown by three reviews on back-supporting and upper-limb supporting exoskeletons (de Looze et al., 2016; McFarland and Fischer, 2019; Theurel and Desbrosses, 2019). Joint moments, shear and compression forces at lower spine level may also be reduced when using back-supporting exoskeletons (de Looze et al., 2016; Theurel and Desbrosses, 2019). Subject-reported feelings of both general and local physical strain, on the other hand, showed mixed results with studies reporting an increase (Hensel and Keil, 2019; Luger et al., 2019a), a decrease (Madinei et al., 2020; Smets, 2019) or no change when using an exoskeleton (Rashedi et al., 2014). However, the relevance of such changes in muscle activity, biomechanical load and perceived discomfort or fatigue is not determined yet (Steinhilber et al., 2020b) and may depend on the exoskeleton's support characteristics (Alemi et al., 2020), the evaluated occupational task (Alemi et al., 2020), and also on the exact task execution (Steinhilber et al., 2020a). Moreover, the influence of using an exoskeleton on the musculoskeletal system in other body regions than the target region remains largely unclear. Although several studies show altered joint moments and forces at lumbosacral level when using upper-limb exoskeletons (McFarland and Fischer, 2019) or changed muscle activity in the leg musculature when using back exoskeletons (de Looze et al., 2016), these findings are inconsistent and incomplete since only a few studies so far have addressed the aspect of evaluating others than the target areas. Taken together, the previous reviews provide a good overview on this topic of growing interest. However, they did only include some selected types of exoskeletons (McFarland and Fischer, 2019; Theurel and Desbrosses, 2019), provide an overview without including a systematic literature search (Theurel and Desbrosses, 2019), are not up to date anymore since they have been published in 2016 (de Looze et al., 2016) or in 2019, so they did not consider many studies evaluating exoskeletons that have been published within the last two years (McFarland and Fischer, 2019; Theurel and Desbrosses, 2019), and did not include quantitative analysis for evaluating the effects of exoskeletons (de Looze et al., 2016; McFarland and Fischer, 2019; Theurel and Desbrosses, 2019).

Therefore, an overview of all studies that evaluated occupational exoskeletons including meta-analyses will provide a valuable overview of the current state of knowledge for scientists, occupational physicians and ergonomists. Furthermore, such an overview may help practitioners to judge whether an exoskeleton may be a suitable intervention to counteract work-related physical loads or to support workers with reduced physical capacity in terms of occupational reintegration. This systematic review with meta-analysis aims to determine the effects of using an exoskeleton on physical stress and strain of the user in occupationally relevant tasks compared to not using an exoskeleton. Several parameters related to physical stress and strain will be evaluated.

2. Methods

This systematic review was prepared following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (PRISMA; Moher et al., 2009). The protocol of the current review is registered at the international prospective register of systematic reviews (PROSPERO) of the National Institute for Health Research (registration number: CRD42020168701) (Bär et al., 2020).

2.1. Eligibility criteria

English, Dutch or German papers were included when they reported results of an experimental study, evaluated an exoskeleton in an occupational context in the field or in the laboratory. Publications in scientific journals, conference papers or dissertations were admitted. No restrictions on the type of study design were set; however, they had to include a control condition evaluating identical tasks but without using the exoskeleton. We included studies that assessed adults (aged 18 years or above) who could be either workers or non-workers (e.g., novices). The review was limited to studies on occupational purpose; those evaluating exoskeletons for military or rehabilitative use were excluded. However, we did not exclude those studies which did not specify the exoskeletons purpose when an occupational use of the device could be possible. We set no restrictions to the type of exoskeleton evaluated. We included studies that reported at least one of the following outcomes:

1. Biomechanical stress or strain, including muscle activity, joint moments, compression forces and shear forces.
2. Physiological strain, including heart rate parameters (i.e., heart rate, cardiac cost), energy expenditure (i.e., energy expenditure, metabolic cost, oxygen consumption), and blood pressure.
3. Participant-reported strain, including perceived musculoskeletal discomfort, fatigue, exertion, effort, pressure and pain.

For the data collection and meta-analysis, only results presented as means, medians or integrals were consulted; such that peak values were excluded.

2.2. Search strategy

This literature review is based on the results of a systematic electronic literature search of nine different databases (cf. Fig. 1). Additionally, reference lists of included studies as well as the researchers' personal databases were screened for further relevant studies. The primary search strategy was created for MEDLINE (PubMed), designed according to the PICO-scheme including MeSH-terms (Appendix 1) and adjusted for all other databases (Appendix 2). The detailed search strings can be found in Appendix 1 and 2. The searches were conducted on 17 March 2020; with the exception of EMBASE (OVID) on 25 January 2019.

[a Automatic exclusion from the pooled analyses by Review Manager; b Studies and/or contacted authors did not provide sufficient data for the pooled analyses; Databases screened: Cochrane Central Register of Controlled Trials (CENTRAL; Wiley Online Library), MEDLINE

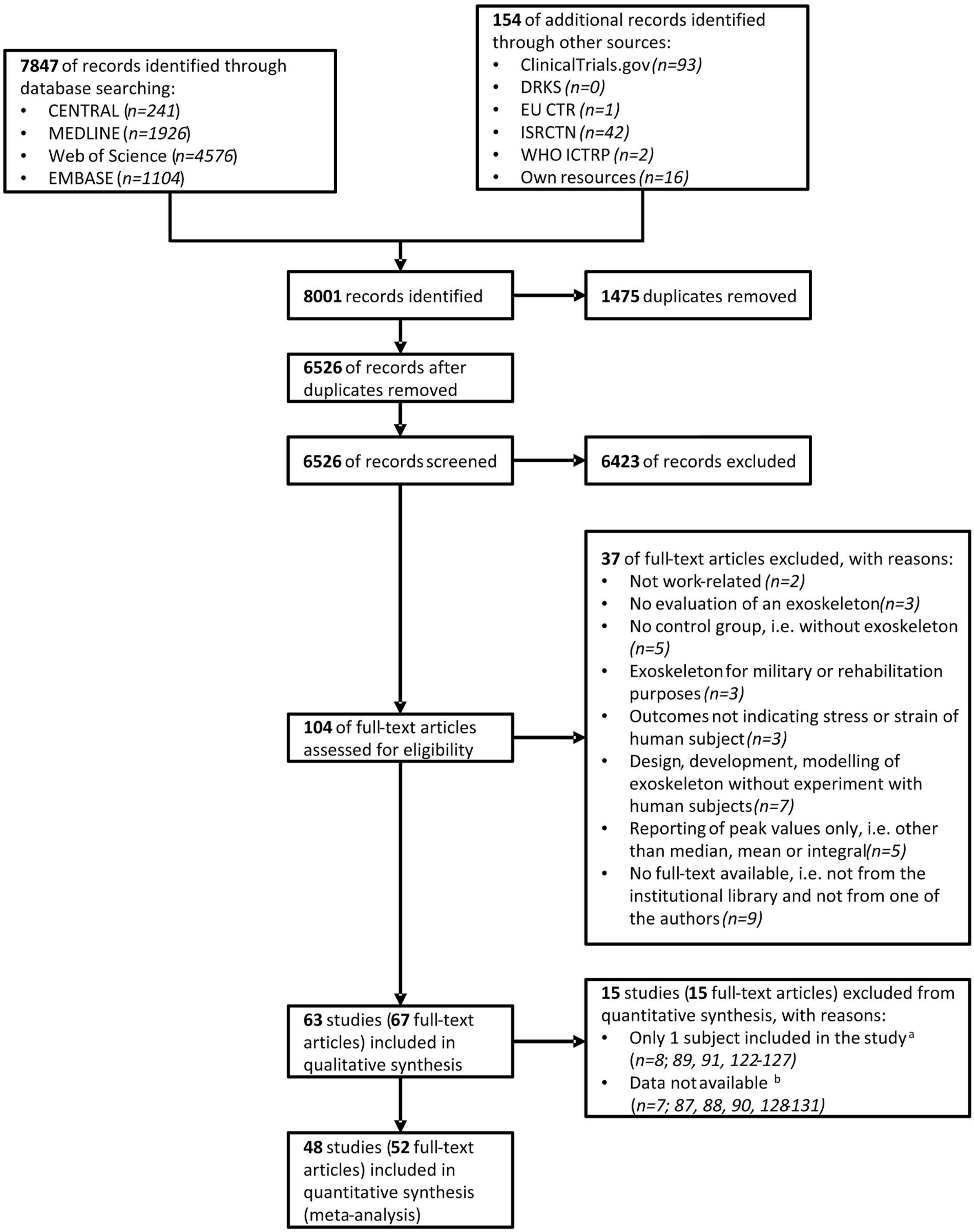

Fig. 1. Study flow diagram.

(PubMed) EMBASE (OVID), Web of Science (Thomson Reuters), U.S. National Library of Medicine (ClinicalTrials.gov), German Clinical Trials Register (DRKS; DRKS.de), EU Clinical Trials Register (EU CTR; ClinicalTrialsRegister.eu), ISRCTN Registry (ISRCTN.com), World Health Organization International Clinical Trials Registry Platform (WHO ICTRP; WHO.int/ICTRP/en)]

2.3. *Study selection*

All records identified by the literature search were proofed for duplicates with Rayyan QCRI (Ouzzani et al., 2016) and additionally checked by one reviewer (AWMF, 2012). First, two reviewers (MB, TL) independently screened the titles and abstracts of all selected studies. They then independently assessed the full texts of the remaining studies for eligibility. Disagreement or obscurity was resolved by discussion or, when necessary, by consulting a third review author (BS).

2.4. Data extraction

Two review authors (MB, TL) extracted the main characteristics from the included studies (author and year, methods, participants, interventions, outcomes, notes; cf. Appendix 4).

2.5. Risk of bias assessment

Two reviewers (MB, TL) independently assessed the risk of bias in each study using the quality assessment tool for controlled intervention studies as developed by the Risk Assessment Work Group of the United States' National Institutes of Health (Goff and Lloyd-Jones, 2013) and as used in a previous occupational-related review (Padula et al., 2017). Disagreement was resolved by discussion or, if necessary, by consulting a third reviewer (BS).

The quality assessment tool consists of 14 items, to which we responded with yes (score of 1), no (score of 0) or other (CD, cannot determine; NA, not applicable; NR, not reported; equal to a score of 0). Six items received a higher weighting of two instead of one, because we considered them more relevant in the risk of bias assessment than the other eight items. Based on the allocation by Padula et al. (2017) and modified using the criteria outlined in the Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2019b), the 14 items were allocated into seven superior clusters. (Cf. Appendix 6).

The susceptibility to bias of each cluster was rated based on the sum of the assigned items to be high (<50% score), moderate or unclear (50–99% score) or low (100% score). A good study quality indicates low risk of bias, a fair quality indicates moderate or susceptible risk of bias, and a poor quality indicates significant or high risk of bias (Goff and Lloyd-Jones, 2013).

2.6. Meta-analysis

The outcome data of the included studies was extracted by two review authors (MB, TL) and transferred into Review Manager 5.3 software (Review Manager, 2014) for calculating the treatment effects. We used standardized mean differences (SMD) for continuous outcomes, for which a higher SMD can be interpreted as a larger effect (Higgins et al., 2019b), without being able to interpret the exact SMD-value to indicate a small, moderate or large effect (e.g. Cohen 1988 (Cohen, 1988)). In case of missing data or data not reported in a usable manner, the study authors were contacted for data sharing. If numerical outcome data such as standard deviations or correlation coefficients were missing and could not be obtained from the study authors, we calculated them from other available statistics, such as p-values, according to the methods as described in Section 6.5.2.3 of the Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2019a) or we measured them from available figures. If the provided data was insufficient and study authors did not respond, we excluded the study from the meta-analysis.

We grouped the results of the included studies based on similarity of the intervention (type of support) and outcome. We classified the evaluated exoskeletons into the following five supporting body areas: (1) back, (2) lower limb, (3) upper limb, (4) ankle or (5) wrist. The study results of any measurement method related to each of the included outcomes muscle activity, joint compression force, joint shear force, joint moments, heart rate, blood pressure or metabolic costs within these outcome-groups were considered as similar. The study results of any measurement method that was used to report participant-reported outcomes (e.g., numeric rating scale, visual analogue scale) were considered as similar.

We pooled the data from the studies per outcome in forest plots. The results of each study were plotted as point estimates with corresponding 95% confidence intervals. We used a random-effects model to pool the results of the studies (Borenstein et al., 2009) for all outcome analyses. Heterogeneity of the results was assessed using the I^2 statistic, as provided by Review Manager 5.3 (Review Manager, 2014) and provided descriptively. I^2 values greater than 75% can be interpreted as a substantial heterogeneity (Section 10.10.2; Deeks et al., 2019). Independent meta-analyses were performed for each type of exoskeleton as previously defined. If more than one exoskeleton was tested within a study against a control condition, the exoskeletons were observed independently, meaning that the identical data of the control measurement was used for calculating the effects of the different exoskeletons. Furthermore, the outcomes were assigned to a joint function (for muscle activity) or to a body region (for both the participant-reported as well as biomechanical outcomes), which means that there can be more than one meta-analysis for the same outcome when more than one body region or joint function has been included in one or more studies. If more than one reported study outcome belonged to a single body region or joint, and also if several tasks and task conditions were conducted within one study, we combined the reported means and standard deviations as described in Section 6.5.2.10 of the Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2019a). If several time points were measured, we calculated the means and pooled standard deviations of all time points for both conditions (with and without exoskeleton) to include studies with endurance protocols as well. For the outcome muscle activity, we grouped various muscles based on their main function, taking into account the exoskeleton used and the performed work task as listed in Table 1. For the physiological outcomes, we defined the categories heart rate (including cardiac cost), energy expenditure (including oxygen consumption and metabolic cost) and blood pressure. For the biomechanical outcomes, including shear and compression forces and joint moments we defined the following joints/body areas: shoulder, arm, back (lumbosacral level) and hip. For the participant-reported outcomes we defined the following body areas: general, hands & wrists, neck & shoulders & arms, back, chest, hips & upper legs, knees & lower legs & feet.

3. Results

3.1. Study selection

Fig. 1 presents the study selection process in a flow diagram. Out of originally 8001 identified articles, 67 records from 63 studies remained in the qualitative analysis; of which 52 references from 48 studies were considered for the quantitative meta-analysis (reasons for exclusion are listed in Fig. 1).

3.2. Data extraction

Proportions of the characteristics of the 63 included studies of study setting (e.g. laboratory or field, continent of execution), time area of publication, number and sex of included subjects, type of exoskeleton, tasks, duration of experimental conditions and outcomes are presented in Appendix 3. The study characteristics of the qualitative analysis of each study are provided in Appendix 4. The study outcomes described as absolute value and percentage change for the experimental conditions compared to the control condition (i.e., without exoskeleton) are separately calculated and provided in Appendix 5. All outcomes have to be considered as acute effects of using an exoskeleton since the designs of the included studies used protocols of short duration (no longer than 3 days).

3.3. Risk of bias assessment

The risk of bias assessment according to the seven categories is presented as percentage of all 63 included studies in Fig. 2. All studies showed a high risk of bias, because at least one out of the seven risk of bias categories was judged as high. The ratings of the 14 single items

Table 1
Muscles included for each muscle group based on the main anatomical muscle function.

Muscle group	Main functions	Included muscles
Shoulder elevation	Arm abduction, arm elevation, arm anteversion, shoulder elevation	•M. deltoideus acromialis/medialis •M. deltoideus scapularis/posterior •M. deltoideus clavicularis/anterior •M. trapezius descendens/upper •M. serratus anterior •M. biceps brachii
Shoulder depression	Arm adduction, shoulder depression, arm retroversion	•M. trapezius ascendens/lower •M. teres major •M. triceps brachii •M. latissimus dorsi
Shoulder rotation	Internal rotation, external rotation	•M. teres major •M. infraspinatus •M. deltoideus scapularis/posterior •M. deltoideus clavicularis/anterior
Elbow extension	Extension	•M. triceps brachii
Elbow flexion	Flexion, pronation	•M. biceps brachii
Trunk extension	Extension	•M. erector spinae spinalis •M. erector spinae longissimus •M. erector spinae iliocostalis •M. multifidus
Trunk flexion	Flexion	•M. rectus abdominis •M. obliquus externus •M. obliquus internus
Hip extension	Extension	•M. gluteus maximus •M. semitendinosus •M. biceps femoris
Hip flexion	Flexion	•M. rectus femoris
Knee extension	Extension	•M. rectus femoris •M. vastus lateralis •M. vastus medialis
Knee flexion	Flexion	•M. biceps femoris •M. semitendinosus •M. gastrocnemius
Ankle plantarflexion	Plantarflexion	•M. gastrocnemius •M. soleus
Ankle dorsiflexion	Dorsiflexion	•M. tibialis anterior
Wrist extension	Extension, ulnar extension	•M. extensor carpi ulnaris
Wrist flexion	Flexion	•M. flexor digitorum superficialis

included in this assessment are tabulated in Appendix 6.

3.4. Meta-analysis

In the following, SMD along with their 95% confidence interval (CI) in the experimental condition (i.e., using an exoskeleton) compared to the control condition (i.e., not using an exoskeleton) are reported.

3.4.1. Intervention: back-supporting exoskeletons

3.4.1.1. Outcome: biomechanical stress or strain. The activity of the musculature responsible for trunk extension showed a statistically significant reduction (SMD 0.58; 95% CI 0.28 to 0.88; $I^2 = 54\%$; 16 studies, 198 subjects) when using a back-supporting exoskeleton. Furthermore, muscle activity of hip extension muscles (SMD 0.53; 95% CI 0.19 to 0.86; $I^2 = 0\%$; 5 studies, 73 subjects), and muscles that act as knee flexors (SMD 0.54; 95% CI 0.21 to 0.88; $I^2 = 0\%$; 5 studies, 73 subjects) were statistically significantly reduced when using a back-supporting exoskeleton. There were no statistically significant changes in the musculature responsible for trunk flexion (SMD −0.05; 95% CI −0.27 to 0.17; $I^2 = 0\%$; 11 studies, 140 subjects), shoulder depression (SMD 0.59; 95% CI −0.20 to 1.39; $I^2 = 67\%$; 3 studies, 41 subjects), knee extension (SMD −0.19; 95% CI −0.64 to 0.26; $I^2 = 0\%$; 3 studies, 39 subjects), and ankle dorsiflexion (SMD −0.08; 95% CI −0.73 to 0.57; I^2 = n/a.; 1 study, 18 subjects) when using a back-supporting exoskeleton. (Cf. Fig. 3)

Both shear forces in the sagittal plane at the lumbosacral spine level (SMD 0.30; 95% CI −0.63 to 1.23; I^2 = n/a.; 1 study, 9 subjects) and compression forces at the lumbosacral spine level (SMD 0.29; 95% CI −0.64 to 1.22; $I^2 = 95\%$; 1 study, 9 subjects) showed no statistically significant differences when using a back-supporting exoskeleton. In contrast, moments at the lumbosacral spine level showed a statistically significant reduction (SMD 0.78; 95% CI0.15 to 1.41; $I^2 = 32\%$; 3 studies, 33 subjects) when using a back-supporting exoskeleton. (Cf. Appendix 7).

3.4.1.2. Outcome: physiological strain. Neither the outcomes heart rate (SMD 0.01; 95% CI −0.61 to 0.64; $I^2 = 54\%$; 5 studies, 48 subjects), energy expenditure (SMD 0.24; 95% CI −0.12 to 0.61; $I^2 = 0$; 3 study, 41 subjects), nor blood pressure (SMD 0.41; 95% CI −0.53 to 1.35; I^2 = n/a; 1 study, 9 subjects) showed statistically significant differences when using a back-supporting exoskeleton. (Cf. Appendix 7).

3.4.1.3. Outcome: participant-reported strain. General perceived musculoskeletal strain (SMD 0.92; 95% CI 0.32 to 1.52; $I^2 = 72\%$; 6 studies, 77 subjects) and perceived musculoskeletal strain in the target area of the back (SMD 0.73; 95% CI 0.38 to 1.09; $I^2 = 0\%$; 3 studies, 48 subjects) both showed a statistically significant reduction when using a back-supporting exoskeleton.

Perceived musculoskeletal strain in the non-target areas hips & upper legs (SMD 0.15; 95% CI −0.19 to 0.50; $I^2 = 0\%$; 3 studies, 48 subjects) and neck & shoulders & arms (SMD 0.21; 95% CI −0.25 to 0.68; I^2 = n/a; 1 study, 18 subjects) showed no statistically significant changes, whereas perceived musculoskeletal strain at the chest showed a statistically significant increase (SMD −0.86; 95% CI −0.55 to −0.18; I^2 = n/a; 1 study, 18 subjects) when using a back-supporting exoskeleton. (Cf. Fig. 4)

3.4.2. Intervention: lower–limb-supporting exoskeletons

3.4.2.1. Outcome: biomechanical stress or strain. No statistically significant changes were observed for the knee flexor (SMD 0.75; 95% CI −0.02 to 1.51; $I^2 = 67\%$; 3 studies, 65 subjects), the knee extensor (SMD 0.52; 95% CI −1.10 to 2.13; $I^2 = 92\%$; 3 studies, 65 subjects), and hip extensor musculature (SMD 0.20; 95% CI −0.51 to 0.92; I^2 = n/a; 1 study, 15 subjects) when using a lower-limb-supporting exoskeleton. The activity of the musculature responsible for ankle dorsiflexion showed a statistically significant reduction (SMD 1.22; 95% CI 0.43 to 2.01; I^2 = n/a; 1 study, 15 subjects), whereas the musculature responsible for ankle plantarflexion (SMD 0.72; 95% CI −0.08 to 1.52; I^2 = 70%; 3 studies, 65 subjects), trunk extension (SMD 0.08; 95% CI −0.28 to 0.43; $I^2 = 0\%$; 2 studies, 60 subjects) and shoulder elevation (SMD −0.11; 95% CI −0.53 to 0.30; I^2 = n/a; 1 study, 45 subjects) showed no statistically significant changes when using a lower-limb-supporting exoskeleton. (Cf. Appendix 8).

3.4.2.2. Outcome: physiological strain. Both heart rate (SMD −0.08; 95% CI −0.55 to 0.39; I^2 = n/a; 1 study, 35 subjects) and energy expenditure (SMD −0.19; 95% CI −0.58 to 0.20; $I^2 = 0\%$; 3 studies, 51 subjects) did not show statistically significant changes when using a lower-limb-supporting exoskeleton. (Cf. Appendix 8).

3.4.2.3. Outcome: participant-reported strain. The general perceived strain showed a statistically significant increase (SMD −0.36; 95% CI

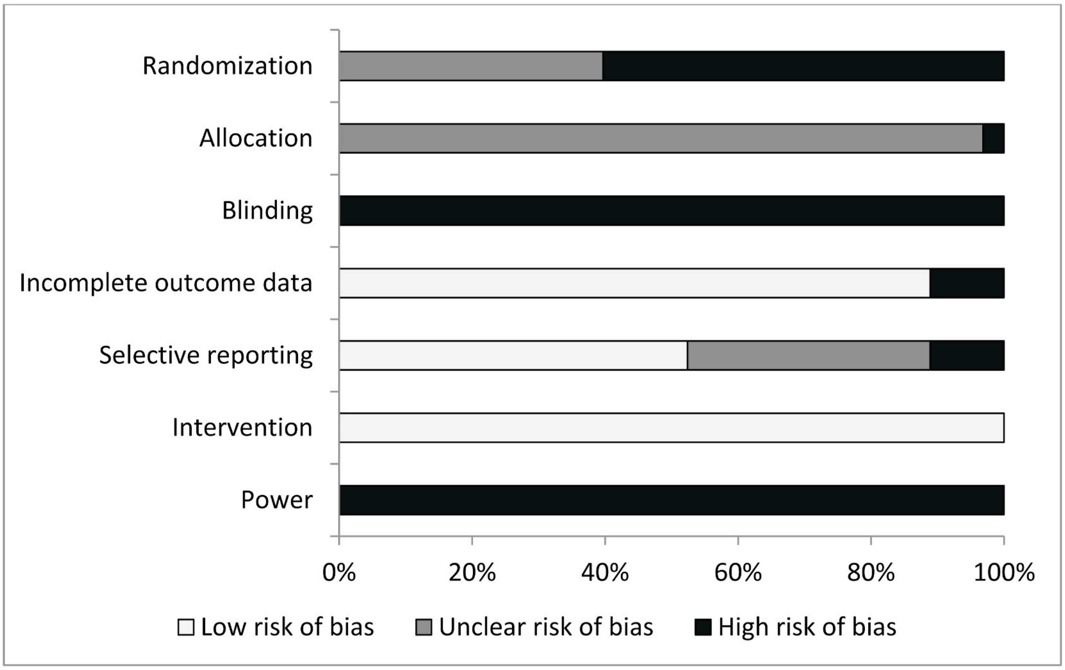

Fig. 2. Risk of bias graph: review authors' judgements (based on (Goff and Lloyd-Jones, 2013; Padula et al., 2017)) about each risk of bias item presented as percentages of all 63 included studies.

−0.70 to −0.02; $I^2 = 13\%$; 2 studies, 80 subjects) when using a lower-limb-supporting exoskeleton. Perceived strain in the target areas hips & upper legs (SMD 0.34; 95% CI −0.34 to 1.02; I^2 = n/a; 1 study, 17 subjects) and knees & lower legs & feet (SMD −0.09; 95% CI −0.76 to −0.58; I^2 = n/a; 1 study, 17 subjects) showed no statistically significant changes when using a lower-limb-supporting exoskeleton. Perceived strain in the non-target area neck & shoulders & arms (SMD −0.04; 95% CI −0.71 to 0.63; I^2 = n/a; 1 study, 17 subjects) showed no statistically significant changes when using a lower-limb-supporting exoskeleton, whereas there was a statistically significant reduction in the back (SMD 0.81; 95% CI 0.10 to 1.51; I^2 = n/a; 1 study, 17 subjects). (Cf. Appendix 8).

3.4.3. *Intervention: upper-limb-supporting exoskeletons*

3.4.3.1. Outcome: biomechanical stress or strain. The activity of the muscles responsible for shoulder elevation (SMD 0.41; 95% CI 0.15 to 0.67; $I^2 = 33\%$; 13 studies, 144 subjects) and shoulder rotation (SMD 0.48; 95% CI 0.19 to 0.77; $I^2 = 41\%$; 12 studies, 136 subjects) showed a statistically significant reduction when using an upper–limb-supporting exoskeleton. No statistically significant changes have been detected for the muscles responsible for shoulder depression (SMD 0.14; 95% CI −0.12 to 0.41; $I^2 = 0\%$; 8 studies, 94 subjects) when using an upper-limb-supporting exoskeleton. The activity of the muscles responsible for trunk extension showed a statistically significant increase when using an upper-limb-supporting exoskeleton (SMD −0.43; 95% CI −0.72 to −0.14; $I^2 = 22\%$; 9 studies, 88 subjects). None of the other observed muscle groups showed statistically significant changes of activation when using an upper-limb-supporting exoskeleton: trunk flexors (SMD 0.08; 95% CI −0.29 to 0.45; $I^2 = 0\%$; 3 studies, 32 subjects); hip flexors (SMD 0.09; 95% CI −0.90 to 1.07; I^2 = n/a; 1 study, 8 subjects); hip extensors (SMD 0.14; 95% CI −0.84 to 1.13; I^2 = n/a; 1 study, 8 subjects); knee flexors (SMD −0.03; 95% CI −1.01 to 0.95; I^2 = n/a; 1 study, 8 subjects); knee extensors (SMD 0.09; 95% CI −0.90 to 1.07; I^2 = n/a; 1 study, 8 subjects); elbow flexors (SMD 0.37; 95% CI −0.03 to 0.78; $I^2 = 0\%$; 5 studies, 48 subjects); elbow extensors (SMD −0.15; 95% CI −0.52 to 0.22; $I^2 = 0\%$; 4 studies, 42 subjects); ankle dorsi-flexors (SMD −0.26; 95% CI −0.96 to 0.43; $I^2 = 0\%$; 2 studies, 16 subjects); ankle plantar-flexors (SMD 0.00; 95% CI −0.98 to 0.98; I^2 = n/a; 1 study, 8 subjects); and wrist flexors (SMD 0.32; 95% CI −0.42 to 1.07; I^2 = n/a; 1 study, 14 subjects). (Cf. Fig. 5; Appendix 9)

None of the outcomes indicating forces at the lumbosacral level in the lower back showed statistically significant changes when using an upper-limb-supporting exoskeleton, shear force in the mediolateral direction (SMD 0.21; 95% CI −0.60 to 1.01; I^2 = n/a; 1 study, 12 subjects), shear force in anterior-posterior direction (SMD −0.49; 95% CI −1.90 to 0.93; $I^2 = 82\%$; 2 studies, 24 subjects), and compression force (SMD −0.79; 95% CI −1.84 to 0.26; $I^2 = 67\%$; 2 studies, 24 subjects). No statistically significant changes have been detected for arm torque (SMD −0.50; 95% CI −1.50 to 0.50; I^2 = n/a; 1 study, 8 subjects) but shoulder torque showed a statistically significant reduction (SMD 1.56; 95% CI 0.62 to 2.49; I^2 = n/a; 1 study, 12 subjects) when using an upper-limb-supporting exoskeleton. (Cf. Appendix 9).

3.4.3.2. Outcome: physiological strain. Heart rate showed no statistically significant decrease (SMD 0.33; 95% CI −0.05 to 0.70; $I^2 = 0\%$; 6 studies, 57 subjects) whereas energy expenditure showed a statistically significant decrease (SMD 0.85; 95% CI 0.26 to 1.45; $I^2 = 0\%$; 2 studies, 24 subjects) when using an upper-limb supporting exoskeleton. (Cf. Appendix 9).

3.4.3.3. Outcome: participant-reported strain. General perceived strain (SMD 0.81; 95% CI 0.16 to 1.46; $I^2 = 0\%$; 2 studies, 20 subjects) as well as perceived strain in the target area neck & shoulders & upper arms (SMD 0.38; 95% CI 0.12 to 0.63; $I^2 = 0\%$; 8 studies, 85 subjects) showed a statistically significant decrease when using an upper-limb-supporting exoskeleton.

Perceived strain in none of the non-target areas showed statistically significant changes when using an upper-limb supporting exoskeleton: back (SMD 0.07; 95% CI −0.19 to 0.34; $I^2 = 0\%$; 8 studies and 85 subjects); hips & upper legs (SMD −0.10; 95% CI −0.38 to 0.18; $I^2 = 0\%$; 6 studies and 59 subjects); knees & lower legs & feet (SMD −0.19; 95% CI −0.58 to 0.21; $I^2 = 23\%$; 3 studies, 27 subjects); hands & wrists (SMD 0.19; 95% CI −0.15 to 0.54; $I^2 = 0\%$; 3 studies, 27 subjects). (Cf. Fig. 6)

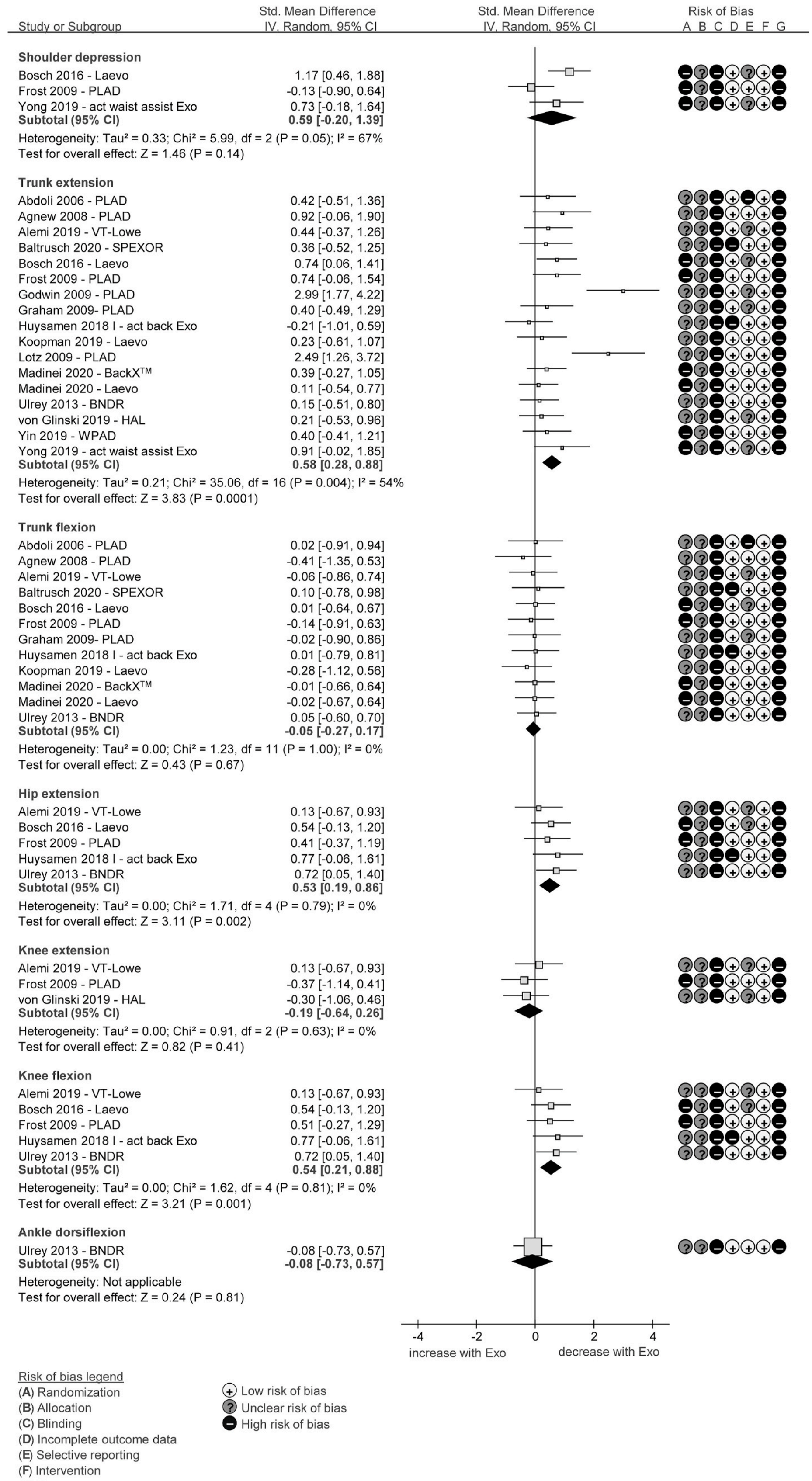

Fig. 3. Study findings (i.e. SMD and risk of bias) for studies evaluating the effects of using a back supporting exoskeleton on muscle activity (muscles were grouped according to joint movements). [IV = inverse variance; CI = confidence interval; Exo = exoskeleton].

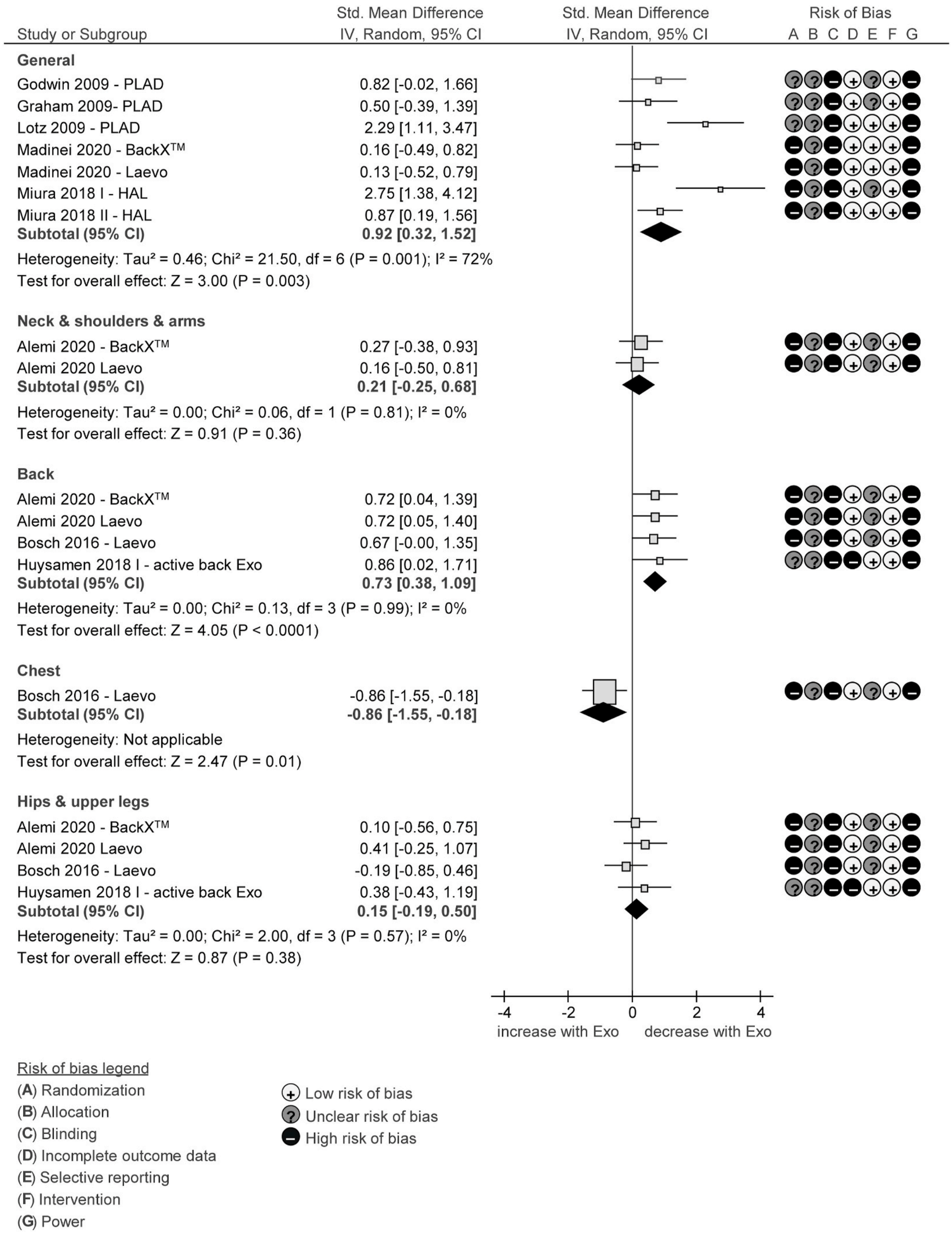

Fig. 4. Study findings (i.e. SMD and risk of bias) for studies evaluating the effects of using a back supporting exoskeleton on perceived strain. [IV = inverse variance; CI = confidence interval; Exo = exoskeleton].

3.4.4. *Intervention: ankle-supporting exoskeletons*

3.4.4.1. Outcome: physiological strain. The outcomes heart rate (SMD −0.66; 95% CI −2.12 to 0.80; I^2 = n/a; 1 study, 4 subjects) and energy expenditure (SMD −0.45; 95% CI −1.87 to 0.97; I^2 = n/a; 1 study, 4 subjects) showed no statistically significant changes when using an ankle-supporting exoskeleton. (Cf. Appendix 10).

3.4.5. *Intervention: wrist-supporting exoskeletons*

3.4.5.1. Outcome: biomechanical stress or strain. The muscle activity of the wrist flexors (SMD −0.23; 95% CI −0.64 to 0.18; I^2 = n/a; 1 study, 23 subjects), wrist extensors (SMD −0.07; 95% CI −0.48 to 0.34; I^2 = n/a; 1 study, 23 subjects) and shoulder elevators (SMD −0.44; 95% CI −0.85 to 0.02; I^2 = n/a; 1 study, 23 subjects) showed no statistically significant changes when using a wrist supporting exoskeleton. (Cf. Appendix 11).

4. Discussion

4.1. *Summary of findings*

This systematic review with meta-analyses is the first aiming to determine the effects of using exoskeletons on physical stress and strain of the user in occupational tasks. We included 48 studies in the pooled meta-analyses with a total of 700 participants. Exoskeletons were

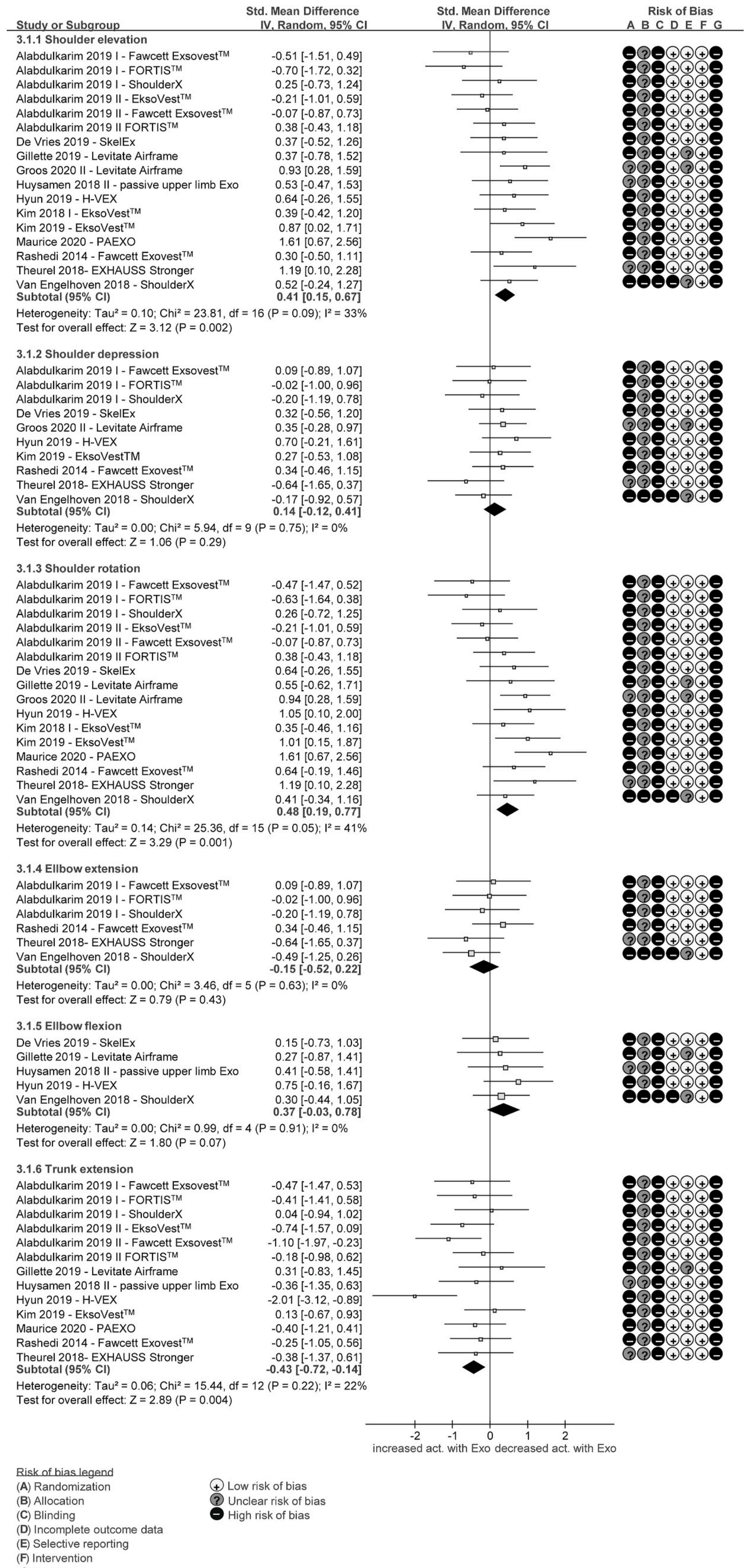

Fig. 5. Study findings (i.e. SMD and risk of bias) for studies evaluating the effects of using an upper limb supporting exoskeleton on muscle activity (muscles were grouped according to joint movements). - Part 1 [IV = inverse variance; CI = confidence interval; Exo = exoskeleton].

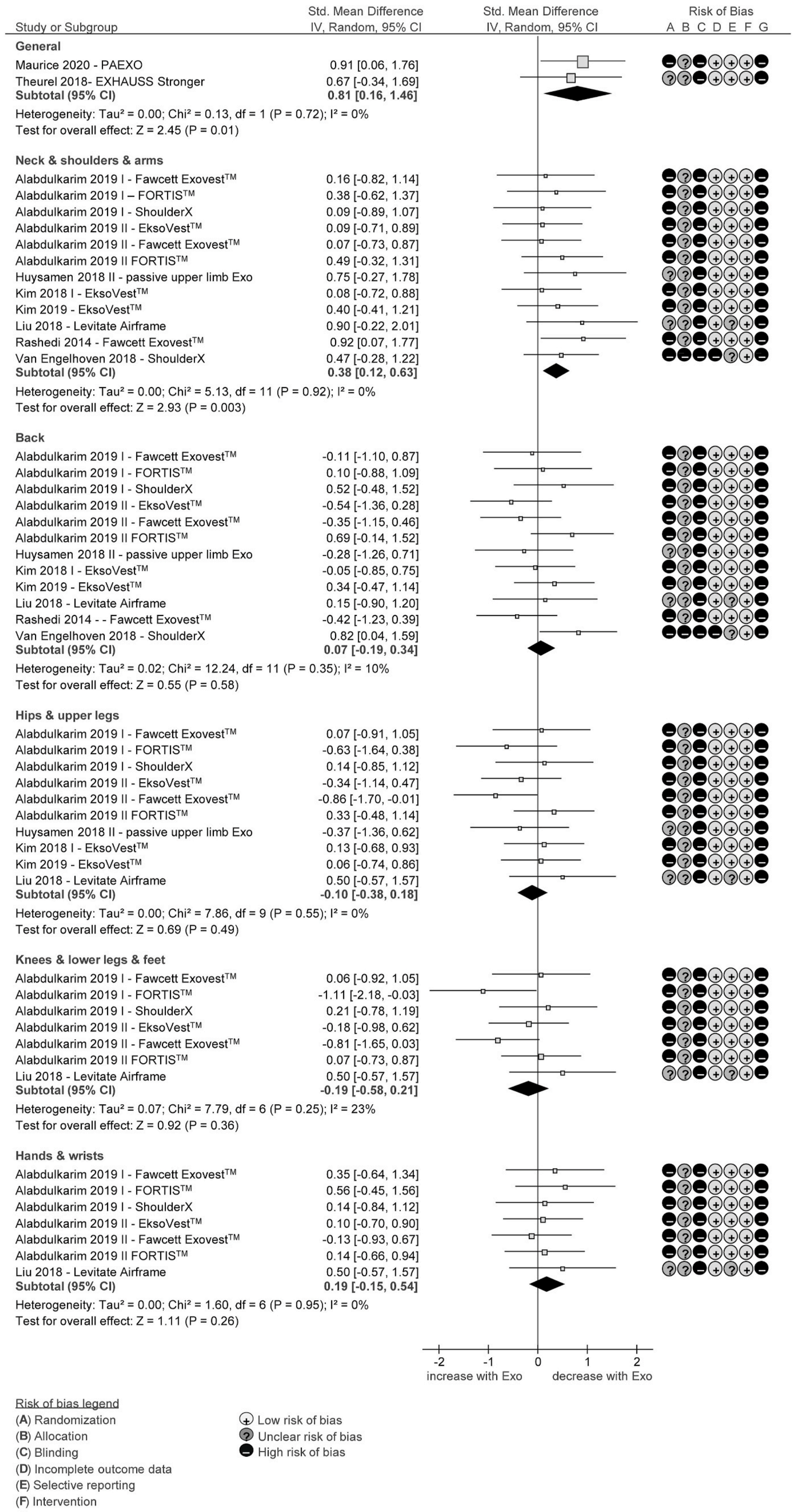

Fig. 6. Study findings (i.e. SMD and risk of bias) for studies evaluating the effects of using an upper limb supporting exoskeleton on perceived strain. [IV = inverse variance; CI = confidence interval; Exo = exoskeleton].

grouped into five categories according to the supported body region, i.e. back, upper extremities, lower extremities, wrist and ankle. The meta-analyses indicated that using an exoskeleton can reduce stress and strain in the supported areas, supported by a reduced muscle activity, but the evaluation of various inter-related parameters is incomplete.

4.2. Quality and applicability of the evidence

This review provides an overview on the actual existing literature on occupational exoskeletons. Although the findings of the meta-analyses show statistically significant evidence of reducing parameters indicating physical stress or strain by using an exoskeleton, there is no evidence to recommend using an exoskeleton for preventing WMSD and possible collateral risks cannot be estimated yet. Therefore controlled long-term evaluations including various outcome parameters and observing various body areas (not only the target-areas) are inevitable. We detected all included studies to have a high risk of bias. Most of the studies did not include an adequate randomization process or did not describe the randomization method used. However, an exact randomization can be challenging because many studies evaluating exoskeletons include comprehensive protocols and multiple tasks, and the donning and doffing of the exoskeletons can be difficult on the equipped subjects (e.g. electrodes, sensors). Regardless, experimental conditions should be randomized as exact as possible and should be described in the methods. The item allocation was mainly rated with an unknown risk of bias resulting from treatment allocation not being concealed; however, concealment when evaluating exoskeletons is not possible which equally counts for the item blinding. Often studies did not report drop-out rates, but if reported, they were low in most of the studies. None of the studies conducted a power analysis before determining their sample sizes. Similarly, no effect sizes were reported by the authors and the relevance of the findings in the single studies was not discussed. Some papers included in this review primarily aimed to report the development or function of an exoskeleton with pilot measurements including only one or a few subjects. Although the main focus was not evaluating the effects of using an exoskeleton in these studies, still, larger sample sizes would provide more usable insights of the exoskeleton's properties. Also, across the actual intervention studies only three included more than twenty subjects (Ferrigno et al., 2009; Knott, 2017; Luger et al., 2019a, 2019b). It is recommended to define a sufficiently large sample size with the goal of reaching a power of at least 80% for the differences between the intervention and control conditions. Selective reporting was rated with a high or unknown risk of bias for more than half of the studies. We detected outcomes not being evaluated or measured using reliable and valid measures or without clarifying these. Some outcomes and subgroup analyses were conducted or reported without defining and describing them in the methods section. All outcomes and subgroups to analyze should be defined in advance and evaluated via valid and reliable measurements. Outcomes and measurements should be described sufficiently in the methods section; therefore, methods, results and discussion sections should be reported separately and not mixed as occurred in some of the papers.

Although there was a large number of studies included in the current review and meta-analyses, which resulted in a total of N = 700 subjects and up to N = 198 in some individual analyses, the value and applicability of the results is very restricted. Many studies focused only on a few parameters, particularly muscle activity, but evaluations of the associated passive musculoskeletal structures or physiological parameters are limited. Equally, many studies evaluated only the areas directly supported by the individual exoskeleton but not the surrounding areas. Possible risks that may result from load shifting from one to another area, the carrying of additional weight of the exoskeleton itself and/or from changed movement patterns due to wearing and using an exoskeleton have been reported in some studies (Theurel and Desbrosses, 2019; Weston et al., 2018) and need to be clarified.

All studies evaluated short duration periods with simulated tasks that ranged between a couple of seconds to 45 min and field observations that lasted between 2-h work shifts to a full working day. Wearing and using an exoskeleton is usually unfamiliar for subjects and may eventually change movement patterns and/or could adapt perceived strain after a longer period of using them regularly (Moyon et al., 2019). Furthermore, we cannot deduce any conclusions about long-term effects from evaluations of particularly short-duration laboratory simulations. The current sample of included studies is not representative for real working populations and situations, due to most of the included studies being performed in the laboratory using novices. Although the transferability of the results presented to practice is limited, evaluating exoskeletons under laboratory conditions using simulated work-tasks is an important first step to get insights into their potential effects. However, as one next step studies including longer testing protocol durations, reflecting the duration of a whole working shift could provide information about adaptations over the shift. Further studies including randomized-controlled trials in the field could provide further knowledge for practical applicability of the various exoskeletons.

4.3. Interpretation of findings

4.3.1. Back-supporting exoskeletons

Twenty studies evaluated back-exoskeletons included in these meta-analyses evaluating eight different exoskeletons (6 passive, 2 active). All of them tended to support the users' back in lifting and lowering activities and during static trunk forward flexion postures.

In our analyses, using a back-supporting exoskeleton resulted in statistically significant reduced muscle activity in the target area (i.e. trunk and hip extension groups), lower perceived back strain, smaller moments at the lumbosacral spine level, and no changes in lumbar shear and compression forces compared to not using an exoskeleton. Effects were strongest for the joint moments [SMD 0.78; 95% CI 0.15–1.41], followed by back perceived strain [SMD 0.73; 95% CI 0.38–1.09], trunk [SMD 0.58; 95% CI 0.28–0.88] and hip [SMD 0.53; 95% CI 0.19–0.86] extensor muscle activity. Most prevalent changes in trunk extensor muscle activity occurred when evaluating exoskeletons in endurance protocols (cf. Fig. 3). The small number of studies evaluating forces and moments at the lumbar spine (Abdoli-Eramaki et al., 2006; Agnew, 2008; Frost et al., 2009; Koopman et al., 2019) and their inconclusive results indicate that an estimation of the effect of using back-supporting exoskeletons on passive musculoskeletal structures is still not possible. However, lumbar forces and moments are important indicators that have been associated with work-related low back pain (LBP) (Coenen et al., 2013, 2014; Norman et al., 1998).

In the non-target areas, i.e. those not directly supported by the exoskeleton, no changes occurred except for the muscle activity of the knee flexor group which statistically decreased significantly. Both the knee flexor and hip extensor muscle groups mainly include the M. biceps femoris. Likely, a reduction of M. biceps femoris activity rather comes from a hip extension support provided by the exoskeletons. However, a reduced muscle activity of one muscle or muscle group possibly caused by supporting a joint movement might again have adverse effects on contiguous joints (e.g. reduced joint stability) that we cannot estimate. In a review about the effects of using exoskeletons on physical workload, mainly including muscle activity and joint angles, forces and moments (de Looze et al., 2016), an increase in leg muscle activity when using back-supporting exoskeletons was mentioned. Although we could not detect any statistically significant changes in other leg-related muscle groups, nor in other non-target areas and parameters, many of the included studies did not extensively evaluate these non-target regions. This makes it impossible to accept or reject the occurrence of any additional musculoskeletal stress or strain as a consequence of using a back-supporting exoskeleton.

We found statistically significant reduced general perceived musculoskeletal strain but no changes in the metabolic parameters when using a back-supporting exoskeleton. Observing the forest plots of both outcomes shows a large inconsistency between the included studies, which may again be due to the different exoskeletons and experimental protocols evaluated. (Cf. Appendix 7).

4.3.2. Lower-limb-supporting exoskeletons

Nine studies evaluated lower-limb-exoskeletons, which included eight different exoskeletons (4 passive, 4 active). The function and the supported area were highly variable across the evaluated exoskeletons; some provided a substitution for prolonged standing (e.g. Chairless Chair) (Groos et al., 2020; Luger et al., 2019a, 2019b), whereas others supported the musculoskeletal system in movements like walking, squatting or kneeling addressing the ankle, knee and/or hip joint (Knott, 2017; Lee et al., 2020; MacLean and Ferris, 2019; Pillai et al., 2020; Sado et al., 2019).

In the overall pooled analyses, muscle activity in the target areas was partly reduced when using an exoskeleton, most likely dependent on the exoskeleton used. Within the non-target areas, participants perceived significantly less strain in their back (resulting from one study only (Groos et al., 2020)) that investigated an exoskeleton to substitute prolonged standing postures included). Prolonged standing is associated with LBP (Andersen et al., 2007; Gregory and Callaghan, 2008), so avoiding long-duration standing postures by using an exoskeleton could result in less stress and strain of the users' back. The general perceived strain statistically increased significantly when using an exoskeleton, possibly caused by the additional weight carried or by discomfort arising by wearing an external structure on the body. The estimation of the effects of using a lower-limb-supporting exoskeleton on stress and strain of the user is very limited because of the very low number of studies evaluating these exoskeletons. Furthermore, the variety of different lower-limb-supporting exoskeletons needs to be considered. (Cf. Appendix 8).

4.3.3. Upper-limb-supporting exoskeletons

Twenty studies evaluating upper-limb-exoskeletons were included in the meta-analyses, assessing 15 different exoskeletons (12 passive, 3 active). In some exoskeletons the weight of a tool is supported by an additional mechanical arm, which transfers the weight of the handled tool directly to the hips and/or torso; whereas most regular upper–limb-supporting exoskeletons directly support the weight of the upper extremities when performing the task and handling the tools (McFarland and Fischer, 2019). Such distinctions can result in different effects by using one of the exoskeletons.

Despite the different functions of the exoskeletons, the overall pooled analyses showed statistically significant reduced stress and strain in the target area when using an upper-limb-supporting exoskeleton; i.e., in muscle activity of the shoulder elevators and rotators (note that many muscles included in these two groups are similar), shoulder moments (resulting from one study only (de Vries et al., 2019)) and perceived strain. No changes have been observed in the muscle activity of the shoulder depression group, which represents the antagonistic shoulder muscles for most of the work tasks realized in the studies.

Within the non-target areas, trunk extensor muscle activity was significantly increased statistically when using an upper-limb exoskeleton. The weight of the upper-limb exoskeleton that has to be carried by the user could imply an additional load on the musculoskeletal system of the trunk and/or lower limbs and, therefore, collateral risk for WMSD. Forces at lumbosacral spine-level have not been statistically influenced significantly according to our meta-analysis; however, only two studies were included (Kim et al., 2018; Weston et al., 2018), and one of these studies found increased compression forces when using an exoskeleton with an additional mechanical arm (Weston et al., 2018). To pursue the question of adverse effects of increased spinal loading by wearing an upper limb exoskeleton, further evaluations including longer-lasting study protocols would be helpful. The general perceived musculoskeletal strain and energy expenditure were both statistically reduced significantly, whereas heart rate did not statistically change when wearing an upper-limb-supporting exoskeleton. (Cf. Appendix 9).

4.3.4. Ankle- and wrist-supporting exoskeletons

There was only one study evaluating an ankle-supporting exoskeleton and one study evaluating two wrist-supporting exoskeletons. Therefore, a discussion on their effects when using them is restricted (cf. Appendix 10 and 11). However, ankle-supporting exoskeletons might be able to support walking while carrying loads which is relevant in some professions (Bougrinat et al., 2019), and wrist-supporting exoskeletons can be helpful in computer work (Ferrigno et al., 2009). Therefore these areas should be considered in the development and evaluation of exoskeletons.

4.4. Strengths and limitations

A strength of this systematic review with included meta-analyses is its high methodological quality by following standards like using the PRISMA guidelines (Moher et al., 2009) and considering the Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2019b). Preparing all calculations in Review Manager 5.3 (Review Manager, 2014) enabled us to combine results with different scales using the option of SMD for continuous outcomes. However, interpreting these results is difficult (Cochrane Handbook Section 12.6.1 (Higgins et al., 2019b)) because absolute changes cannot be deduced. For assessing the quality of the included studies, a detailed and specialized risk of bias assessment tool was used that best reflected the type of studies included in this review, which were a mixture of experimental and randomized cross-over designs.

This review also has some limitations. First of all, we clustered various outcome parameters, i.e. muscle groups and participant-reported outcomes, based on muscle main function or body region (cf. 2.1 Eligibility criteria). This may provide a quick overview for the various body areas, but may also be inconclusive as some muscles have various functions such as the M. biceps femoris and M. deltoideus. Likewise, we integrated several muscles in more than one muscle group and, thus, pooled analyses. For the grouping of both muscle activity and participant-reported outcomes, very specific results may get lost in the analyses. For the outcome parameter "perceived musculoskeletal strain", we included all participant-reported outcomes (cf. 2.1 Eligibility criteria), although some of these parameters may not refer to exactly the same perceived feeling. The various currently existing exoskeletons use different techniques to support the wearer (e.g. active or passive, springs or elastic bands, rigid and/or soft structures, including a mechanical arm or not). To perform meta-analyses with groups of adequate sizes we clustered the devices based on the body region supported. However, this restricts the quantitative analyses by not providing the effects of every special type of exoskeleton which can be found in Appendix 5.

A second limitation might be the broad spectrum of statistical heterogeneity identified in our meta-analyses (I^2 ranging from 0% to 92%). A high level of heterogeneity (i.e. high I^2 statistic) was the case for knee extensor muscle activity in lower-limb-supporting exoskeletons (i.e. 92%). This specific example of considerable heterogeneity may be the result of the diversity of included exoskeletons (passive, active, different functions), variety in evaluated muscles (different for each of the three studies) and different task protocols. Similar reasons may apply to other pooled analyses that show considerable heterogeneity (i.e. $I^2 > 75\%$; Deeks et al., 2019).

We excluded outcomes provided as peak values in this systematic review as we had to restrict the extent of this paper. As peak load has also been related to LBP (Norman et al., 1998); future work should also consider the evaluation of peak value outcomes. We furthermore excluded outcomes such as usability, acceptability and performance. Although these outcomes might be interesting and relevant for field evaluations and practical recommendations, we focused on acute physical stress and strain particularly because the development of occupational exoskeletons is fairly new and long-term investigations may provide a more valid evaluative reflection of usability and acceptability among workers.

The further development and the evaluation of occupational exoskeletons are quickly proceeding currently. Therefore the reviews about the effects of wearing these exoskeletons should be updated constantly, including further databases (e.g. Scopus) for considering all relevant existing articles.

5. Conclusions

Using an occupational exoskeleton seems to reduce muscle activity of the wearer in the exoskeleton's supported body areas and occasionally influences other parameters indicating physical or perceived musculoskeletal stress and strain. However, the impact on workers' health is unknown mainly because of a lack of studies following high methodological criteria and evaluating stress and strain of the user thoroughly and with inter-related outcomes, including passive as well as active musculoskeletal structures and also subjective outcomes in supported as well as non-supported body areas.

From the existing literature and our research question it is only possible to estimate acute effects on physical stress and strain of using an exoskeleton based on short-duration laboratory simulations. Long-term effects under real working conditions are currently not known, which means that we cannot formulate any conclusions or practical recommendations of the effects of using an exoskeleton on the prevalence of WMSD. Future studies need to include prospective field randomized controlled trials to gain insights into the implementation of exoskeletons on aspects of workers' health and well-being.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The work of the Institute of Occupational and Social Medicine and Health Services Research Tübingen is supported by an unrestricted grant of the employers' association of the metal and electric industry Baden-Württemberg (Südwestmetall). One of our own studies evaluating a lower-limb-supporting exoskeleton was included in the meta-analysis (Luger et al.; 68), for which we received a financial contribution of our industry partner AUDI AG (Ingolstadt, Germany). In another research project evaluating a back-supporting exoskeleton (Steinhilber et al.; 138), we received a financial contribution of our industry partners AUDI AG (Ingolstadt, Germany), BMW AG (München, Germany), Daimler AG (Stuttgart, Germany), Itturi GmbH (Köln, Germany), BASF SE (Ludwigshafen am Rhein, Germany), Deutsche Post DHL Group (Bonn, Germany), MTUAero Engines AG (München, Germany), and DACHSER SE (Kempten, Germany). In addition, Mona Bär received a grant (Stipendium "Arbeit und Gesundheit"), as the review is part of her doctoral thesis. None of the above mentioned industry partners was involved in financing or carrying out the current literature review.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apergo.2021.103385.

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Chapter 3

Using a passive back exoskeleton during a simulated sorting task: Influence on muscle activity, posture, and heart rate.

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Using a Passive Back Exoskeleton During a Simulated Sorting Task: Influence on Muscle Activity, Posture, and Heart Rate

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Objective: To evaluate using a back exoskeleton in a simulated sorting task in a static forward bent trunk posture on muscle activity, posture, and heart rate (HR).

Background: Potentials of exoskeletons for reducing musculoskeletal demands in work tasks need to be clarified.

Methods: Thirty-six healthy males performed the sorting task in 40°-forward bent static trunk posture for 90 seconds, in three trunk orientations, with and without exoskeleton. Muscle activity of the erector spinae (ES), biceps femoris (BF), trapezius descendens (TD), rectus abdominis (RA), vastus laterals (VL), and gastrocnemius medialis was recorded using surface electromyography normalized to a submaximal or maximal reference electrical activity (%RVE (reference voluntary electrical activity)/%MVE). Spine and lower limb postures were assessed by gravimetric position sensors, and HR by electrocardiography.

Results: Using the exoskeleton resulted in decreased BF muscle activity [−8.12%RVE], and minor changes in ES [−1.29% MVE], RA [−0.28%RVE], VL [−0.49%RVE], and TD [+1.13% RVE] muscle activity. Hip and knee flexion increased [+8.1°; +6.7°]. Heart rate decreased by 2.1 bpm. Trunk orientation had an influence on BF muscle activity.

Conclusion: Using the back exoskeleton in a short sorting task with static trunk posture mainly reduced hip extensor muscle activity and changed lower limb but not spine posture. Implications of using a back exoskeleton for workers' musculoskeletal health need further clarification.

Application: The detected changes by using the Laevo® illustrate the need for further investigation prior to practical recommendations of using exoskeletons in the field. Investigating various work scenarios in different kind of workers and long-term applications would be important elements.

Keywords: Assistive device, electromyography, back support, working posture, nonneutral trunk postures

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INTRODUCTION

Musculoskeletal disorders (MSD) in the back area, including low back pain (LBP), represent the most reported health problem among the working population in the European Union (DeKok et al., 2019). Low back pain has been reported to have an estimated lifetime prevalence up to 75% among the general population (Burton & Kendall, 2014) and a 12-month prevalence ranging from 25% among employees in the United States (Dick et al., 2020) to 43% among workers in the European Union (DeKok et al., 2019). The consequences include limitations in daily life of the persons concerned (Eurostat, 2010) as well as impairments at and absence days from work (DeKok et al., 2019; Valirad et al., 2015). Several physical risk factors have been reported to be related to LBP, including working in awkward positions like trunk forward flexion, heavy physical work and lifting (Coenen et al., 2014; Coenen et al., 2013; da Costa & Vieira, 2010; Dick et al., 2020).

Lately, practitioners and researchers have focused on the occupational application of exoskeletons for reducing physical workload by supporting movements and postures of workers (Bär et al., 2021; Toxiri et al., 2019). "Exoskeletons are assistive systems worn on the body that act mechanically on the body. In an occupational context, they aim to support functions of the skeletal and locomotor system during physical work." (Steinhilber, Luger, et al., 2020). For supporting the lower back in work tasks, several passive exoskeletons have been described; some are already commercially available and others still are in a developmental stage. Most of the commercially available exoskeletons use passive components to generate an assistive torque for storing or releasing energy, such as spring-like structures or soft elastic bands (Toxiri et al., 2019).

A variety of studies evaluated passive back supporting exoskeletons (BSEs) in an occupational context regarding their effects on acute physical stress and strain. The meta-analyses of a recent systematic review indicated the capability of using BSEs to reduce muscle activity in the supported areas (Bär et al., 2021), which is frequently used as objective physical strain indicator reflecting the necessary amount of muscle activation to realize a given motor task when normalized to the muscle activity during a maximum voluntary contraction (MVC) (Burden, 2010). Most of the included studies were performed in the laboratory and evaluated dynamic tasks, like lifting and lowering. Only few studies examined BSEs in static postures including forward trunk bending (Bär et al., 2021; Madinei et al., 2020b). However, there is some evidence for reduced back extensor muscle activity ranging between 11%-61% (Agnew, 2008; Bosch et al., 2016; Graham et al., 2009; Koopman et al., 2019; Madinei et al., 2020b; Ulrey & Fathallah, 2013; Wei et al., 2020) and reduced hip extensor muscle activity ranging between 17%-24% (Bosch et al., 2016; Ulrey & Fathallah, 2013) when using a BSE in static forward bent postures. Within these studies, the reported reductions have not always reached statistical significance (Ulrey & Fathallah, 2013), and in some of the various observed bending postures there have been no changes or even increases in trunk extensor muscle activity (Koopman et al., 2019; Madinei et al., 2020b). One main function of exoskeletons is the load transfer to other body areas (Toxiri et al., 2019; Weston et al., 2018). However, physical stress and strain parameters in these non-supported areas have been evaluated rarely (Bär et al., 2021) and most of the studies have not included posture into their observations so far (Kermavnar et al., 2021).

Physical back loading might be reduced by using a passive BSE in work tasks requiring static postures holding the trunk in a forward bent position. However, from the existing literature no conclusions can be drawn yet on their effectiveness with respect to LBP reduction and prevention or on the occurrence of possible collateral effects. Furthermore, most of the existing studies on this topic only observed working postures in the sagittal plane and did not include an orientation of the trunk to the side, that is, rotation which is often required at workplaces and may modify the intended support provided by the exoskeleton due to modified individual inclination angles. Therefore, this study evaluated the effects of using a passive BSE (Laevo® V2.56) during a sorting task with 40°-trunk forward flexion, with and without additional trunk rotation induced by a 45°-sideward workstation orientation. During initial measurements, a direct increase in physiological response such as heart rate (HR) and muscle activity within the first seconds was observed and lasted on a steady state over several minutes. Thus, for detecting acute effects of the exoskeleton and also avoiding muscular fatigue, a 90-second period for performing the sorting task was chosen. We included the outcome measures muscle activity, body posture, and HR. Concerning the exoskeletons' function, our primary outcome measure in this study was muscle activity of the erector spinae (ES) and biceps femoris (BF), which are responsible for back and hip extension. We hypothesized that both ES and BF muscle activity are reduced when wearing the exoskeleton. The secondary outcomes were muscle activity of the vastus lateralis (VL), gastrocnemius medialis (GM), trapezius descendens (TD), and rectus abdominis (RA), posture of the spine as well as hip flexoin (HF) and knee flexion (KF), and HR. We had no particular expectations with respect to the secondary outcomes. We included VL and GM because these muscles might be affected due to load shifting when wearing the exoskeleton. We included TD because the exoskeleton shoulder straps might bother wearers. We included RA because it acts antagonistic to the ES, and trunk bending might be hindered by the exoskeletons' extension moment resulting in increased RA muscle activity. Body posture might be influenced by wearing the exoskeleton, as previous studies reported that wearers complained about reduced freedom of movement (Baltrusch et al., 2019). We included HR to monitor an eventual cardiovascular response of using the exoskeleton.

METHODS

Sample Size and Study Design

This manuscript describes one part of a larger, explorative laboratory study, evaluating the

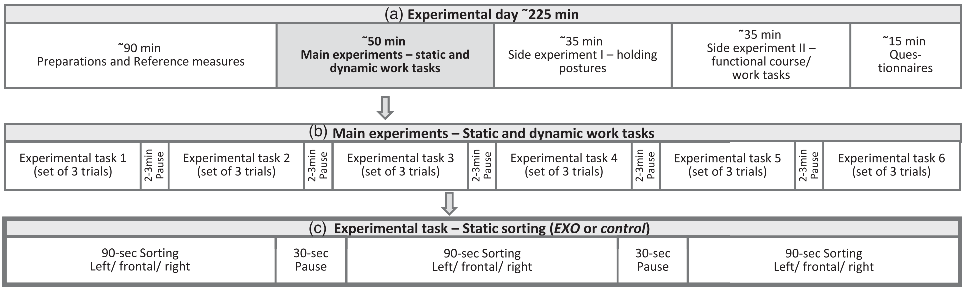

Figure 1. Line (a) shows one exemplary experimental day for one subject. Line (b) shows the sequence of the six main experimental conditions (randomized order): Static_sorting_*EXO*/Static_sorting_*control*/Dynamic_lifting_Stoop_posture_*EXO*/Dynamic_lifting_Stoop_posture_*control*/ Dynamic_lifting_Squat_posture_*EXO*/Dynamic_lifting_Squat posture_*control* which were performed three times each (including three *Trunk orientations*). Each set of static sorting tasks lasted 330 s, and each set of dynamic lifting tasks lasted 375 s. Line (c) shows one set of the static sorting task which is the basis of this manuscript. *Trunk orientations* (left/frontal/right) were performed in randomized order.

Laevo® V2.56 exoskeleton on physiological and biomechanical parameters (ClinicalTrials.gov, NCT03725982). The overall study was designed according to the Declaration of Helsinki and approved by the Ethics Committee of the University and University Hospital of Tübingen (617/2018BO2). The overall study required a sample size of 36 subjects based on a Single Williams Latin Square design (Luger, Bär, Seibt, Rimmele, et al., 2021). The current article focuses on the static sorting task (Figure 1), for which we maintained a within-subject design with *Device* (without (control) vs. with (EXO)) and *Trunk orientation* (ipsilateral vs. frontal vs. contralateral) as the within-subject variables. Randomization was realized by drawing three lots: (1) order of *control* and EXO; (2) order of the *Trunk orientation* (left, frontal, right); (3) measured body side reflecting muscle activity and HF and KF angles. All randomizations were balanced across the subjects.

Participants

Thirty-six healthy males (mean age 25.9 ± 4.6 years, mean body height 178.7 ± 7.3 cm, mean body weight 73.5 ± 8.9 kg) participated in the study. Inclusion criteria were: 18–40 years of age, BMI of 18.5–30 kg/m^2, free of any acute or cardiovascular diseases, physical disability, systemic diseases, or neurological impairments that would hinder the subject from performing the tasks and wearing the exoskeleton. Only male subjects were included due to a continuing domination of male workers in the manufacturing industries.

Experimental Procedure and Task

On a first day lasting 1 h, the subjects got informed about the study procedure and signed the informed consent. Inclusion and exclusion criteria were clarified and anthropometric measures (i.e. body height and weight) were collected. The required exoskeleton size (S/L) was chosen and the exoskeleton was adjusted to best fit the subjects. Subsequently, subjects got familiarized with wearing the exoskeleton and performing the task. On a second day lasting 4 h, the subjects got prepared with the measurement equipment and performed the six conditions of the simulated static sorting task with either a 30 s or 120 s rest break in between (Figure 1).

The task included sorting screws and pins for 90 s with the trunk bent forward in 40°. This inclination angle was ensured by the signal of a position sensor placed on the spinous process of the 10th thoracic vertebrae (T10) which was visually controlled on a screen by the researchers. The mean T10 inclination angle was 38.9° (cf. Table 2). The feet position was kept constant during all experimental conditions and defined prior to the experiment and marked in the study

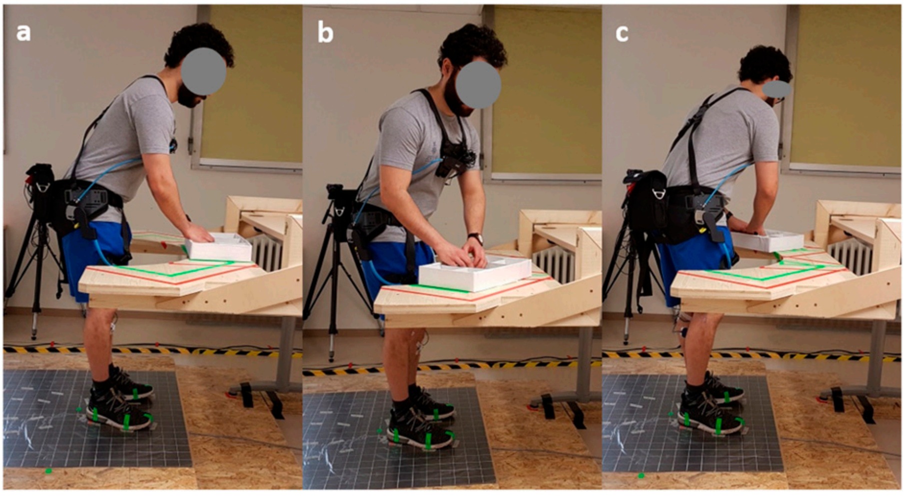

Figure 2. Sorting task; (a) frontal; (b) 45° trunk orientation to the right; (c) 45° trunk orientation to the left.

setup, while participants were requested to stand comfortably upright, positioning their feet equably, facing straight ahead, and extending but not overstretching their legs. Trunk orientations deviating from the sagittal plane were realized by positioning the task setup in a 45°-rotation from the sagittal (Figure 2). The different feet and posture requirements were continuously controlled for by the researchers and corrected by verbal instructions when necessary.

Exoskeleton

The Laevo® exoskeleton (V2.56, Laevo B.V., Delft, the Netherlands; 2.8 kg) is a passive BSE that supports back extension. The exoskeleton consists of a hip belt with two attached joints including a gas pressure spring located close to the pivot of the hip joints. A chest pad and two leg pads are attached to the springs over rigid metal bars, movable by two-dimensional joints in the chest pad. Bending the trunk forward compresses the springs and generates a moment which supports back and hip extension. The springs can be turned off and be adjusted to start the support at different trunk flexion angles (ranging from 0° to 45° in steps of 5°). Depending on the subject's body proportions, the support angle was adjusted to assure contact but no pressure on the chest by the chest pad during an upright standing position (i.e., 0Nm), monitored by a force sensor built into the chest pad (38×10 mm; Type KM38-1 kN, ME-Messsysteme GmbH, Henningsdorf, Germany) and visually controlled on a screen by the researchers.

MEASUREMENT AND DATA ANALYSIS

Muscle activity. The muscle activity of erector spinae lumbalis at level of lumbar vertebrae L1 (ES), BF, RA, VL, GM and TD muscles was recorded unilaterally (body side was randomized) via surface electromyography (EMG). This procedure was due to practical reasons of having no more EMG channels left. The skin over the muscles was shaved and cleaned using abrasive paste (Skin Prep Gel, Nuprep®, Aurora, USA). Pre-gelled Ag/AgCl surface electrodes with an active area of 15 mm diameter (KendallTM H93SG electrocardiography (ECG) Electrodes, Covidien, Zaltbommel, the Netherlands) were used in bipolar configuration (inter-electrode center distance 25 mm) and located over the muscle bellies according to international standards (Criswell, 2010; Hermens et al., 2000). The electrodes over the VL were in some cases placed slightly more distal compared to the standard recommendations to avoid any contact with the exoskeleton's leg pad. The ground electrode was placed over cervical vertebrae C7 (PS12-II, THUMEDI® GmbH & Co. KG, Thum, Germany, physical resolution 24 bit; overall CMRR >98 dB; overall effective sum of noise <0.5 μV RMS; linearity typically ±0.1 dB at 30−1200 Hz). Electromyography raw signals were differential amplified, filtered (high-pass, second order, −3 dB at 4 Hz; low-pass, 11th order, −3 dB at 1300 Hz), sampled (4096 Hz), analog-digital-converted, analyzed, and continuously stored. The signals were real-time transformed in the frequency domain (1024-point Fast Fourier Transformation using a Bartlett-window with 50% overlap), digitally filtered (high-pass, 11th order, −3 dB at 16 Hz) and powerline interferences were removed by an average filter (11th order, −3dBat 50 Hz and its first seven harmonics, bandwidth of 4 Hz was replaced by its spectral neighbors). The electrical activity (eA) [μV] was calculated as the root-mean-square (RMS) of the EMG amplitude by real-time estimation (250 ms moving window with 50% overlap) from the power spectrum and stored synchronously to the raw data.

The eA of the BF, VL, RA, GM, and TD were normalized to the eA of a submaximal reference voluntary contraction (Supplemental Appendix 1), presented as reference voluntary eA (%RVE; Mathiassen et al., 1995). RVE normalization was done since less demanding than MVC based normalization and less affected by motivational aspects (Steinhilber & Rieger, 2013). The eA of the ES, was normalized using a maximal voluntary eA (%MVE; Mathiassen et al., 1995) during MVC, since this evaluated muscle is located in the targeted area of the exoskeleton and has often been reported expressed as %MVE in studies already investigating the Laevo® exoskeleton (Bosch et al., 2016; Koopman et al., 2019). The median (50th percentile) normalized muscle activity [%MVE/%RVE] was calculated for each experimental condition: *control* and *EXO*, *ipsilateral* (measured side equals trunk orientation), *frontal*, and *contralateral* (measured side opposes trunk orientation) over the 90-second task.

Body posture. For recording body posture, we used two-dimensional gravimetric position sensors (PS12-II; Thumedi GmbH & Co. KG) placed on the skin over thoracic vertebrae T1 and T10, lumbar vertebrae L1 and L5, and on the anterior side of the femur and tibia, fixed with double-sided adhesive tape (25×5 mm, 3M transparent Medical Standard, Top Secret®, Gesellschaft für Haarästhetik mbH, Fürth, Germany). The sensors continuously measured inclination angles respective to the gravitational axis in anteroposterior direction (resolution 0.1° and 125 ms in time; maximum static error 0.5°; maximum repetition error 0.2°). For further evaluations the differences between angles during the experimental conditions and a reference posture were used (Supplemental Appendix 1); subtracting the reference angles from the experimental angles. Four joint angles were calculated: thoracic kyphosis (TK), lumbar lordosis (LL), hip flexion (HF), and knee flexion (KF) (Table 1; Supplemental Appendix 2). The medians were calculated for each condition over the 90-second tasks. HF and KF were grouped into *ipsilateral*, *frontal*, and *contralateral*. TK and LL were grouped into *frontal* and *lateral* (including both, left and right trunk orientations).

Heart rate. The HR was recorded continuously using ECG sampled at 1,000 Hz (PS12-II; Thumedi GmbH & Co.KG). Two pre-gelled Ag/AgCl surface electrodes with an active area of 15 mm diameter (KendallTM H93SG ECG Electrodes, Covidien, Zaltbommel, the Netherlands) were placed ~5 cm cranial and ~3 cm lateral from the distal end of the sternum and over the anterior to mid-axillary line at the fifth left rib. The median HR was calculated over the 90-second periods for the conditions *frontal* and *lateral*.

Statistical Analysis

We visually inspected the data histograms including their skewness and kurtosis. Electromyography and position sensor data showed no normal distribution. Subsequently, a log-transformation (LOG10) for the statistical analysis was performed. Heart rate data showed normal distribution, which was used directly for further evaluation. Differences between conditions were analyzed by repeated-measures analyses of variance with the fixed factors *Device* (*EXO* vs. *control*) and *Device* × *Trunk orientation* (three levels: *ipsilateral* vs. *frontal* vs. *contralateral*, for the outcome parameters

TABLE 1: Calculation and Interpretation of the four joint angles

Joint angle	Calculation	Interpretation
Thoracic kyphosis	Anteroposterior inclination angles or tangent lines (Cobb method) over the processus spinosi of T1 and L1 according to the Cobb angle boundaries (Takács et al., 2018)	0° reflects curvature in upright stance posture, a positive value means the upper back is curving more (direction kyphosis), and negative value means the upper back is curving less (direction lordosis) compared to upright stance
Lumbar lordosis	Anteroposterior inclination angles or tangent lines (Cobb method) over the processus spinosi of L1 and L5 according to the Cobb angle boundaries (Takács et al., 2018)	0° reflects curvature in upright stance, a positive value means the lower back is curving less (direction kyphosis), a negative value means the lower back is curving more (direction lordosis) compared to upright stance
Hip flexion	Difference value between the anteroposterior inclination angles of L5 and femur	Smaller angles [°] reflect more hip extension (direction upright stance) and greater angles reflect more hip flexion
Knee flexion	Difference value between the anteroposterior inclination angles of femur and tibia	Smaller angles [°] reflect more knee extension (direction upright stance) and greater angles reflect more knee flexion

muscle activity, KF and HF; or two factors: *frontal* vs. *lateral*, for the outcome parameters TK, LL and HR). In case of significant interaction effects, we used Tukey HSD for post hoc pairwise comparisons. We calculated F-values, *p*-values and effect size partial eta squared (η_p^2) using the F-ratios strategy (Bakeman, 2005) for fixed effects, and T-value, *p*-value and effect size Cohen's d using the pooled standard deviation strategy (Cohen, 1988) for post hoc pairwise comparison. Effect sizes are interpreted by Cohen (1988) as follows: small ($\eta_p^2 \geq 0.02$; d≥0.2), medium ($\eta_p^2 \geq 0.13$; d≥0.5), or large ($\eta_p^2 \geq 0.26$; d≥0.8). A significance level of $\alpha \leq 0.05$ was used. All statistical evaluations were performed in JMP® (Version 14.2.0, SAS Inc., Carry, NC, USA).

RESULTS

Descriptive information about the trunk inclination angle and the supporting moment of the exoskeleton are provided in Table 2.

Median values with interquartile ranges (IQR) or mean values with standard deviations (SD), and differences between the exoskeleton conditions are provided in Table 3a for muscle activity, 3b for posture and 3c for HR.

Corresponding statistics for main effects of the exoskeleton condition *Device* (*EXO* vs. *control*), the interaction effects between *Device* and *Trunk orientation* (*Device* × *Trunk orientation*) and the pairwise comparisons for *Device* × *ipsilateral*, *Device* × *frontal,* and *Device* × *contralateral* or *Device* × *lateral* are provided in Table 4a for muscle activity, 4b for posture and 4c for HR.

Muscle Activity

A significant main effect of *Device* for ES occurred when using the *EXO* resulting in a decreased muscle activity (−1.3%MVE; $p = 0.007$; $\eta_p^2 = 0.193$) without significant interaction effect for *Device* × *Trunk orientation*. BF had a significant main effect of *Device*; its muscle activity decreased when using the *EXO* (−8.1%RVE; $p < 0.001$; $\eta_p^2 = 0.389$). BF also showed a significant *Device* × *Trunk orientation* interaction effect. Its muscle activity decreased when using the *EXO* with *ipsilateral* and *frontal* orientations. RA had a significant main effect of *Device* when using the *EXO* showing a decreased muscle activity (−0.3%RVE; $p < 0.001$; $\eta_p^2 = 0.450$) and the VL had a significant main effect for *Device* when using the *EXO* showing a decreased muscle activity (−0.49%RVE; $p = 0.018$;

TABLE 2: Descriptive Information (mean ± SD) of the trunk inclination angle as measured at vertebra T10 and supporting moment provided by the exoskeleton as measured by the force sensor in the exoskeleton's chest pad

	Trunk orientation	Control	Exoskeleton
Trunk inclination [°]	Left	37.97 (±3.72)	38.63 (±3.86)
	Frontal	39.42 (±3.65)	39.92 (±4.12)
	Right	38.39 (±3.72)	38.90 (±3.86)
Supporting moment [Nm]	Ipsilateral	-	23.25 (±5.77)
	Frontal	-	22.81 (3.75)
	Contralateral	-	22.67 (±4.20)

η_p^2 = 0.155), both without significant interaction effects for *Device* × *Trunk orientation.* The GM had no main effect for *Device*. However, there was a significant interaction effect for *Device* × *Trunk orientation* without significant effects within the essential pairwise comparisons. The TD muscle had a significant main effect for *Device* showing an increased muscle activity when using the *EXO* (+1.1%RVE; p = 0.002; η_p^2 = 0.235) without a significant interaction effect for *Device* × *Trunk orientation*.

Body Posture

Device had no significant main effects on TK and LL. *Device* had a significant main effect on HF, showing increased flexion angles (i.e. flexing more) when using *EXO* (+8.1°; $p < 0.001$; η_p^2 = 0.525). *Device* × *trunk orientation* had a significant effect on HF, but without a relation to differences between *EXO* and *Control*, meaning that the HF increased when using the *EXO,* no matter which *Trunk orientation* was applied with similar effect sizes. *Device* had a significant main effect on KF, which increased (i.e. flexing more) when using the *EXO* (+6.7°; $p < 0.001$; η_p^2 = 0.496), without a significant interaction effect for *Device* × *Trunk orientation.*

Heart Rate

Device had a significant main effect on HR, which decreased when using the *EXO* (−2.1bpm; $p < 0.001$; η_p^2 = 0.339) without interaction effects for *Device* × *Trunk orientation*.

DISCUSSION

The results of this study confirmed our hypothesis, because ES and BF muscle activity both reduced when wearing the exoskeleton. Since BF was reduced more than ES, this indicates that the exoskeleton supports hip extension to a larger extend than back extension during work tasks performed in a static forward bent trunk posture. Extra support for the latter indication is the finding that both HF and KF increased when wearing the exoskeleton. With respect to the other secondary outcomes, RA, VL, and TD muscle activity slightly changed when wearing the exoskeleton, but for GM muscle activity and spinal posture we could not detect statistically significant changes. HR slightly decreased when using the exoskeleton but no substantial effect on cardiovascular strain can be deduced from this finding. The factor trunk orientation had a significant effect on BF, so that BF muscle activity significantly reduced in the ipsilateral and frontal but not in the contralateral working direction when wearing an exoskeleton.

Muscle Activity

The Laevo® is designed to support the lower back by providing an extension moment in, i.e., static holding tasks, aiming to reduce lower back physical loading and eventually long-term lower back complaints. Previous studies investigating work tasks requiring static ~40° forward bent working

TABLE 3: Median or mean values, corresponding IQR or SD, absolute and relative differences showing *EXO* compared to *control*. (a) Median RMS of normalized eA (b) Median angles (c) Mean heart rate.

a		Control		EXO		Difference	
Muscle activity [%MVE/% RVE]	Trunk orientation	Median	(IQR)	Median	(IQR)	[%MVE/% RVE]	[%]
Erector spinae [%MVE]	Total	12.25	(6.87)	10.96	(5.58)	−1.29	−10.5
	Ipsilateral	10.44	(5.93)	9.97	(4.83)	−0.47	−4.5
	Frontal	12.74	(7.02)	11.55	(6.70)	−1.19	−9.4
	Contralateral	13.60	(6.95)	11.28	(6.24)	−2.32	−17.1
Biceps femoris [%RVE]	Total	35.98	(28.99)	27.86	(25.09)	−8.12	−22.6
	Ipsilateral	32.93	(22.58)	20.28	(22.78)	−12.65	−38.4
	Frontal	35.72	(26.98)	30.40	(22.18)	−5.32	−14.9
	Contralateral	39.63	(33.06)	35.75	(33.2)	−3.88	−9.8
Rectus abdominis [%RVE]	Total	1.85	(1.74)	1.57	(1.38)	−0.28	−15.2
	Ipsilateral	1.90	(1.66)	1.57	(1.55)	−0.33	−17.3
	Frontal	1.83	(1.66)	1.54	(1.66)	−0.29	−15.8
	Contralateral	1.82	(1.90)	1.71	(1.37)	−0.12	−6.5
Vastus lateralis [%RVE]	Total	3.85	(3.58)	3.35	(2.72)	−0.49	−12.8
	Ipsilateral	4.58	(15.75)	3.47	(6.22)	−1.1	−24.1
	Frontal	3.88	(3.51)	3.23	(1.65)	−0.65	−16.7
	Contralateral	3.34	(2.32)	3.18	(2.84)	−0.15	−4.6
Gastrocnemius medialis [%RVE]	Total	54.11	(46.96)	54.11	(38.73)	+0.67	+1.2
	Ipsilateral	56.77	(46.78)	50.33	(48.27)	−6.45	−11.4
	Frontal	68.93	(29.27)	66.39	(37.09)	−2.54	−3.7
	Contralateral	25.05	(24.75)	44.49	(32.82)	+19.44	+77.6
Trapezius descendens [%RVE]	Total	3.77	(6.12)	4.90	(7.39)	+1.13	+30.1
	Ipsilateral	4.36	(4.21)	4.94	(6.37)	+0.59	+13.5
	Frontal	4.72	(7.7)	4.93	(11.69)	+0.21	+4.4
	Contralateral	3.45	(5.57)	4.71	(7.41)	+1.26	+36.4

b		Control		EXO		Difference	
Posture [°]	Trunk orientation	Median	(IQR)	Median	(IQR)	[°]	[%]
Thoracic kyphosis	Total	14.53	(12.64)	12.45	(9.74)	−2.08	−14.3
	Frontal	11.35	(12.25)	10.60	(10.36)	−0.75	−6.6
	Lateral	15.63	(10.95)	13.08	(10.00)	−2.55	−16.3
Lumbar lordosis	Total	12.30	(5.64)	12.38	(4.86)	+0.07	+0.6
	Frontal	13.60	(5.14)	12.85	(6.28)	−0.75	−5.5
	Lateral	12.18	(5.83)	11.95	(4.93)	−0.23	−1.8
Hip flexion	Total	31.93	(14.59)	40.00	(13.16)	+8.08	+25.3
	Ipsilateral	33.23	(15.76)	39.95	(13.75)	+6.73	+20.2
	Frontal	33.00	(15.20)	40.65	(12.64)	+7.65	+23.2
	Contralateral	26.25	(14.73)	36.58	(14.90)	+10.33	+39.3
Knee flexion	Total	10.73	(13.36)	17.45	(16.33)	+6.73	+62.7
	Ipsilateral	11.28	(13.03)	17.48	(13.45)	+6.20	+55.0
	Frontal	10.53	(11.85)	16.83	(17.14)	+6.30	+59.9
	Contralateral	10.10	(14.26)	19.70	(17.28)	+9.60	+95.0

c		Control		EXO		Difference	
Heart rate [bpm]	Trunk orientation	Mean	*(SD)*	Mean	*(SD)*	[bpm]	[%]
	Total	85.29	(10.19)	83.16	(10.49)	−2.13	−2.5
	Frontal	85.58	(10.37)	83.25	(10.73)	−2.33	−2.7
	Lateral	85.14	(10.17)	83.11	(10.44)	−2.03	−2.4

IQR = interquartile range; SD = standard deviation; RMS = root mean square; eA = electrical activity; MVE/RVE = maximal/reference voluntary electrical activity; bpm = beats per minute; ipsilateral: the measured side equaling the working direction; contralateral: the measured side opposing the working direction; lateral: includes both sideward working directions.

postures presented promising results with lower back muscle activity reductions ranging from ~8% during fastening (i.e. ~1.5% RVE; (Luger, Bär, Seibt, Rieger, & Steinhilber, 2021)) to ~36% during assembling (i.e. ~3.5%MVE; (Bosch et al., 2016)). Also, the current study showed that ES muscle activity decreased by ~11% (i.e. ~1.5%RVE) when wearing the Laevo®. The divergent results may be the result of the tasks that were not exactly the same. When contrasting these results with studies that examined repetitive lifting and lowering, reductions in back extensor activity are slightly higher with 3–7%MVE (i.e. 8–20% relative reduction; (Baltrusch et al., 2020; von Glinski et al., 2019; Yin et al., 2019)). Although work tasks requiring static postures belong to the first factors for back MSD (da Costa & Vieira, 2010), the type of task performed may be indicative of the BSE's efficacy, which may be stronger in lifting and lowering.

While the reduction of lower back muscular load was not as notable as desired, the muscular load on the hip extensor decreased to a greater extend with ~23% (i.e., ~8.1%RVE). Previous studies support this finding with reduced hip extensor muscle activities ranging from 20-36% (Bosch et al., 2016; Luger, Bär, Seibt, Rieger, & Steinhilber, 2021). This difference in muscle load reduction of the trunk and hip extensors may indicate the supportive character of the Laevo® for extending the hips because the BSE creates a hip extensor moment rather than a trunk extensor moment (Luger, Bär, Seibt, Rimmele, et al., 2021; Ulrey & Fathallah, 2013). This finding can be supported by the detected medium effect sizes for the ES and large effect sizes for the BF; however, the quantity of a muscle activity reductions which are clinically relevant is not known and therefore an interpretation in terms of preventing MSD is difficult.

Several studies observed an increased abdominal muscular load as a compensation strategy of the BSE to increase the stiffness and stabilization of the trunk (Alemi et al., 2019; Madinei et al., 2020b). The current study, however, observed a minimally reduced muscle activity level of the RA when wearing the Laevo®, although the magnitude was only 0.3%RVE. As reported by other studies, the overall activity level of the abdominal muscles is low to very low (Koopman et al., 2019; Luger, Bär, Seibt, Rieger, & Steinhilber, 2021). Therefore, the relevance of this finding with respect to consequences for musculoskeletal health may be limited. A similar interpretation may hold for the leg and shoulder muscles. Concerns were raised that muscular load may increase in the shoulder due to the exoskeleton designs (i.e. shoulder straps) and in the legs due to a load shift resulting from the changed working postures and movements due to wearing the exoskeleton (Bosch et al., 2016; Kim et al., 2020; Theurel & Desbrosses, 2019). However, the current study cannot support these theories, since marginal or no differences were found for the VL (0.5%RVE), GM (0.0%RVE) and TD (1.1%RVE; (Kim et al., 2020)).

TABLE 4: F-values and *p*-values of the repeated measures ANOVAs with corresponding effect sizes (partial eta squared or Cohens´ d (*d*)). Main effects of the exoskeleton condition (*Device*) and the interaction effects for device with trunk orientation (*Device × Trunk orientation*). Pairwise comparison for variables with significant interaction effects. (a) log-transformed RMS values of the normalized eA of the muscles. (b) log-transformed angles (c) HR.

a	Main effect			Interaction effect			Pairwise comparisons of *EXO* vs. *Control* in three *Trunk orientations*					
	Device			Device × Trunk orientation			Ipsilateral		Frontal		Contralateral	
Muscle activity	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*p*	*d*	*p*	*d*	*p*	*d*
Erector spinae	8.15	**0.007***	$\mathbf{0.193^{\mu}}$	0.82	0.446	0.023^{σ}	-	-	-	-	-	-
Biceps femoris	22.26	**<0.001***	$\mathbf{0.389^{\lambda}}$	3.27	**0.044***	$\mathbf{0.085^{\sigma}}$	**<0.001***	$\mathbf{-0.414^{\sigma}}$	**0.021***	$\mathbf{0.359^{\sigma}}$	0.732	-0.280^{σ}
Rectus abdominis	28.67	**<0.001***	$\mathbf{0.450^{\lambda}}$	1.42	0.248	0.039^{σ}	-	-	-	-	-	-
Vastus lateralis	6.19	**0.018***	$\mathbf{0.155^{\mu}}$	2.22	0.117	0.063^{σ}	-	-	-	-	-	-
Gastrocnemius medialis	0.33	0.57	0.009	5.97	**0.004***	$\mathbf{0.146^{\mu}}$	0.810	−0.051	1	−0.075	0.090	0.109
Trapezius descendens	10.75	**0.002***	$\mathbf{0.235^{\mu}}$	0.78	0.460	0.022^{σ}	-	-	-	-	-	-

b	Main effect			Interaction effect			Pairwise comparisons of *EXO* vs. *Control* in two/three *Trunk orientations*					
	Device			Device × Trunk orientation			Lateral/Ipsilateral		Frontal		Contralateral	
Posture	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*p*	*d*	*P*	*d*	*p*	*d*
Thoracic kyphosis	1.27	0.268	0.038^{σ}	0.69	0.411	0.021^{σ}	-	-	-	-	n/a	n/a
Lumbar lordosis	0.47	0.499	0.012	1.87	0.180	0.048^{σ}	-	-	-	-	n/a	n/a
Hip flexion	38.72	**<0.001***	$\mathbf{0.525^{\lambda}}$	3.22	**0.046***	$\mathbf{0.084^{\sigma}}$	**<0.001***	$\mathbf{0.839^{\lambda}}$	**<0.001***	$\mathbf{0.917^{\lambda}}$	**<0.001***	$\mathbf{0.876^{\lambda}}$
Knee flexion	34.39	**<0.001***	$\mathbf{0.496^{\lambda}}$	2.76	0.071	0.073^{σ}	-	-	-	-	-	-

c	Main effect			Interaction effect			Pairwise comparisons of *EXO* vs. *Control* in two *Trunk orientations*			
	Device			Device × Trunk orientation			Lateral		Frontal	
Heart rate	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*p*	*d*	*p*	*d*
20.13	**<0.001***	$\mathbf{0.339^{\lambda}}$	0.22	0.643	0.006	-	-	-	-	

RMS = root mean square; eA = electrical activity.
*Significant *p*-value (α≤0.05); $^{\lambda}$ large effect size (η_p^2 ≥0.26/d≥0.8); $^{\mu}$ medium effect size (η_p^2 ≥0.13/d≥0.5); $^{\sigma}$ small effect size (η_p^2 ≥0.02/d≥0.2).

Combining these findings with the absence of arising perceived discomfort in the shoulders (Steinhilber, Bär, et al., 2020) and legs (Bosch et al., 2016) indicates that the exoskeleton may not have notable bothersome side effects.

Body Posture

Spine posture, especially lumbar flexion, has been related to the musculoskeletal health of the low back area (Adams & Hutton, 1985). Smaller lumbar spine flexion angles tend to reduce the risk of low back disorders due to lower compression forces on the anteroposterior portions of the vertebral discs as mentioned by Ulrey and Fathallah (2013). In this study, using the *EXO* did not result in substantial spine posture changes, which is in line with two previous studies evaluating the Laevo® (Kim et al., 2020; Koopman et al., 2019). Therefore, using the Laevo® may probably not negatively influence the spine posture in work tasks requiring static forward bending trunk postures. Using other BSEs in static bending postures resulted in reduced lumbar flexion (Koopman et al., 2020; Ulrey & Fathallah, 2013) which could have beneficial effects; however, this needs further exploration.

One main function of the Laevo® exoskeleton is the load transfer to the leg and chest pads inducing pressure to these areas (Bosch et al., 2016); the resulting forces depend on the exoskeletons' pivot point inclination angle (Koopman et al., 2019). In this study HF and KF increased when using the *EXO*. Similarly, in a fastening work task requiring a similar trunk forward bent posture (~40°) using the *EXO* resulted in increased HF and KF (Luger, Bär, Seibt, Rieger, & Steinhilber, 2021). In comparison; using the Laevo® resulted in reduced HF in deeper trunk bending angles and systematically increased knee extension in several bending angles (Koopman et al., 2019) or resulted in knee overextension holding a likewise trunk bending angle (Bosch et al., 2016), while using another BSE holding a stooped posture with different weights carried did not result in significant HF and KF changes (Ulrey & Fathallah, 2013). Changes in lower limb posture may be a result of adjusting a comfortable and postural stable posture while performing the particular work task. The various effects on lower limb posture between studies may be caused by differences in support characteristics of the device, but also by variation in task execution (Luger, Bär, Seibt, Rieger, & Steinhilber, 2021). In this study, we explicitly prevented knee overextension by verbal instructions and visual control, wherefore lower limb posture might have been influenced. However, the most similar study results (i.e. increased HF and KF) described by Luger, Bär, Seibt, Rieger, and Steinhilber (2021) occurred when not controlling the lower limb posture as strict as in this investigation. Therefore, it is likely that the increased flexions are not provoked by our strict instructions. Using the *EXO* had a large effect on HF and KF in this investigation; however, the clinical relevance cannot be concluded from changed flexion angles alone, further parameters like joint forces should be monitored therefore in future studies.

It is indicated that using BSEs results in variable postural changes, but generally posture has not been evaluated sufficiently in previous studies. Koopman et al. (2019) showed that only very slight changes in lumbar postures may cause major changes in back muscle activity, which has been most frequently used as indicator for lower back strain in evaluations of exoskeletons (Bär et al., 2021; de Looze et al., 2016), but mainly without additionally monitoring postures. Furthermore, changes in HF angles showed significant interactions with lumbar spine moments (Koopman et al., 2019), which is an indicator for mechanical loading that has been described as a risk factor for LBP (Coenen et al., 2013). From our results, we cannot draw any conclusions of the occurring postural changes being beneficial or disadvantageous in terms of musculoskeletal loading; however, these changes illustrate the need of further investigation in terms of posture and related changes in physical load acting on the musculoskeletal system.

Heart Rate

The slight HR reductions observed in this study (−2 bpm) when using the *EXO* do not seem to be relevant in terms of cardiovascular health, because the average HR ranged 83–85 bpm across the experimental conditions, a range that is far from the endurance limit of physical exertion (105–110 bpm) for physical work shifts (Sammito et al., 2016). Further, the here presented work task may be of too short duration for detecting changes with respect to cardiovascular strain over a complete working shift. Additionally, using a BSE in functional tasks did not significantly influence HR (Luger, Bär, Seibt, Rieger, & Steinhilber, 2021) or in longer lasting simulated working protocols decreased HR without reaching statistical significance (Godwin et al., 2009; Lotz et al., 2009). With the current knowledge we cannot state whether using a BSE has an influence, either positive or negative, on cardiovascular health.

Interaction Effect of Device × Trunk Orientation

Symmetric postures are often hard to realize in various industries, e.g. in bricklaying (Vink & Koningsveld, 1990), and the asymmetric counterpart is associated with an increased risk for developing back disorders (Punnett et al., 1991). This was indicative for investigating the BSE not only in the traditional sagittal plane requiring a symmetric working posture (i.e. frontal trunk orientation) but also in the asymmetric counterparts, trunk rotation to the left and right. An additional reason to investigate *Trunk orientation* with respect to the efficacy of the BSE was that the BSE's support characteristics may be dependent on the interaction between the exoskeleton's or trunk inclination angle and the trunk orientation or rotation. With respect to the primary outcomes, we only found that *Trunk orientation* had a significant interaction effect on hip extensor muscle activity. The post hoc analyses revealed that using the exoskeleton lead to small but statistically significant interaction effects only for the *frontal* and *ipsilateral Trunk orientations* with the most prominent reductions in BF muscle activity in *ipsilateral Trunk orientation*. With respect to the secondary outcomes, a statistically significant interaction with *Trunk orientation* was found for the HF angle showing large effect sizes. Hip flexion increased in all three *Trunk orientations* but most prominent increases in the angle were in the contralateral *Trunk orientation*. Combining these two results does not provide an explanation why the BSE led to more pronounced changes in the one than in the other *Trunk orientation*. However, when comparing the three *Trunk orientations* while wearing the BSE, it seems as if a larger HF angle may result in a lower hip extension muscular load (cf. Table 3). Hip flexion when using the exoskeleton seems to depend on *Trunk orientation* and may be influenced by the amount of support provided by the exoskeleton as has been set by the "smart joint."

Limitations

We have to acknowledge a few study limitations. First, we included a healthy, male study population, aged 18–40 years. This does not reflect the general working population and the effects of using an exoskeleton might differ for groups of workers including all sexes (Kim et al., 2020; Madinei et al., 2020a), including healthy, symptomatic and reintegrating workers, and including aging workers. Second, the Laevo® was only adjustable to a restricted extend, where we for example experienced difficulties in placing the leg pads according to the manufacturer's instructions (i.e., on the upper part of the thighs) in a few smaller subjects. Only two out of the 36 subjects used the S-sized exoskeleton. Further, the exoskeletons structures cannot fully be prevented from shifting when the wearer is moving; however, in this static work task we did not observe any crucial movement of the device. For avoiding a collision with the leg pad the VL electrode was placed more distal on the muscle bellies than recommended. Although the absolute muscle activation level for this muscle might possibly be less representative for the task in single subjects, this does not influence any of our outcomes as comparisons are based on a within subject design. Third, although we used a familiarization session for using the exoskeleton and executing the sorting task on a separate day, a single practice lasting 1 h may not be extensive enough for getting accustomed to the device sufficiently. According to Moyon et al. (2019)

subjects reached a familiarization level four out of seven. Fourth, this experiment included a short sorting task, which does not enable to providing data on muscular fatigue or cumulative strains. Conclusions regarding the long-term use of the BSE in full work-shifts and in various tasks are thus not possible. Fifth, the trunk inclination angle was controlled for and subjects were instructed not to overstretch their knees. Consequently, possible changes in body posture may have been masked in comparison to a freestyle task execution.

CONCLUSION

Using the Laevo® exoskeleton in a short-cyclic assembly task requiring a static forward bent posture did not result in substantial changes of lower back muscle activity, but rather reduced hip extensor muscle activity, which indicated the supportive character of hip extension. We detected increased HF and KF angles but only minor changes in spine posture. *Trunk orientation* had an impact on hip extensor muscle activity and HF angles. However, it remains unclear whether the small effects of using the Laevo® on lower back muscle activity and spinal posture and the small interacting effects of *Trunk orientation* on the hip area might have an impact on musculoskeletal health. Thus, it remains questionable if the exoskeleton has the potential to operate as intervention for back MSDs. The occurrence of changes in posture and physical strain, as well as the inconsistency between several studies indicate that further investigation on this topic is necessary before an application of exoskeletons at work can be recommended. Therefore, we suggest including several work tasks and postures, realistic working scenarios with longer lasting protocols (e.g., work shifts at least), various interrelated parameters (e.g., postures, muscle activity, moments and forces), and conducting long-term studies with populations including all genders and both healthy and symptomatic workers.

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KEY POINTS

- The Laevo® reduced both back and hip extensor muscle activity when working in a 40°-static trunk forward bent posture; however, hip extensor muscle activity reduced to a larger extent.
- Hip and knee flexion increased when using the Laevo®, whereas spine posture remained unchanged.
- There have not been many studies evaluating the body posture in work tasks requiring a static forward bent posture, a clear conclusion about the effects of the Laevo® on working posture therefore is difficult.
- Trunk rotation, that is, task orientation, should be considered as a potential influencing factor for the impact of using the Laevo® on muscle activity and postural angles; hip extensor muscle activity as well as hip flexion was influenced by trunk orientation in this evaluation.
- The appearing changes in muscle activity, posture and heart rate cannot be interpreted to be positive or negative in terms of musculoskeletal health; they rather indicate the need of further investigation including different work tasks and longer protocols.

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SUPPLEMENTAL MATERIAL

The online supplemental material is available with the manuscript on the *HF* website.

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Chapter 4

A passive back exoskeleton supporting symmetric and asymmetric lifting in stoop and squat posture reduces trunk and hip extensor muscle activity and adjusts body posture – A laboratory study.

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A passive back exoskeleton supporting symmetric and asymmetric lifting in stoop and squat posture reduces trunk and hip extensor muscle activity and adjusts body posture – A laboratory study

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A B S T R A C T

The influence of a passive exoskeleton was assessed during repetitive lifting with different lifting styles (squat, stoop) and orientations (frontal/symmetric, lateral/asymmetric) on trunk and hip extensor muscle activity (primary outcomes), abdominal, leg, and shoulder muscle activity, joint kinematics, and heart rate (secondary outcomes). Using the exoskeleton significantly and partially clinically relevant reduced median/peak activity of the erector spinae (≤6%), biceps femoris (≤28%), rectus abdominis (≤6%) and increased median/peak activity of the vastus lateralis (≤69%), trapezius descendens (≤19%), and median knee (≤6%) and hip flexion angles (≤11%). Using the exoskeleton had only limited influence on muscular responses. The findings imply the exoskeleton particularly supports hip extension and requires an adjusted body posture during lifting with different styles and orientations. The potential of using exoskeletons for primary/secondary prevention of musculoskeletal disorders should be investigated in future research including a greater diversity of users in terms of age, gender, health status.

1. Introduction

Although the prevalence of low back pain (LBP) slightly decreased over the past twenty years (Wu et al., 2020), it remains the most common musculoskeletal problem worldwide. For instance, the general prevalence estimates for the U.S. are between 23% (Dick et al., 2020) and 26% (Luckhaupt et al., 2019). Luckhaupt et al. (2019) report the estimated work-relatedness of LBP prevalence to be 23%. Among certain professions, the prevalence of LBP may be as high as 70% for baggage handlers (Bergsten et al., 2015), 72% for manual material handling workers (Muslim and Nussbaum, 2015), 74% for operation room staff (Bin Homaid et al., 2016) and 89% for wind farmers (Jia et al., 2016). Various individual, psychosocial and physical risk factors are associated with work-related back pain, of which the physical risk factors show the strongest association (Dick et al., 2020). Especially lifting intensity or load, lifting frequency, and awkward body postures such as repetitive bending, torso rotation, backward bending and pulling objects are reported with respect to LBP prevalence.

For lifting intensity, odds ratios of LBP prevalence are reported from 1.1 (Coenen et al., 2014) to 1.9 (Dick et al., 2020) for the general working population to 3.8 for wind farmers (Jia et al., 2016). Odds ratios of LBP for lifting frequency vary from 1.1 for the general working population (Coenen et al., 2014) to 2.4 (Stričević and Papez) or 3.6 (Andersen et al., 2019) for nurses. The odds ratio of LBP for awkward postures may be very high, for example 4.5 for nurses who are exposed to trunk rotation during weight-bearing (Bin Homaid et al., 2016). The high odds ratios for these physically demanding occupations emphasize the need for reducing the physical load on the lower back due to lifting and working in awkward body postures.

In recent decades, the application of exoskeletons as workplace intervention for reducing physical demands has rapidly evolved. Exoskeletons are assistive systems worn on the body that act mechanically on the body. In an occupational context, they aim to support functions of the skeletal and locomotor system during physical work (Steinhilber et al., 2020). Currently, most commercially available exoskeletons provide support using passive structures, i.e., springs or other elastic structures. Passive back-supporting exoskeletons showed promising results with respect to a reduced physical load on the lower back during occupational lifting. Objectively measured physical low back load by muscle activity showed reductions mainly during symmetric lifting

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when wearing a passive exoskeleton of 8% (Koopman et al., 2020a), 13% (Baltrusch et al., 2020), 20% (Alemi et al., 2020), and 24% (Abdoli-Eramaki and Stevenson, 2008). However, there are also studies reporting no change in lower back muscle activity when wearing such an exoskeleton (e.g., Baltrusch et al., 2019). In asymmetric lifting, i.e. lifting with trunk rotation, lower back muscle activity also decreased (14%) but to a lesser extent than in symmetric lifting (Alemi et al., 2020). Several studies also measured antagonistic abdominal muscle activity, of which the majority reported no changes (Abdoli-Eramaki and Stevenson, 2008; Baltrusch et al., 2019, 2020), and some reported small but mixed changes when wearing an exoskeleton (Alemi et al., 2020). Subjectively measured physical low back load by local discomfort is reported during lifting by Kozinc et al. (2020), who showed a 43% reduction (i.e., from 2.8 to 1.6 on the CR10 Borg scale).

Some studies have been published investigating the influence of a passive back-supporting exoskeleton on physical load during occupational lifting, of which only a few incorporated trunk rotation in the occupational lifting task. Different lifting styles, i.e., squat and stoop lifting postures, have, to our knowledge, also only been marginally investigated in relation to exoskeletons. Therefore, the current study examined the effect of a passive back-supporting exoskeleton, the Laevo® (more information, see **2. Materials and methods**), during repetitive symmetric and asymmetric lifting in a squat and stoop lifting posture of an 11.6-kg load. We included the following outcome measures: muscle activity, kinematics, and heart rate. The Laevo® is designed to reduce stress in the lower back by supporting the trunk in work activities that require a forward bending posture, realized by transferring the load to the legs. For this reason, we recorded muscle activity of the erector spinae and biceps femoris to be our primary outcomes, and that of the rectus abdominis, vastus lateralis, gastrocnemius medialis and trapezius descendens as well as joint angles and heart rate to be secondary outcomes. We hypothesized that the median and peak muscle activity of the erector spinae and biceps femoris would be reduced when wearing the exoskeleton. The results of this study may contribute to the general knowledge about the possibility of applying passive back-supporting exoskeletons to reduce work-related physical demands that can induce musculoskeletal disorders.

2. Materials and methods

2.1. Sample size and study design

The data presented in this manuscript are part of a larger, explorative, laboratory study (ClinicalTrials.gov, NCT03725982), within which the physiological and biomechanical influences of wearing the Laevo® V2.56 were investigated during four different simulated vocational tasks: a static sorting task, a dynamic lifting task, a set of functional tasks (Luger et al., 2021), and a set of static holding tasks in different forward trunk flexion angles. In this manuscript, only the dynamic lifting task is evaluated in detail.

The study population for the overall study was determined based on the three independent variables task (static sorting vs. dynamic lifting), exoskeleton (with vs. without) and working posture (squat vs. stoop). A selection of combinations from the three independent variables resulted in six different experimental conditions tested (i.e., static-without-stoop, static-with-stoop, dynamic-without-stoop, dynamic-without-squat, dynamic-with-stoop, dynamic-with-squat). We used a standardized Single Williams Latin Square design (Bate and Jones, 2008) for six conditions to prevent first-order carry-over effects and applied its six-fold, resulting in a required sample size of 36 subjects.

The current manuscript focuses on the dynamic lifting task maintaining a within-subject design, within which we investigated an additional independent variable next to exoskeleton and working posture, resulting in twelve different conditions: exoskeleton (with vs. without), working posture or lifting style (squat vs. stoop) and lifting orientation (symmetric vs. asymmetric ipsilateral vs. asymmetric contralateral). A stooped lifting style was included because in several industrial settings, workers do not always have the possibility to bend their knees (e.g., lifting from or into a lattice box). The three lifting orientations were assigned randomly using six possible orders of the three experimental conditions according to a Double Williams Latin Square design (Bate and Jones, 2008). The order of the conditions was assigned randomly to each subject by drawing two lots, one for the exoskeleton/lifting style/task and one for the lifting orientation. An additional lot was drawn to determine which body side of the subject would be prepared for recordings of muscular activity, which was balanced across subjects (i.e., 18 lots for left, 18 lots for right).

2.2. Participants

Thirty-nine male participants (18–40 years old) were recruited to participate in the study. After excluding three participants due to time restrictions (N = 1) or a too high BMI (N = 2), 36 participants were enrolled in the study. The exclusion criteria were a BMI higher than 30 kg/m^2, acute or cardiovascular diseases, physical disability, systemic diseases, or neurological impairments preventing the subjects from performing the lifting task and wearing the exoskeleton. The study population (N = 36) had a mean age of 25.9 years (SD 4.6), weight of 73.5 kg (SD 8.9), height of 178.8 cm (SD 7.3), BMI of 22.9 kg/m^2 (SD 2.1), rest blood pressure of 129/79 mmHg (SD 7/7), and its majority was righthanded (4 left; 32 right). The participants signed an informed consent prior to study participation. The study was designed in accordance with the Declaration of Helsinki and approved by the local Ethics Committee of the University and University Hospital of Tübingen (617/2018BO2).

2.3. Procedure

Before the study was executed, subjects visited the lab 1–5 days before to get a short explanation about the study, read and sign the informed consent form, check for eligibility, and collect basic anthropometric data. During this first 1.5-h visit, subjects were familiarized with both the exoskeleton and the simulated vocational tasks. Additionally, the position with respect to the box on the platform for the dynamic lifting task was individually determined. The position of both feet was marked so that when changing conditions, the same feet position could be maintained. The height of and distance to the platform with the box for the dynamic lifting task were individually adjusted: while the subject was standing upright with minimally bent knees (ensuring the knees were not overstretched) in 70° trunk inclination, the upper arm was orthogonal to the floor and the elbow angle approximately 160°. The second visit lasted ~4 h and comprised the four of vocational tasks as previously listed. Prior to the experiment, the subjects were equipped with the measurement equipment after the skin was shaved and cleaned (Skin Prep Gel, Nuprep®, Aurora, USA), and performed a set of reference contractions and postures for normalization of muscle activity and correction of posture (cf. **2.6.1 Muscular activity**; **2.6.2 Posture, joint angles**; Table 1).

2.4. Dynamic lifting task

The lifting task was performed in two sets of five repetitions, interrupted with a 35-s break. Successive experimental conditions were interspersed with 60-s breaks. The pace of the repetitive lifting task was set at 5s per lift and timed with an acoustic signal. One lifting repetition included the following four movements: (1) pick up a 11.6-kg load (i.e., a 10-kg load placed in a 1.6-kg box [W × D × H of 60 × 40 × 22 cm] with handles on both sides [19 cm]) at approximately 70° trunk inclination (stoop) coming from an upright position; (2) recapture an upright position while holding the load close to the body with flexed elbows; (3) put the load down with the upper body in approximately 70° forward flexion; (4) recapture an upright position without load. The 10-kg load

Table 1
Normalization procedures for the six muscles of which muscle activity was recorded using bipolar surface electromyography.

Muscle	Normalization procedure
ES	Subjects lay prone with the upper body and hips (hip bones) off the bench and the legs fixed with straps, performing *maximal* hip extension against a barrier while keeping the body horizontal and the arms crossed in front of the chest (modified Biering-Sørensen test; Biering-Sørensen, 1984).
BF	Subjects lay prone with 90° hip and knee flexion, feet flexed, keeping the position while a rope with a 7-kg weight hanging over a pulley was attached around the ankle.
RA	Subjects lay supine with the upper body and hips off the bench and the legs fixed with straps, performing 45° hip flexion while holding an additional 10-kg weight and keeping the arms crossed in front of the chest (reverse Biering-Sørensen test; Biering-Sørensen, 1984).
VL	Subjects lay supine with 90° hip and knee flexion, feet flexed, keeping the position while a rope with a 10-kg weight hanging over a pulley was attached around the ankle.
GM	Subject stood upright, performing bilateral, isometric plantar flexion.
TD	Subject stood upright, feet hip-width apart, arms in 90° abduction but slightly in the frontal plane, elbows extended but not overstretched, while holding a 2-kg weight in each hand (Mathiassen et al., 1995).

was chosen based on input we retrieved from the cooperation partners in this project, who handle this load a common in logistics (see **Acknowledgements**). The lifting task was performed without and with exoskeleton in two different lifting styles, i.e., a squat and stoop posture (Fig. 1), and in three different lifting orientations, i.e., symmetrically (frontal orientation) and asymmetrically (45° rotation to left and right lateral).

2.5. Passive exoskeleton

We evaluated a passive exoskeleton (Laevo® V2.56, Laevo B.V., Delft, the Netherlands; 2.8 kg) that supports trunk and hip extension by two laterally arranged semi-rigid bars (torso structures) and two connecting springs (smart joints; see Fig. 2). The torso structures connect a chest pad and a hip belt and are exchangeable to fit different body sizes. The smart joins can be set to different starting support angles (0–45°, 5°-increments) or no support (off). The Laevo® was adjusted to best fit the subject's body composition, whereby the angle support in the smart joints was adjusted to avoid any contact pressure with the chest pad in upright stance. This was controlled by a built-in force sensor in the chest pad (38 × 10 mm; Type KM38-1 kN, ME-Meßsysteme GmbH, Henningsdorf, Germany).

2.6. Measurements

2.6.1. Muscular activity

The electrical activity of six muscles was recorded unilaterally by surface electromyography (EMG) by placing two pre-gelled Ag/AgCl surface electrodes (42 × 24 mm, KendallTM H93SG ECG Electrodes, Covidien, Zaltbommel, the Netherlands) in bipolar configuration (inter-electrode distance 25 mm) on the muscle bellies (Criswell, 2010; Hermens et al., 2000). The following muscles were measured: erector spinae lumbalis (ES at lumbar vertebra L1), biceps femoris (BF), rectus abdominis (RA), vastus lateralis (VL), gastrocnemius medialis (GM) and trapezius descendens (TD). The ground electrode was placed over the cervical vertebrae C7. EMG signals were continuously recorded during the lifting task and during the normalization contractions (see Table 1; Biering-Sørensen, 1984). The procedures included single repetitions of 5-s maximal and 10-s submaximal contractions (see Luger et al. (2021) for an explanation of the choice for maximal or submaximal contraction).

The collected EMG signals were differential amplified, transmitted, filtered (high-pass, 2nd order, −3 dB at 4Hz; low-pass, 11th order, −3 dB at 1,300Hz), sampled (4,096Hz), analyzed and stored (PS12-II, THUMEDI® GmbH & Co. KG, Thum, Germany; physical resolution 24 bit; overall CMRR >98 dB; overall effective sum of noise <0.5 μV RMS; linearity typically ±0.1 dB at 30−1,200Hz). The data were real-time transformed in the frequency domain (1024-point Fast Fourier Transformation using a Bartlett-window with 50% overlap), digitally filtered (high-pass, 11th order, −3 dB at 16Hz) and powerline interferences were removed by an average filter (11th order, −3 dB at 50Hz and its first seven harmonics, bandwidth of 4Hz was replaced by its spectral neighbors). The root-mean-square (RMS) of the electrical activity [μV] was real-time calculated (250-ms moving window with 50% overlap) from the power spectrum and stored synchronously to the raw data. The RMS-values of the BF, VL, RA, GM, and TD were normalized to the median RMS-values of the most stable 5-s period of each submaximal reference voluntary contraction (RVC) and expressed as percent of the electrical activity during the RVC, i.e. reference voluntary electrical activity (%RVE; Mathiassen et al., 1995). The RMS-values of the ES were normalized to the 90th percentile RMS-values of the most stable 3-s period of the maximal voluntary contraction (MVC) and expressed as percent of the electrical activity during the MVC, i.e. maximal voluntary electrical activity (%MVE; Mathiassen et al., 1995). The 10th percentile, 50th percentile (median) and 90th percentile (peak) normalized RMS-values of all muscles were calculated (Jonsson, 1982) for each experimental condition and used for further analysis. Each value reflects the mean of all ten lifts, i.e., both sets of five lifting actions (cf. **2.4 Dynamic lifting task**). Due to the unilateral electrode application we

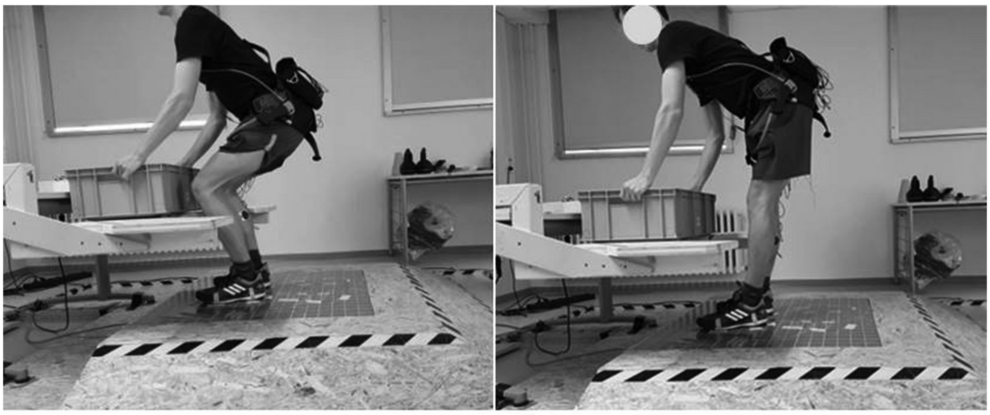

Fig. 1. Simulated dynamic lifting task with exoskeleton applying a squat (left) or stoop (right) lifting technique.

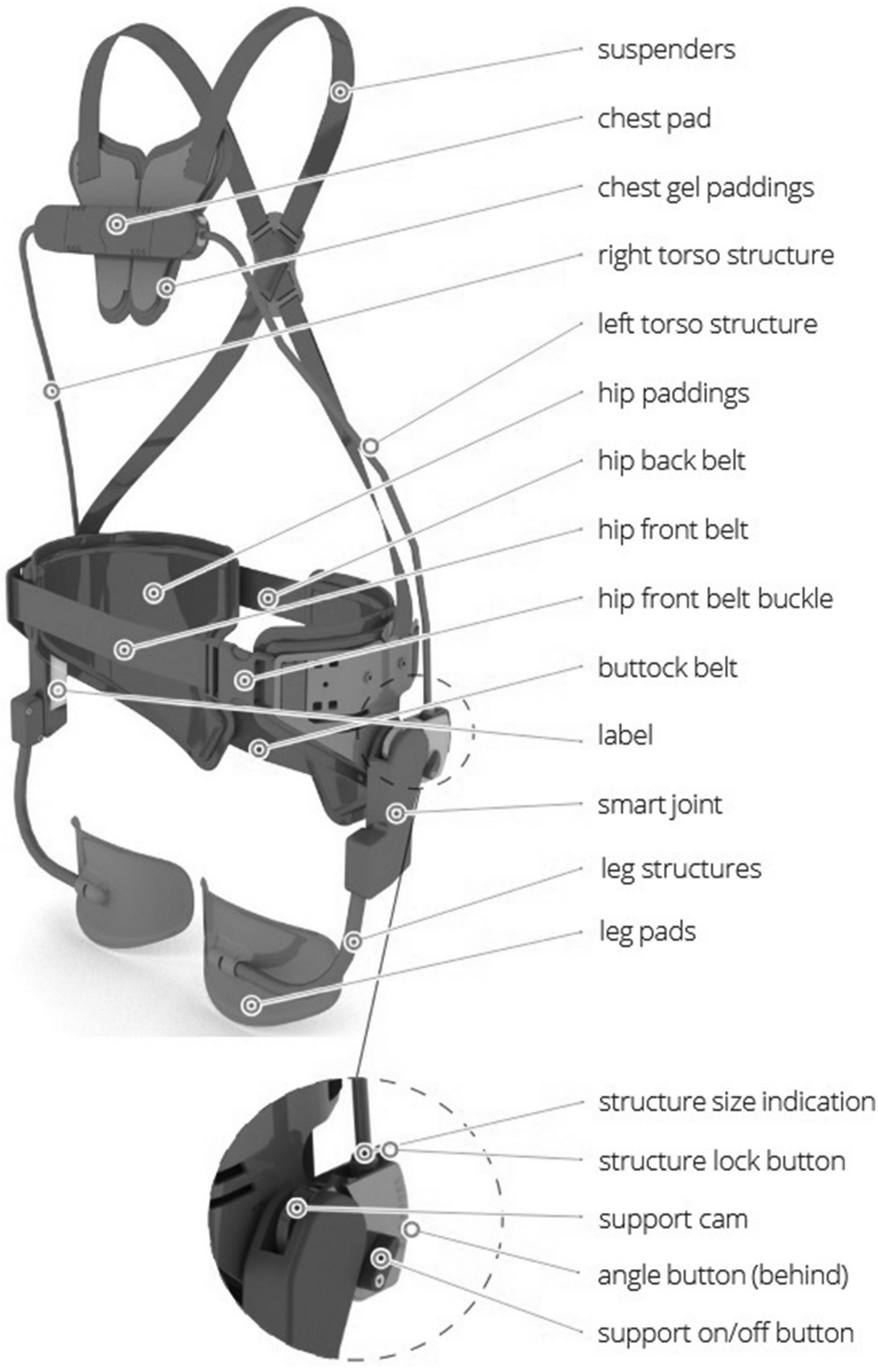

Fig. 2. The passive exoskeleton Laevo® V2.56 (Laevo B.V., Delft, The Netherlands; http://www.laevo.nl/wp-content/uploads/2018/10/2018-07-16-Laevo-Instructions-V2.56-EN.pdf).

refer to frontal, ipsilateral and contralateral for distinguishing between lifting orientations.

2.6.2. Posture, joint angles

Joint inclination angles with respect to the absolute perpendicular (gravitational axis) in the anteroposterior (flexion) and mediolateral (lateral flexion) directions were recorded using two-dimensional gravimetric position sensors (PS12-II; sample rate at 8Hz; resolution 0.1° and 125 ms in time; maximum static error 0.5°; maximum repetition error 0.2°) attached to the skin with double-sided adhesive tape (25 mm×5m, 3M transparent Medical Standard, Top Secret®, Gesellschaft für Haarästhetik mbH, Fürth, Germany). Sensors were placed at thoracic vertebrae T1 and T10, lumbar vertebrae L1 and L5, and the anterior side of the femur and tibia. The position sensors continuously recorded the inclination angles during the lifting task and reference posture. The reference posture included a 5-s recording of the subject standing upright against a wall, while contacting the wall with his heels, back, and buttocks and keeping his head in natural position. The median inclination angles of the most stable 1-s period of the reference posture were subtracted from the experimental recordings. Therefore, all further measures represent angular deviations or differential measures between two sensors with respect to this individual upright standing position.

We calculated five joint angles, i.e., knee flexion (KF), hip flexion (HF), lumbar lordosis (LL), and thoracic kyphosis (TK) (Table 2; Takács et al., 2018). Additionally, we provide results of the trunk inclination (TI), but this was a control measure and not an outcome measure. The minimum, median and maximum values of each joint angle were calculated for each experimental condition and used for further analysis. Each value reflects the mean of all ten lifts, i.e., both sets of five lifting actions (cf. **2.4 Dynamic lifting task**).

2.6.3. Heart rate

The activity of the heart was recorded using electrocardiography (ECG) by two pre-gelled Ag/AgCl surface electrodes (42 × 24 mm, KendallTM H93SG ECG Electrodes, Covidien, Zaltbommel, the Netherlands) placed ~5 cm cranial and ~3 cm left-lateral from the distal end of the sternum and over the anterior to midaxillary line at the fifth left rib. ECG was continuously recorded during the dynamic lifting task, sampled at 1,000Hz and stored (PS12-II). From the ECG signals, the median heart rate (HR) was calculated for each experimental condition and used for further analysis.

2.7. Statistical analysis

After visual inspection of the histograms and interpretation of skewness and kurtosis values, some parameters approached a normal distribution. The muscle activity levels of all muscles showed positively skewed data and were log-transformed (LOG10) prior to statistical analyses, but the back-transformed summary outcomes are reported as least squares means in tables and figures.

We used repeated-measures analyses of variances (RM-ANOVA) to assess the effect of the fixed factors *exoskeleton*, *exoskeleton* × *lifting style*, *exoskeleton* × *lifting orientation*, and *exoskeleton* × *lifting style* × *lifting orientation* on the outcome parameters of muscle activity, posture, and heart rate. The factor *lifting orientation* had three levels for all parameters except for lumbar lordosis, thoracic kyphosis, and heart rate, where it was reduced to two levels, i.e., frontal vs. lateral. In case of significant fixed factors with more than two levels, we applied Tukey HSD for post hoc pairwise comparisons. For each RM-ANOVA, *F*-value, *p*-value and effect size partial eta squared (η_p^2) using the *F* ratios strategy (Bakeman, 2005) are reported. For post hoc pairwise comparisons, *T*-value, *p*-value and effect size Cohen's *d* using the pooled standard deviation strategy (pooled standard deviated strategy; Cohen, 1988) are reported. Effects sizes are interpreted according to Cohen (1988) as small ($\eta_p^2 \geq 0.02$; $d \geq 0.2$), medium ($\eta_p^2 \geq 0.13$; $d \geq 0.5$), or large ($\eta_p^2 \geq 0.26$; $d \geq 0.8$).

Statistical analyses were performed using JMP® (Version 14.2.0, SAS Inc., Carry, NC, USA) and statistical significance was accepted at $\alpha \leq 0.05$. We considered muscle activity levels of the erector spinae (ES) and biceps femoris (BF) to be the primary outcomes and all other parameters to be secondary outcomes.

3. Results

The normalized EMG values and statistical results of ES and BF are summarized in Table A1 and Table A2 in **Appendix A**. Normalized EMG values and statistical results of RA, VL, GM, and TD are summarized in Table B1 and Table B2 in **Appendix B**. The values and statistical results of KF, HF, LL, TK, and HR are summarized in Table C1 in and Table C2 in **Appendix C**.

3.1. Muscular activity

3.1.1. Primary outcomes – erector spinae and biceps femoris

Exoskeleton had significant main and interaction effects on ES. Wearing the Laevo® resulted in an average 8.7% increase (0.3%MVE; $\eta_p^2 = 0.16$) in ES_{10}, −2.3% decrease (−0.4%MVE; $\eta_p^2 = 0.16$) in ES_{50} (Fig. 3), and −4.2% decrease (−1.3%MVE; $\eta_p^2 = 0.40$) in ES_{90}. *Exoskeleton* × *Lifting style* had a significant effect on ES_{90} (η_p^2=0.27; Fig. 4). In squat posture, wearing the exoskeleton resulted in reduced ES_{90} ($d = -0.21$). *Exoskeleton* × *Lifting orientation* had a significant effect on ES_{10} (η_p^2=0.14; Fig. 5) and ES_{50} (η_p^2=0.18). In frontal orientation, ES_{10} was higher with exoskeleton compared to without exoskeleton ($d = 0.23$). In contralateral orientation, ES_{50} was lower with exoskeleton than without exoskeleton ($d = -0.14$). *Exoskeleton* × *Lifting style* × *Lifting orientation* had a significant effect on ES_{90} (η_p^2=0.20). In squat posture, wearing the exoskeleton resulted in reduced ES_{90} for all three orientations ($-0.17 < d < -0.26$).

Exoskeleton had a significant main effect on BF. Wearing the Laevo® resulted in an average −18.6% decrease (−1.2%RVE; $\eta_p^2 = 0.36$) in BF_{10}, −17.1% decrease (−4.9%RVE; $\eta_p^2 = 0.38$) in BF_{50} (Fig. 3), and −8.1% decrease (−5.2%RVE; $\eta_p^2 = 0.25$) in BF_{90}.

3.1.2. Secondary outcomes – rectus abdominis, vastus lateralis, gastrocnemius medialis and trapezius descendens

Exoskeleton had significant main and interaction effects on RA. Wearing the exoskeleton resulted in an average −3.2% decrease (−0.04%RVE; $\eta_p^2 = 0.14$) in RA_{10}, −4.7% decrease (−0.2%RVE; $\eta_p^2 = 0.36$) in RA_{50} (Fig. 3), and −2.9% decrease (−0.2%RVE; $\eta_p^2 = 0.16$) in RA_{90}. *Exoskeleton* × *Lifting style* had a significant effect on RA_{10} (η_p^2=0.13); in squat posture, RA_{10} reduced ($d = -0.07$) when wearing the exoskeleton. *Exoskeleton* × *Lifting style* × *Lifting orientation* had a significant effect on RA_{10} (η_p^2=0.13); but the post hoc test showed no significant differences in wearing the exoskeleton.

Exoskeleton had significant interaction effects on VL. *Exoskeleton* × *Lifting style* had a significant effect on VL_{50} (η_p^2=0.12) and VL_{90} (η_p^2=0.12); only for VL_{50}, post hoc tests showed that in squat posture, activity reduced ($d = -0.26$) when wearing the exoskeleton. *Exoskeleton* × *Lifting style* × *Lifting orientation* had a significant effect on VL_{10} (η_p^2=0.11), VL_{50} (η_p^2=0.10) and VL_{90} (η_p^2=0.13); only for VL_{50}, post hoc

Table 2
Calculation and interpretation of the five joint angles.

Joint angle	Calculation	Interpretation
Trunk inclination	Anteroposterior inclination angle of thoracic vertebrae T10	0° reflects full extension (upright stance) and 180° full flexion
Hip flexion	Difference value between the anteroposterior inclination angles of lumbar vertebrae L5 and femur	0° reflects full extension (upright stance) and 180° full flexion
Knee flexion	Difference value between the anteroposterior inclination angles of femur and tibia	0° reflects full extension (straight legs) and 180° full flexion
Thoracic kyphosis	Anteroposterior inclination angles or tangential lines (Cobb method) over the processus spinosi of thoracic vertebrae T1 and lumbar vertebrae L1 according to the Cobb angle boundaries (Takács et al., 2018)	0° reflects curvature closer to upright stance and a positive value means the upper back is curving more compared to upright stance
Lumbar lordosis	Anteroposterior inclination angles or tangential lines (Cobb method) over the processus spinosi of lumbar vertebrae L1 and lumbar vertebrae L5 according to the Cobb angle boundaries (Takács et al., 2018)	0° reflects curvature closer to upright stance and a positive value for lumbar lordosis means the lower back is curving (opposite of the lordosis) compared to upright stance

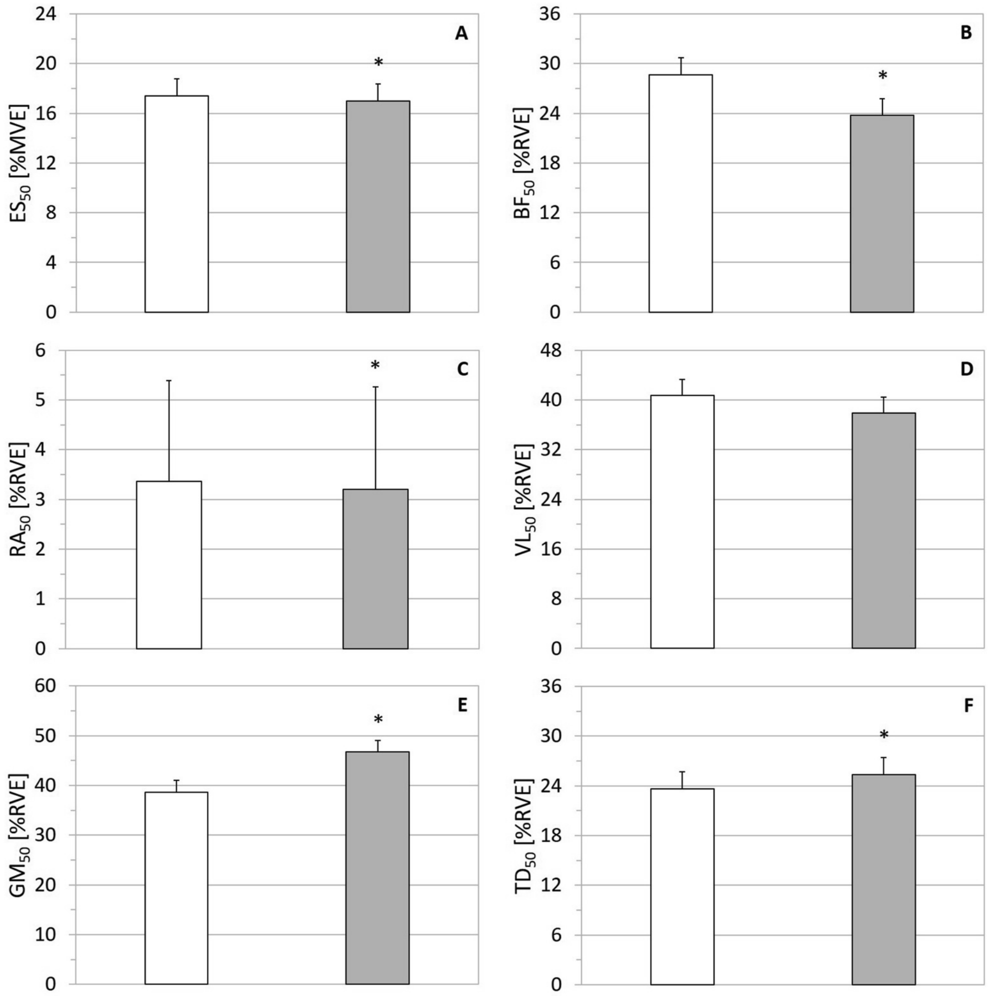

Fig. 3. Exoskeleton main effect on normalized median muscle activity of the erector spinae (ES50; A), biceps femoris (BF_{50}; B), rectus abdominis (RA_{50}; C), vastus lateralis (VL_{50}; D), gastrocnemius medialis (GM_{50}; E) and trapezius descendens (TD_{50}; F). White bars represent without exoskeleton, grey bars represent with exoskeleton. Note that * indicates a significant difference from the control condition (i.e., no exoskeleton).

Fig. 4. *Exoskeleton* × *Lifting Style* interaction effect on normalized peak erector spinae muscle activity (ES_{90}). White bars represent without exoskeleton, grey bars represent with exoskeleton. Note that * indicates a significant post hoc difference from the control condition (i.e., no exoskeleton).

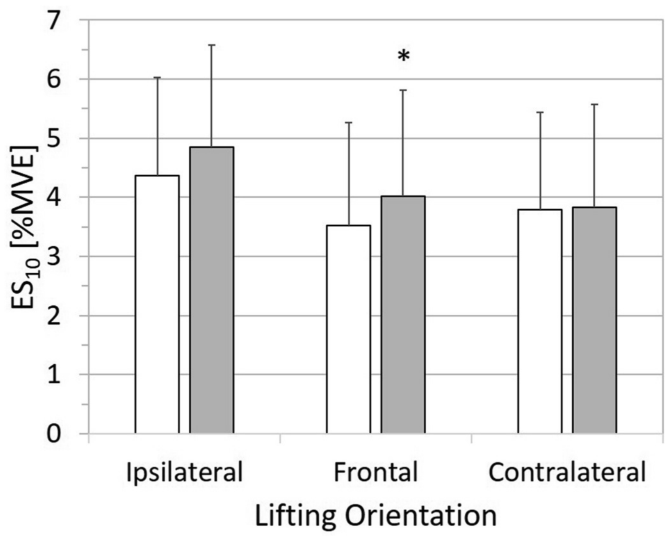

Fig. 5. *Exoskeleton* × *Lifting Orientation* interaction effect on normalized static erector spinae muscle activity (ES_{10}). White bars represent without exoskeleton, grey bars represent with exoskeleton. Note that * indicates a significant post hoc difference from the control condition (i.e., no exoskeleton).

tests showed that in squat posture with contralateral orientation, activity decreased ($d = -0.38$) when wearing the exoskeleton.

Exoskeleton had significant main and interaction effects on GM. Wearing the exoskeleton resulted in an average 27.0% increase (2.2% RVE; $\eta_p^2 = 0.61$) in GM_{10}, 21.1% increase (8.1%RVE; $\eta_p^2 = 0.51$) in GM_{50} (Figs. 3), and 11.4% increase (10.5%RVE; $\eta_p^2 = 0.52$) in GM_{90}. *Exoskeleton* × *Lifting orientation* had a significant effect on GM_{50} (η_p^2=0.21) and GM_{90} (η_p^2=0.13); in both frontal and contralateral orientations, GM_{50} (d = 0.17–0.43) and GM_{90} (d = 0.12–0.29) increased when wearing the exoskeleton. *Exoskeleton* × *Lifting style* × *Lifting orientation* had a significant effect on GM_{90} (η_p^2=0.15); wearing the exoskeleton increased GM_{90} in squat posture with frontal and contralateral orientation (d = 0.21–0.22) and in stoop posture with contralateral orientation (d = 0.41).

Exoskeleton had significant main and interaction effects on TD. Wearing the exoskeleton resulted in an average 12.4% increase (0.4% RVE; $\eta_p^2 = 0.27$) in TD_{10} and −7.4% increase (1.8%RVE; $\eta_p^2 = 0.12$) in TD_{50} (Fig. 3). *Exoskeleton* × *Lifting style* had a significant effect on TD_{90} (η_p^2=0.14); but post hoc tests showed no significant differences when wearing the exoskeleton. *Exoskeleton* × *Lifting orientation* had a significant effect on TD_{50} (η_p^2=0.14); in ipsilateral orientation, TD_{50} increased when wearing the exoskeleton (d = 0.22). *Exoskeleton* × *Lifting style* × *Lifting orientation* had a significant effect on TD_{50} (η_p^2=0.10); wearing the exoskeleton increased TD_{50} in stoop posture with ipsilateral orientation (d = 0.31).

3.2. Posture, joint angles

Exoskeleton had significant main and interaction effects on knee flexion, hip flexion, lumbar lordosis, and thoracic kyphosis. Wearing the exoskeleton resulted in an average 3.0° increase (>100%; $\eta_p^2 = 0.59$) in KF_{MIN}, 22.9% increase (4.9°; $\eta_p^2 = 0.61$) in KF_{50}, and 4.6% increase (2.2°; $\eta_p^2 = 0.18$) in KF_{MAX}. *Exoskeleton* × *Lifting style* had a significant effect on KF_{50} (η_p^2=0.26) and KF_{MAX} (η_p^2=0.56); wearing the exoskeleton in stoop posture resulted in increased KF_{50} and KF_{MAX} (d = 0.54–0.72), and in squat posture in increased KF_{50} (d = 0.36; see Fig. 6). *Exoskeleton* × *Lifting orientation* had a significant effect on KF_{MIN} (η_p^2=0.09) and KF_{MAX} (η_p^2=0.10); wearing the exoskeleton decreased KF_{MAX} in contralateral orientation (d = 0.12) but increased KF_{MIN} in all three orientations (d = 0.41–0.59). *Exoskeleton* × *Lifting style* × *Lifting orientation* had a significant effect on KF_{50} (η_p^2=0.12) and KF_{MAX} (η_p^2=0.09); wearing the exoskeleton increased KF_{MAX} in a stoop posture with any orientation (d = 0.44–0.69) and increased KF_{50} in all but in squat posture with contralateral orientation (d = 0.35–0.84).

Wearing the exoskeleton resulted in an average 3.3° increase in HF_{MIN} (>100%; $\eta_p^2 = 0.73$), 20.4% increase (6.3°; $\eta_p^2 = 0.69$) in HF_{50}, and 3.9% increase (2.8°; $\eta_p^2 = 0.25$) in HF_{MAX}. *Exoskeleton* × *Lifting style* had a significant effect on HF_{50} (η_p^2=0.45; Fig. 6) and HF_{MAX} (η_p^2=0.52); wearing the exoskeleton in stoop posture resulted in increased HF_{50} (d = 0.91) and HF_{MAX} (d = 0.52) and in squat posture in increased HF_{50} (d = 0.54).

Wearing the exoskeleton resulted in an average 10.0% increase (2.1°; $\eta_p^2 = 0.27$) in LL_{MAX}. *Exoskeleton* × *Lifting orientation* had a significant effect on LL_{MAX} (η_p^2=0.13); in both frontal and ipsilateral orientations (d = 0.18–0.26), wearing the exoskeleton increased LL_{MAX}.

Wearing the exoskeleton resulted in an average 0.3% increase (0.02°; $\eta_p^2 = 0.13$) in TK_{50}, and −13.3% decrease (−1.9°; $\eta_p^2 = 0.37$) in TK_{MAX}. *Exoskeleton* × *Lifting style* had a significant effect on TK_{MIN} (η_p^2=0.13), TK_{50} (η_p^2=0.24) and TK_{MAX} (η_p^2=0.31); wearing the exoskeleton resulted in stoop posture in decreased TK_{50} ($d = -0.08$) and TF_{90} ($d = -0.42$) and in squat posture in increased TK_{10} (d = 0.18). *Exoskeleton* × *Lifting orientation* had a significant effect on TK_{MAX} (η_p^2=0.17); wearing the exoskeleton resulted in decreased TK_{MAX} both in frontal and lateral orientations ($-0.14 < d < -0.26$).

3.3. Heart rate

Exoskeleton had a significant main effect on the heart rate, with an average reduction of −1.5bpm (η_p^2=0.40) when wearing the exoskeleton compared to not wearing the exoskeleton.

4. Discussion

4.1. Muscle activity of trunk and hip extensor muscles

Using the exoskeleton resulted in ~9% statistically significant increased 10th percentile trunk extensor activity (i.e., ~0.3%MVE). Reason for this increased 10th percentile level may be that the exoskeleton does not provide a sufficient facilitation or relaxation, meaning that parts of the trunk extensors stay more or less activated during the complete lifting and lowering process. Using the exoskeleton also resulted in slightly but significantly reduced median and peak trunk extensor activity of 2% (0.4%MVE) and 4% (1.3%MVE), respectively. These findings are much smaller than reported in other studies, with magnitudes in mean activity of 8% (von Glinski et al., 2019), 14% (3% MVE; Baltrusch et al., 2020), and 20% (7%MVE; Yin et al., 2019) and in peak activity of 8% (6%MVE; Koopman et al., 2020a), 10% (4%MVE; Madinei et al., 2020a), and 24% (4%MVE; Lazzaroni et al., 2019). A potential reason for these differences in magnitude may be the overall posture of the participants during the lifting task; when the trunk inclination angle increases, it is more likely that the exoskeleton reduces

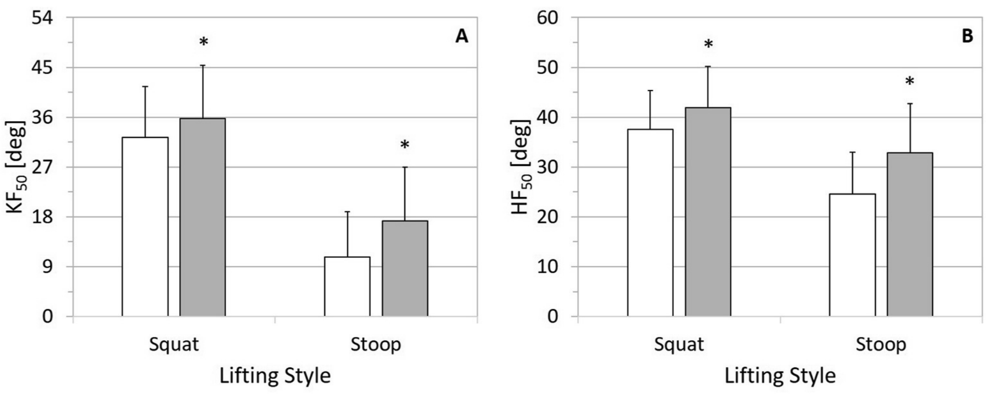

Fig. 6. Exoskeleton × Lifting Style interaction effect on median knee flexion angle (KF50; A) and median hip flexion angle (HF50; B). White bars represent without exoskeleton, grey bars represent with exoskeleton. Note that * indicates a significant post hoc difference from the control condition (i.e., no exoskeleton).

trunk extensor activity due to a larger assistive torque provided by the back-supporting exoskeleton (Koopman et al., 2019; Madinei et al., 2020b). For example, Bosch et al. (2016) reported an increased trunk inclination of 15% (~4.9°) and a concomitant decreased mean trunk extensor muscle activity of 38% (~3.5%MVE). On the contrary, this study observed that lumbar lordosis increased by 10% (~0.9°) and trunk inclination (calculated post-hoc) increased by 7% (~1.9°), with the result that median trunk extensor activity reduced by only 2% (~0.4% MVE). An additional reason may be the varying amount and mode of support provided by the different back-supporting exoskeletons evaluated in the studies, which resulted in different trunk-inclination vs. supporting-moment relations.

Although reduced mean and peak muscular loads in the lower back were not as pronounced as observed in other studies, the influence of using the exoskeleton on hip extensor activity, on the contrary, was much larger. We observed reductions of 8–17% (5%RVE) in median and peak hip extensor activity, which confirms previous studies, where reductions of 25% mean activity (5%MVE; Huysamen et al., 2018) and 17% peak activity (8%MVE; Ulrey and Fathallah, 2013) were reported. The fact that the exoskeleton had a larger effect on hip extension than on trunk extension, as was also the case in the study of Ulrey and Fathallah (2013), may be due to both the Laevo® and Bending Non-Demand Return exoskeleton (BNDR) creating a hip extensor moment. Therefore, both exoskeletons may support hip extensors while back extensors may not be supported that much. Consequence, this may be a reason why the current results show that the biceps femoris is supported but the erector spinae not that much.

Previous studies reported that reductions of trunk extensor activity due to using an exoskeleton are more pronounced in symmetric compared to asymmetric lifting orientations that require some trunk rotation (Alemi et al., 2020; Madinei et al., 2020a). In the present study, no clear effects have been found between the different symmetrical and asymmetrical lifting orientations with respect to trunk and hip extensors. Differences in lifting style, i.e., squat versus stoop, were, however, more pronounced, albeit only significant in squatting. Using the exoskeleton in squat posture resulted in a ~7% reduced peak trunk extensor activity, i.e., from ~33%MVE without to ~31%MVE with exoskeleton. This agrees with previous work (Alemi et al., 2019; Koopman et al., 2020b), within which reduced peak trunk extensor loads of as high as 32% (17%MVE) and 19% (24%MVE) were reported with exoskeleton, respectively. However, both studies also reported significantly reduced peak activity in stoop lifting posture of 25–28% (12–35%MVE), which was only 2% (0.6%MVE, i.e., from ~31.1 to ~30.5%MVE) in the current study and not statistically significant. The current results suggest that a squat lifting style may increase the exoskeletons effectiveness compared to a stoop lifting style. A potential reason could be the increased hip flexion angle, which was larger in squatting than in stooping and resulted in a substantial lumbar EMG reduction.

4.2. Muscle activity of abdominal, leg and shoulder muscles

The load-transfer-mechanism of back-supporting exoskeletons may increase the antagonistic abdominal muscle load for increasing trunk stiffness and stabilization (Granata and Orishimo, 2001; Stokes et al., 2011) and make the exoskeleton effective in reducing the load on trunk and, potentially, hip extensors (Alemi et al., 2019; Madinei et al., 2020b). However, this strategy as observed by several studies (Alemi et al., 2019; Baltrusch et al., 2019) may be at the expense of increased spinal compression (Gardner-Morse and Stokes, 1998; Granata et al., 2005; Vera-Garcia et al., 2006). However, the current study as well as some other studies actually reported slightly decreased abdominal muscle activity (Huysamen et al., 2018; Koopman et al., 2019; Ulrey and Fathallah, 2013). This requires more research, investigating whether antagonistic activity may be influenced by using an exoskeleton depending on the task performed and the exoskeleton's working mechanism.

In line with previous studies, wearing and using the exoskeleton did not have a big influence on both the shoulder muscles (Alemi et al., 2019; Frost et al., 2009; Madinei et al., 2020a) and knee extensor muscles (Alemi et al., 2020; Baltrusch et al., 2019). However, median gastrocnemius medialis muscle activity in the current study showed to significantly increase by about 21% (8%RVE). This finding can be due to the slightly changed working posture, particularly respect to the slightly increased median knee and hip flexion angles (c.f. **4.3 Kinematics**).

4.3. Kinematics

Using the exoskeleton influenced the posture to some extent. Minimal, median, and maximal knee flexion increased by 3.0° (>100%), 4.9° (22.9%), and maximal knee flexion increased by 2.2° (4.6%), respectively, when using the exoskeleton. This was observed with a concomitant increased minimal, median, and maximal hip flexion of 5.2° (>100%), 3.4° (10.9%), and 4.2° (5.8%), respectively. Changes in the same order of magnitude were observed by studies that evaluated a similar lifting task (Baltrusch et al., 2020; Madinei et al., 2020a; Ulrey and Fathallah, 2013) and may imply back-supporting exoskeletons are more effective when both flexion angles slightly increase to better activate the passive structures that transfer the load on the lower back to the legs. Furthermore, with respect to the interaction *Exoskeleton × Lifting style*, our results indicate a 11.0% increased maximal hip flexion angle (6.7°) with exoskeleton in a stoop lifting style. This trend agrees with Ulrey and Fathallah (2013), who observed it increased by 10.2% (6.9°). However, the different relative increases may be due to the spring-characteristic curve and the transmission of the spring-force into a torque by the spring-joint, implying the BNDR (Ulrey and Fathallah, 2013) may require a stronger hip posture adaptation.

Using the exoskeleton did not lead to any impairments in spinal posture. Although significant effects of using the exoskeleton were found on lumbar lordosis and thoracic kyphosis, these reflected minor differences up to 2.1° for peak spinal angles. This is in line with previous study results on repetitive lifting, where differences were either not significant (Abdoli-Eramaki et al., 2006; Baltrusch et al., 2020; Frost et al., 2009; Madinei et al., 2020a) or small but significant (Ulrey and Fathallah, 2013) in the range 2.2–5.4°. The clinical relevance of exoskeleton-induced changes in spinal posture remains unknown yet and should be addressed by future research.

4.4. Cardiovascular response

Using the exoskeleton in repetitive lifting resulted in a slightly reduced heart rate response of 1.5bpm (1.6%), although this change is not relevant. Godwin et al. (2009) and Lotz et al. (2009) found a 3% and 10% reduced heart rate response after 45 min repetitive lifting when using the exoskeleton, which did not reach significance. With the current results, we cannot state whether using a back-supporting exoskeleton during lifting may have beneficial effects on the cardiovascular response and physical strain of the wearer; however, we emphasize that the tasks investigated in the current study and in the other two studies (Godwin et al., 2009; Lotz et al., 2009) are of relatively short duration not reflecting a full work shift of, e.g., 8 h. Consequently, the heart rate in none of the studies reached the so-called endurance limit of physical exertion that ranges between 105 and 110 bpm (Sammito et al., 2016).

4.5. Clinical relevance of the findings

The interpretation of whether exoskeleton-induced changes in physiological parameters are clinically relevant is still difficult at this stage. Although there are approaches and attempts, e.g., to interpret the level of EMG signals (Jonsson, 1978), the postures adopted or joint angles (Bleyer et al., 2008) or changes in heart rate (Sammito et al., 2016), these do not yet show sufficiently high validity. On the one hand, an increase in 10th percentile trunk extensor muscle activity when using the exoskeleton could be accompanied by an increase in the risk for musculoskeletal disorders induced by sustained muscle activation leading to type I motor unit overloading (Westgaard, 1999). On the other hand, a decrease in median and peak muscle activity may be beneficial in preventing musculoskeletal disorders (Jonsson, 1978). Besides the high effort in developing and optimizing exoskeletons, future research on how to interpret physiological parameters is a central requirement to evaluate whether an exoskeleton induces clinically relevant effects or not. Alternatively, long-term studies are necessary to gather evidence whether exoskeletons may help in reducing the prevalence of work-related musculoskeletal disorders; however, this is currently not possible because the various exoskeletons are still undergoing strong development and improvement.

4.6. Study limitations

Several limitations should be noted for the current study. First, the study sample was young (range 19–38 years) and included males only. This does not cover the full range of the working age population and caution is required in generalizing the current results for older and female workers. Second, repetitive lifting with various lifting styles and orientations was simulated under highly controlled laboratory conditions. This does not reflect the actual work environment, meaning that feasibility studies and randomized-controlled studies are necessary to provide more insights into the effectiveness of the current and other back-supporting exoskeletons in the field. Third, we focused on the acute effects of using the Laevo exoskeleton and restricted our evaluation to physiological parameters. It remains unclear whether the here reported results can be generalized to longer periods and how using the Laevo exoskeleton and other exoskeletons may influence subjective and social parameters, e.g., discomfort and acceptability. Fourth, all participants underwent only a brief training session on the day prior to the experiment, which may have been a too limited familiarization period for proper use of the exoskeleton.

5. Conclusions

Physically demanding occupations exposing workers to repetitive lifting and working in awkward body postures are identified with high odds ratios for the prevalence of LBP. Back-supporting exoskeletons seem to be a promising intervention to prevent (primary) or reduce (secondary) the prevalence of LBP. We evaluated the effect of a passive exoskeleton on muscle activity, kinematics, and heart rate during repetitive symmetric and asymmetric lifting in squat and stoop posture. Hip extensor activity decreased to a larger extent (up to 28%, i.e., 15% RVE) than trunk extensor activity (up to 6%, i.e., 2%MVE), which implies the exoskeleton also induces a hip extensor moment. Changes in other muscles were not substantial. Joint kinematics, however, showed small changes in knee flexion and hip flexion that may imply wearers have to adjust their working posture when wearing the exoskeleton. We recommend future research to better determine the task specificity of deploying back-supporting exoskeletons and the generalizability of exoskeletons (e.g., field studies) on physiological, biomechanical, and subjective outcomes across different users (e.g., age, gender, LBP-status).

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A, B, C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apergo.2021.103530.

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Chapter 5

Effects of a passive back-support exoskeleton on knee joint loading during simulated static sorting and dynamic lifting tasks.

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Effects of a Passive Back-Support Exoskeleton on Knee Joint Loading during Simulated Static Sorting and Dynamic Lifting Tasks

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Abstract: Due to the load shifting mechanism of many back-support exoskeletons (BSEs), this study evaluated possible side effects of using a BSE on knee joint loading. Twenty-nine subjects (25.9 (±4.4) years, 179.0 (±6.5) cm; 73.6 (±9.4) kg) performed simulated static sorting and dynamic lifting tasks, including stoop and squat styles and different trunk rotation postures. Ground reaction force, body posture and the force between the chest and the BSE's contact interface were recorded using a force plate, two-dimensional gravimetric position sensors, and a built-in force sensor of the BSE, respectively. Using these parameters and the subject's anthropometry, median and 90th percentile horizontal (HOR_{50}, HOR_{90}) and vertical ($VERT_{50}$, $VERT_{90}$) tibiofemoral forces were calculated via a self-developed inverse quasi-static biomechanical model. BSE use had a variable effect on HOR_{50} dependent on the working task and body posture. Generally, $VERT_{50}$ increased without significant interaction effects with posture or task. HOR_{90} and $VERT_{90}$ were not affected by using the BSE. In conclusion, utilizing the investigated exoskeleton is likely to induce side effects in terms of changed knee joint loading. This may depend on the applied working task and the user's body posture. The role of these changes in the context of a negative contribution to work-related cumulative knee exposures should be addressed by future research.

Keywords: knee force; tibiofemoral force; side effects; assistive device; asymmetric lifting; load shift; forward bent posture

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1. Introduction

Musculoskeletal disorders (MSD), especially in the back, remain the most common health problem affecting workers in the European Union [1] and the United States [2]. Twelve-month prevalence rates of 58% for the occurrence of general MSD [1] and of 25–43% for the back area have been reported [1,2]. Musculoskeletal back pain has been found to be strongly associated to physical risk factors, especially heavy lifting in the workplace and cumulative low back load. Therefore, intervention strategies for physically demanding work incorporating these risk factors need to remain a focus [2,3].

To support workers in their daily work routines, the use of exoskeletons has become a focus area. "Exoskeletons are assistive systems worn on the body that act mechanically on the body. In an occupational context, they aim to support functions of the skeletal and locomotor system during physical work" [4] (p. 3), by transferring forces from exposed body regions to other body sites [5]. Currently, one of the main debates about the use of exoskeletons is whether or not they are effective in preventing work-related MSD [4].

Recently, a growing number of studies have focused on biomechanical, physiological, and subjective stress and strain parameters for determining the impact of using exoskeletons on the musculoskeletal system during occupational tasks [6]. Passive back-support exoskeletons (BSEs) were shown to potentially reduce physical strain in the supported body area in experiments including dynamic tasks such as lifting [7–11] and in tasks with a static forward bent posture [12–16]. Describing the short-term influence of exoskeletons on physical stress and strain parameters in the supported body area is one important step toward identifying potential strategies for relieving these specific musculoskeletal structures in the wearer.

However, the nature of many exoskeletons is shifting the mechanical load from one area to a different area or areas of the body [5], which raises concerns about excessive biomechanical stresses on these other areas [4,17]. In this context, potential side effects of using BSEs have been examined using parameters such as muscle activity and perceived discomfort outside the target region [10–12,18–23]. With respect to side effects, findings for strain parameters in the legs, i.e., mean muscle activity and perceived discomfort have been inconsistent. Some studies report decreases [12,20–22], others report increases [10,11,18–20], or no statistically significant changes [10–12,18,19,23,24]. The ambiguous findings of the available studies and the fact that only few focused extensively on possible side effects in the leg region of using a BSE show that it is unclear whether and how using a BSE affects the musculoskeletal system of the lower limb [6].

To ensure the safe application of BSEs, including the aim of promoting workers' health in physically demanding work, it is imperative to further investigate potential side effects (i.e., potential adverse consequences) of their use. An evaluation of biomechanical joint loading might also give more insight into load transfers or load shifts to other (i.e., non-supported or non-targeted) body areas caused by using a BSE [6,25]. Although the back, shoulder, and neck are much more commonly affected by MSD than the knee, Govaerts et al. (2021) reported a 33% overall prevalence of work-related MSD in the knee among industrial workers [26]. Moreover, there is reasonable evidence that knee disorders are related to physical work exposures partially similar to those reported for back pain, including awkward postures, lifting, and task repetition [1,27]. To the authors' knowledge, so far there has been no published study focusing on the mechanical loading of lower limb joints, particularly the knees, when using a BSE. Hence, the aim of this study was to evaluate the horizontal (anteroposterior) and vertical forces acting on the tibiofemoral joints when using a BSE (Laevo®, Delft, The Netherlands) during simulated industrial work tasks. For this purpose, a self-developed two-dimensional inverse quasi-static biomechanical model was used. We hypothesized that the horizontal and vertical median and 90th percentile tibiofemoral forces increase when using the Laevo® exoskeleton.

2. Materials and Methods

2.1. Sample Size and Study Design

This manuscript comprises one section of a broader, exploratory laboratory experiment, evaluating the effects of the Laevo® V2.56 exoskeleton on physiological and biomechanical parameters using a within-subject-design [28] (registered at ClinicalTrials.gov, NCT03725982). A Single Williams Latin Square design [29] for six conditions ((1) *Exoskeleton*: Laevo® exoskeleton (*EXO*) vs. *Control*; (2) *Task*: *Static* vs. *Dynamic*; (3) *Lifting style*: *Stoop* vs. *Squat*) was used to determine the sample size of 36 and to randomize the order of the main experimental tasks in this study. In addition, a Double Williams Latin Square design [29] was applied to randomize three *Trunk orientation* conditions for the tasks. The order of randomization resulted from drawing lots.

2.2. Participants

Thirty-nine male subjects were recruited to participate in the study, of which three subjects had to be excluded due to time restrictions (N = 1) or not meeting the BMI criterion (N = 2). Thirty-six healthy males completed the experiment, of which data from 29 subjects (mean age 25.9 (±4.4) years, mean body height 179.0 (±6.5) cm, mean body weight 73.6 ± 9.4 kg) were used for the outcome measures described here. The force plate data from seven subjects could not be used due to technical issues. Inclusion criteria were: male gender, age (18–40 years), BMI (18.5–30 kg/m^2), and absence of any acute or cardiovascular diseases, physical disabilities, systemic diseases, or neurological impairments that would not allow subjects to perform the tasks or wear the exoskeleton. BMI was calculated by measuring body height and weight, while the other inclusion criteria were assessed according to subjects' self-report. These restrictions in our study sample were chosen to avoid possible moderating influences of sex/gender, age, or even body composition, which have not previously been studied. Furthermore, male subjects were chosen due to the domination of males in the manufacturing industries. The Laevo® exoskeleton is only adjustable to a restricted extent and might therefore not fit to all body dimensions (e.g., female body composition, BMI > 30 kg/m^2) We chose a rather young age group to ensure that all subjects were able to perform the tasks without an early onset of fatigue.

The study was designed according to the Declaration of Helsinki and approved by the Ethics Committee of the University and University Hospital of Tübingen (617/2018BO2).

2.3. Exoskeleton

We evaluated the passive exoskeleton Laevo® (V2.56, Laevo B.V., Delft, The Netherlands; 2.8 kg), which supports the back during work tasks such as lifting a load and tasks requiring forward bending postures. Torque generation is provided by two two-dimensional joints ("smart joints") with gas pressure springs that are attached to a hip belt located close to the pivot point of the hip joints. Two rigid bars connect the joints to a chest pad placed over the upper part of the sternum and to two leg pads placed over the thighs. The smart joints can be turned on and off, and the joint flexion angle at which the support should begin can be set (range 0–45°, increments of 5°). The exoskeleton was adjusted to fit the subject's physique in two ways: First, by varying the size of the exchangeable rigid bars connecting the chest pad and the smart joints resulting in a chest-to-smart joint distance of 405 mm (S-size) or 435 mm (L-size). Secondly, by adjusting the smart joint support angle to avoid contact forces while standing upright (depending on the subject's torso composition). The force was measured and controlled using an integrated force sensor in the chest pad (38 × 10 mm; Type KM38-1kN, ME-Messsysteme GmbH, Henningsdorf, Germany). The leg-pad-to-smart joint distance could not be adjusted and was always 200 mm.

2.4. Experimental Procedure and Tasks

A 1.5-h visit to our laboratory was mandatory 1–5 days prior to participating in the experiment. This visit included information about the study procedure and signing an informed consent form. Inclusion and exclusion criteria were clarified, anthropometric measurements were collected, and subjects were familiarized with the exoskeleton and tasks. On the day of the experiment, which lasted 4 h, the subject was prepared with the measurement equipment required for the outcome measures and performed a series of experimental tasks [11,19,24]. This manuscript considers six experimental task conditions (*Static-EXO; Static-Control; Dynamic-EXO-Stoop; Dynamic-Control-Stoop; Dynamic-EXO-Squat; Dynamic-Control-Squat*; cf. Figure 1) and focusses on the outcome measures related to knee forces (i.e., tibiofemoral forces).

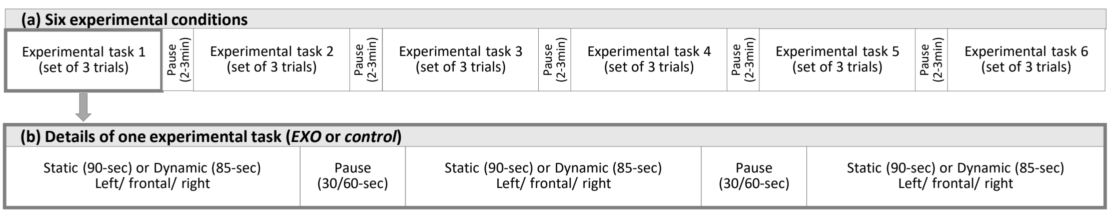

Figure 1. (**a**) shows the sequence of the six experimental conditions; two static and four dynamic: *Static-EXO; Static-Control; Dynamic-EXO-Stoop; Dynamic-Control-Stoop; Dynamic-EXO-Squat; Dynamic-Control-Squat*. The six conditions were performed in randomized order, and each was performed in a set of three *Trunk orientations*. Each set of static sorting tasks lasted 330 s, and each set of dynamic lifting tasks lasted 375 s. (**b**) shows one set of one experimental task. *Trunk orientations* (*left/frontal/right*) were performed in randomized order. Figure modified after Bär et al. (2022) [16].

The experimental tasks were performed while standing on a force plate in front of a table that was adjustable according to the subject's height. The feet position was defined prior to the experiment and kept constant during each task by using markings on the force plate (Figure 2). The feet position was defined while the subjects were instructed to stand comfortably upright with their feet positioned evenly and facing straight ahead. The distance to and height of the table was adjusted to allow the subject to perform the sorting or lifting task in the required body postures (explanation below). The six experimental conditions were performed in sets of three trials, with each trial performed in one of the three trunk orientations. Therefore, the sorting or the lifting box was placed to the front, in a 45° rotation to the left, or in a 45° rotation to the right from the sagittal plane. Reported results in the frontal direction include both knees when the work tasks were performed without trunk rotation. The reported ipsilateral results refer to both trunk orientations (left and right), including the knee belonging to the body side that coincides with the direction of trunk orientation. The reported contralateral results refer to both trunk orientations (left and right), including the knee belonging to the side of the body opposite to the direction of trunk orientation.

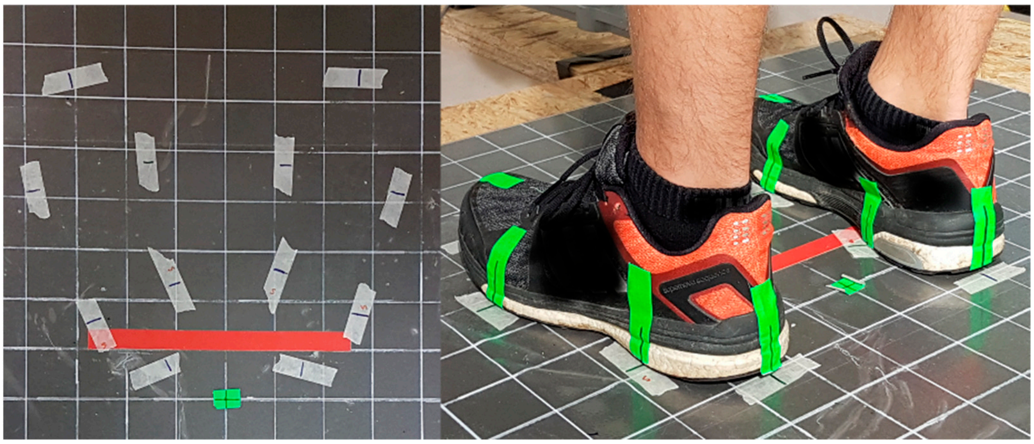

Figure 2. Force plate prepared with a coordinate system and with the individually pre-adjusted and pre-marked foot positions for the different tasks (static and dynamic). Marked landmarks were the heel in line with the Achilles tendon, medial and lateral malleolus, medial and lateral sesamoid, and the forefoot. Tape was placed on the subjects' shoes and on the force plate, and a connecting line was drawn between each pair of foot-to-floor tape markings considering the above outlined landmark positions. The malleolus markers were later used to determine the x and y coordinates of the ankle joint centers for both feet; by calculating the midpoints of the lateral and the medial malleoli.

The simulated static work task included sorting screws and pins while keeping the trunk in a 40° forward bent posture in the sagittal plane, following the tangent line of a two-dimensional gravimetric position sensor (PS12-II; Thumedi GmbH & Co. KG, Thum, Germany) that was placed on the skin over the spinous process of the 10th thoracic vertebrae (T10). The examiner monitored the signal on a screen. Additionally, the subjects were instructed to almost completely extend but never overstretch their knees (stoop knee posture) and to keep their feet in the pre-marked position. The height of the table was adjusted and the y-position of the feet was set while the subjects remained in the forward bent posture, comfortably reaching the sorting material with their hands while their elbows were flexed at approximately 135°. The sorting task lasted 90 s without moving the feet, legs or trunk, and was performed in the two following conditions: with or without the exoskeleton (*Static-EXO* vs. *Static-Control*). The subjects rested for 30 s between each trunk orientation and for 120 s after each static experimental condition. (Figure 3a–c).

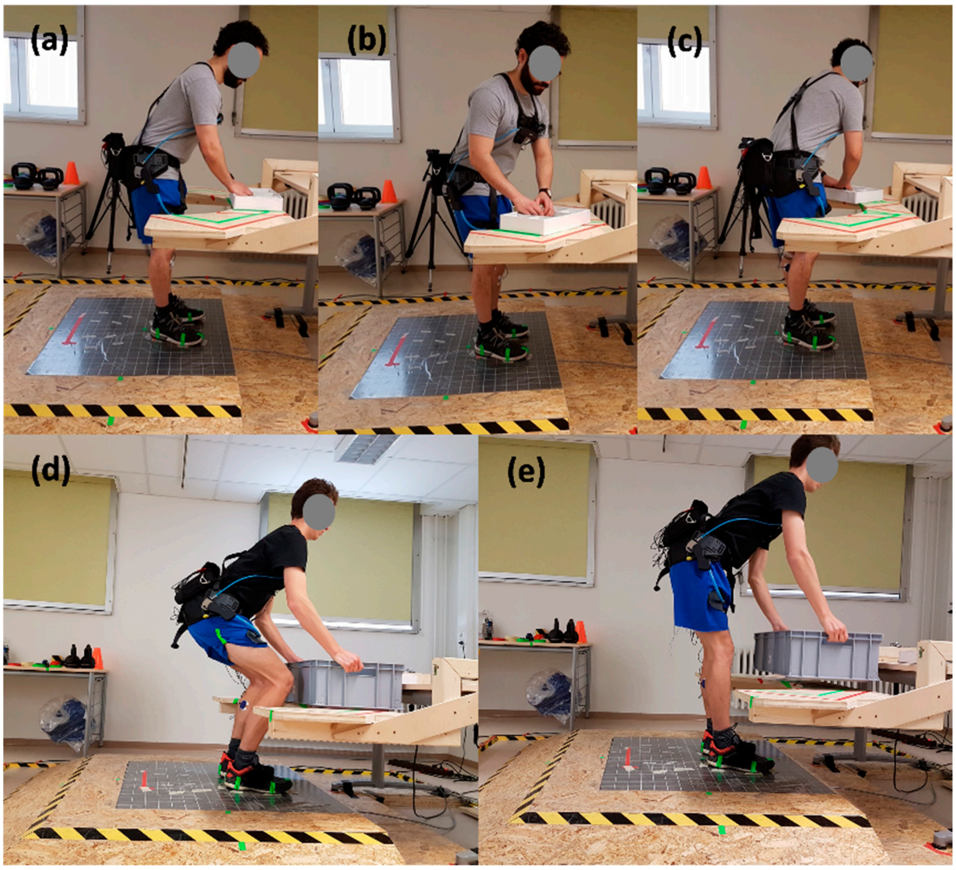

Figure 3. Subjects performing the experimental work tasks using the exoskeleton. (**a**–**c**) [16] show the static sorting task in three *Trunk orientation* conditions: (**a**) frontal, (**b**) right orientation, (**c**) left orientation. (**d**,**e**) show the dynamic lifting task to the front, performing (**d**) the squat style and (**e**) the stoop style.

The simulated dynamic work task included lifting and lowering an 11.6 kg load (i.e., a 10 kg load placed into a 1.6-kg box [W × D × H of 60 × 40 × 22 cm] with handles on both sides [19 cm]). The pre-defined body posture for adjusting the table included bending the upper body at a 70° flexion-angle in the sagittal plane, controlled similarly to the static task, with the legs almost completely extended but not overstretched. The upper arms hung perpendicular to the platform with an elbow flexion of approximately 160° while holding the handles of the box. Each dynamic experimental condition consisted of two sets of five consecutive lifts, keeping a pace of 5 s per lift, timed by an acoustic signal. The subjects rested for 35 s between both sets. Each lifting repetition included the following movements: (1) starting in an upright standing position, bending the trunk forward and picking up the load; (2) resuming the upright position while holding the load close to the body in front of the pelvis with flexed elbows; (3) lowering the load by bending the trunk forward and returning the load to its original position; (4) resuming the initial upright standing position without the load. The lifting task was performed in the following four conditions: with or without the exoskeleton, and holding the knees almost extended (stoop style) or bending the knees (squat style) while lifting (*Dynamic-EXO-Stoop* vs. *Dynamic-Control-Stoop* vs. *Dynamic-EXO-Squat* vs. *Dynamic-Control-Squat*). The subjects rested for 60 s between each trunk orientation and for 180 s after each dynamic experimental condition (Figure 3d,e).

All tasks were approved for their work-related relevance by consulting seven industrial companies who were already testing or had interest in testing BSEs in their companies. The applied tasks and their executions, i.e., body postures, lifting frequency, working height, have best represented the real work situations of these consulted companies.

2.5. Measurement and Data Analysis

The outcome parameters to assess the forces acting on the tibiofemoral joints during the dynamic work task were 50th and 90th percentile horizontal (anteroposterior) forces (HOR_{50}, HOR_{90}), and 50th and 90th percentile vertical forces ($VERT_{50}$, $VERT_{90}$). They were considered as median and peak knee loads during the lifting tasks. During the static work task, only HOR_{50} and $VERT_{50}$ were estimated, since the static body posture over the 90-s sorting task period would induce 90th percentile forces which do not differ much from the median forces. To estimate the forces acting on the knee joints, an inverse quasi-static model was developed, since no established model incorporating the Laevo® exoskeleton that could be applied was available (see Appendix A for a detailed explanation of the model). Quasi-static models have been used previously to detect the risk of injury in industrial workers [30]. For the model, subjects' anthropometrics, including body height, segment lengths, and segment weights [31–33], distances between the devices' contact points, lower limb posture, ground reaction forces below the feet, and the force between the chest and the exoskeleton's contact surface, were recorded.

To measure the lower limb posture, we used gravimetric inclination sensors connected to a sampling and storage device (PS12-II with 2.5D-gravimetrical sensors; THUMEDI GmbH & Co. KG, resolution 0.1° and 125 ms in time; maximum static error 0.5°; maximum repetition error 0.2°) attached to the skin over the anterior tibia and femur using double-sided adhesive tape (25 × 20 mm, 3M transparent Medical Standard, Top Secret®, Gesellschaft für Haarästhetik mbH, Fürth, Germany). The measurement system continuously recorded the anteroposterior and lateral inclination angles respective to the gravitational axis. Possible angular offsets caused by individual placement of the sensors at the tibia and femur were neutralized using the measurement values of a 5-s upright standing period recorded prior to the experiment.

Ground reaction forces were continuously recorded using a three-dimensional force plate that was linked to a signal conditioner and digitizer (FP9090-15-1000; Analog and Digital Amplifier AM6800; resulting resolution 0.5 N and 125 ms in time; overall maximum error 6 N; Bertec Corporation, Columbus, OH, USA). The resulting digital force signals were continuously recorded by self-developed software (University Hospital Tübingen) using the Bertec "Device interface Library for NET", which allows recoded data to be synchronized with data captured by the inclination sensors placed on the lower limbs.

The force plate's platform was prepared with a coordinate system to determine the subject's standing position, which was kept constant for the static and dynamic tasks (see 2.4 Experimental procedure and tasks; Figure 2). The points forming the tangent between the lateral and medial malleoli were marked on the coordinate system and used for further calculations. Prior to each measurement session, a self-calibration procedure was executed to remove possible offsets, for example, caused by temperature variations. The position measurement accuracy was regularly checked by placing a 2 kg weight on five predefined locations on the force plate (at the center and close to the four corners); accuracy was accepted with measured location errors < 10 mm.

The support moment of the exoskeleton was estimated by measuring the contact force between the Laevo® exoskeleton and the chest using a Ø38 mm × 10 mm thick force sensor (Type KM38-1kN, ME-Meßsysteme GmbH, Henningsdorf, Germany; resolution 0.1 N; maximum error 1% = 10 N, shown to be <2.5 N in this study setting) that was manually integrated in the chest pad of the exoskeleton and connected to the previously described sampling and storage device (PS12-II, 24 Bit physical resolution, 4096 Hz sampling rate).

Several of the subjects' anthropometrics (i.e., body height, body weight), segment lengths, and distances (i.e., shank and thigh lengths, distances between sesamoid and malleolus) and segment distances of the exoskeleton (i.e., distance between joints and contact points) were included in the model for the force calculations (Cf. Appendix A).

2.6. Statistical Aanalysis

The normal distribution of the histograms of the outcome parameters was inspected visually and the absolute *z*-values of the skewness and kurtosis of the data were judged to be valid for statistical evaluation [34]. We used repeated-measures analyses of variance (RM-ANOVA) with fixed factors *Exoskeleton (E), Trunk orientation (TO)* and *(E × TO)* to analyze differences between the experimental conditions (1) *Static-EXO* vs. *Static-Control* for the outcome parameters HOR_{50} and $VERT_{50}$. We used RM-ANOVA with fixed factors *E, TO, Lifting Style (LS), E × TO, E × LF, TO × LS, and E × TO × LS* to analyze differences between the experimental conditions (2) *Dynamic-EXO-Squat* vs. *Dynamic-Control-Squat*, and (3) *Dynamic-EXO-Stoop* vs. *Dynamic-Control-Stoop* for the outcome parameters HOR_{50}, HOR_{90}, $VERT_{50}$, $VERT_{90}$. However, only the findings including the *Exoskeleton*-condition are presented in the results section. To evaluate the static sorting task, we included the full 90-s periods. To evaluate the dynamic lifting task, we included only the two phases including the weight: (2) resuming the upright position while holding the load and (3) lowering the load by bending the trunk forward and returning the load to its original position. If statistically significant interaction effects occurred, Student's *t*-tests were used for post-hoc pairwise comparisons. Further interpretations only considered the relevant comparisons (i.e., *EXO* vs. *Control* within each *Trunk orientation*: *ipsilateral*, *frontal*, *contralateral*, within each *Lifting style: Stoop*, *Squat*, and within the combination of *Trunk orientation* and *Lifting style*). For fixed effects, *F*-values, *p*-values, and effect size partial eta squared (η_p^2) were calculated using the *F*-ratios strategy [35], and for the post-hoc pairwise comparison, *T*-value, *p*-value, and effect size Cohen's *d* were calculated using the pooled standard deviation strategy [36]. In agreement with Cohen [36] and *F*-ratios strategy [35], effect sizes were interpreted as small ($\eta_p^2 \leq 0.02$; $d \leq 0.2$), medium (η_p^2 0.13–0.259; d 0.5–0.79), or large ($\eta_p^2 \geq 0.26$; $d \geq 0.8$). For pairwise comparisons, we accepted significance levels of $\alpha \leq 0.05$ for fixed effects, and of $\alpha \leq 0.00333$ for *E × TO*, $\alpha \leq 0.00833$ for *E × LS*, and $\alpha \leq 0.00076$ for *E × TO × LS* (Bonferroni correction for 15, 6, and 66 possible comparisons, respectively). JMP® (Version 14.2.0, SAS Inc., Carry, NC, USA) was used for statistical evaluations.

3. Results

Median values with corresponding interquartile ranges (IQR) and differences between *EXO* and *Control* are provided in Table 1 for the main comparisons of the static and dynamic work tasks, in Table 2 for the *E × TO* and the *E × LS* comparisons for the static and dynamic work tasks, and in Table 3 for the *E × TO × LS* comparisons of the dynamic work task. The related statistics for the main effects of the *Exoskeleton* condition (*EXO* vs. *Control*) and the interaction effects for *E × TO, E × LS, and E × TO × LS* are provided in Appendix B (Table A5) for all examined work tasks. All relevant pairwise comparisons for variables with significant interaction effects are provided in Appendix B (Table A6) for static and dynamic work tasks.

Table 1. Median knee force values and corresponding interquartile ranges (IQR), absolute and relative differences showing *EXO* compared to *Control* for static and dynamic work tasks (main interactions).

Work Task	Parameter	Knee Force *Control* [N]		Knee Force *EXO* [N]		Difference (*EXO-Control*)	
		Median	(IQR)	Median	(IQR)	[N]	%
Static	HOR_{50}	49.69	(57.28)	46.45	(97.75)	−3.24	−6.5%
	$VERT_{50}$	693.05	(527.15)	700.09	(478.77)	**7.04** $^{\mu}$	**1.0%**
Dynamic	HOR_{50}	52.71	(78.66)	36.56	(96.11)	**−16.15** $^{\mu}$	**−30.6%**
	HOR_{90}	251.91	(279.74)	246.99	(314.22)	−4.92	−2.0%
	$VERT_{50}$	596.91	(376.75)	635.64	(375.45)	**38.74** $^{\lambda}$	**6.5%**
	$VERT_{90}$	1010.14	(604.72)	1041.61	(599.21)	31.47	3.1%

Significant differences are shown in bold (*p*-value $\alpha \leq 0.05$). Effect sizes ($^{\lambda}$ large effect size ($\eta_p^2 \geq 0.26$); $^{\mu}$ medium effect size ($\eta_p^2 \geq 0.13$)) are shown for the significant differences. Detailed statistics are displayed in Appendix B. N = newton; HOR_{50} = 50th percentile of the horizontal force; HOR_{90} = 90th percentile of the horizontal force; $VERT_{50}$ = 50th percentile of the vertical force; $VERT_{90}$ = 90th percentile of the vertical force.

Table 2. Median knee force values and corresponding interquartile ranges (IQR), absolute and relative differences showing *EXO* compared to *Control* for static and dynamic work tasks (two-fold interactions (**a**) *EXO* × *Trunk orientation* and (**b**) *EXO* × *Lifting style*).

(a)			Knee Force *Control* [N]		Knee Force *EXO* [N]		Difference (*EXO-Control*)	
Work Task	**Parameter**	**Trunk Orient**	**Median**	**(IQR)**	**Median**	**(IQR)**	**[N]**	**%**
Static	HOR_{50}	ipsi	57.63	(67.71)	60.11	(122.75)	2.48	4.3%
		front	73.32	(44.90)	88.02	(70.05)	14.69	20.0%
		cont	20.73	(23.37)	−5.47	(48.34)	**−26.19** $^{\lambda}$	**−126.4%**
	$VERT_{50}$	ipsi	896.48	(423.04)	904.65	(433.03)	8.17	0.9%
		front	765.16	(202.38)	839.40	(232.69)	74.24	9.7%
		cont	307.59	(168.52)	349.64	(173.52)	42.05	13.7%
Dynamic	HOR_{50}	ipsi	67.12	(96.00)	56.41	(109.21)	−10.70	−15.9%
		front	69.63	(84.01)	59.84	(105.20)	−9.78	−14.1%
		cont	29.84	(41.02)	3.53	(53.79)	**−26.30** $^{\sigma}$	**−88.2%**
	HOR_{90}	ipsi	365.43	(326.53)	371.04	(346.22)	5.62	1.5%
		front	287.50	(178.97)	309.12	(224.50)	21.62	7.5%
		cont	95.25	(115.99)	78.93	(110.65)	−16.32	−17.1%
	$VERT_{50}$	ipsi	767.35	(418.68)	806.37	(413.84)	39.03	5.1%
		front	652.35	(313.27)	696.94	(300.28)	44.59	6.8%
		cont	409.13	(243.75)	421.87	(233.23)	12.74	3.1%
	$VERT_{90}$	ipsi	1406.16	(745.10)	1439.82	(723.97)	33.66	2.4%
		front	1009.79	(529.94)	1057.44	(499.05)	47.65	4.7%
		cont	798.45	(306.43)	809.17	(306.52)	10.72	1.3%
(b)			**Knee force *Control* [N]**		**Knee force *EXO* [N]**		**Difference (*EXO-Control*)**	
Work Task	**Parameter**	**Lifting Style**	**Median**	**(IQR)**	**Median**	**(IQR)**	**[N]**	**%**
Dynamic	HOR_{50}	Squat	90.30	(107.91)	61.75	(112.25)	**−28.55** $^{\sigma}$	**−31.6%**
		Stoop	71.15	(102.42)	75.53	(149.61)	4.39	6.2%
	HOR_{90}	Squat	301.63	(338.34)	261.76	(358.53)	−39.87	−13.2%
		Stoop	274.26	(286.83)	303.18	(349.62)	28.91	10.5%
	$VERT_{50}$	Squat	613.48	(354.58)	653.30	(376.70)	39.82	6.5%
		Stoop	822.45	(681.98)	840.92	(658.81)	18.47	2.2%
	$VERT_{90}$	Squat	1006.89	(451.76)	1054.35	(481.07)	47.45	4.7%
		Stoop	1343.11	(823.42)	1322.57	(771.82)	−20.53	−1.5%

Significant differences for the post hoc analyses are shown in bold (*p*-values $\alpha \leq 0.00333$ for $E \times TO$ and $\alpha \leq 0.00833$ for $E \times LS$). Effect sizes ($^{\lambda}$ large effect size ($d \geq 0.8$); $^{\sigma}$ small effect size ($d \geq 0.2$)) are shown for the significant differences. Detailed statistics are displayed in Appendix B. N = newton; Trunk Orient = *Trunk orientation;* HOR_{50} = 50th percentile of the horizontal force; HOR_{90} = 90th percentile of the horizontal force; $VERT_{50}$ = 50th percentile of the vertical force; $VERT_{90}$ = 90th percentile of the vertical force; ipsi = *ipsilateral*; front = *frontal*; cont = *contralateral.*

Table 3. Median knee force values and corresponding interquartile ranges (IQR), absolute and relative differences showing *EXO* compared to *Control* for the dynamic work task (three-fold interactions *EXO* × *Trunk orientation* × *Lifting style*).

Parameter	**Lifting Style**	**Trunk Orient**	**Knee Force *Control* [N]**		**Knee Force *EXO* [N]**		**Difference (*EXO-Control*)**	
			Median	**(IQR)**	**Median**	**(IQR)**	**[N]**	**%**
HOR_{50}	Squat	ipsi	126.78	(142.73)	101.62	(146.48)	**−25.15**	**−19.8%**
		front	101.04	(91.74)	74.35	(92.33)	−26.69	−26.4%
		cont	50.36	(65.39)	19.57	(69.46)	**−30.79** $^{\sigma}$	**−61.1%**
	Stoop	ipsi	94.59	(117.18)	107.05	(159.15)	12.46	13.2%
		front	118.36	(90.48)	142.74	(124.94)	**24.39** $^{\mu}$	**20.6%**
		cont	29.43	(33.49)	4.26	(58.56)	**−25.17** $^{\mu}$	**−85.5%**

Table 3. *Cont.*

Parameter	Lifting Style	Trunk Orient	Knee Force *Control* [N]		Knee Force *EXO* [N]		Difference (*EXO-Control*)	
			Median	(IQR)	Median	(IQR)	[N]	%
HOR_{90}	Squat	ipsi	509.26	(462.72)	481.07	(404.54)	−28.19	−5.5%
		front	284.71	(173.79)	258.84	(238.40)	−25.87	−9.1%
		cont	151.54	(232.13)	109.48	(160.99)	−42.06	−27.8%
	Stoop	ipsi	361.67	(233.48)	406.50	(313.69)	44.83	12.4%
		front	346.07	(133.70)	392.77	(169.43)	46.70	13.5%
		cont	70.81	(67.34)	60.19	(88.21)	−10.61	−15.0%
$VERT_{50}$	Squat	ipsi	833.72	(360.54)	891.83	(325.38)	58.10	7.0%
		front	623.58	(225.56)	667.24	(236.27)	43.66	7.0%
		cont	393.07	(290.35)	387.06	(261.02)	−6.00	−1.5%
	Stoop	ipsi	1125.73	(771.99)	1142.44	(708.87)	16.72	1.5%
		front	1006.42	(431.70)	1022.66	(423.27)	16.24	1.6%
		cont	413.25	(324.03)	439.88	(323.31)	26.63	6.4%
$VERT_{90}$	Squat	ipsi	1319.08	(557.25)	1387.66	(541.02)	68.58	5.2%
		front	933.70	(363.33)	976.06	(373.88)	42.36	4.5%
		cont	864.42	(365.11)	868.97	(335.23)	4.56	0.5%
	Stoop	ipsi	1912.96	(760.15)	1858.51	(796.44)	−54.45	−2.8%
		front	1396.92	(510.29)	1399.91	(467.59)	2.99	0.2%
		cont	856.06	(364.26)	868.64	(359.74)	12.58	1.5%

Significant differences of the post hoc analyses are shown in bold (p-value $\alpha \leq 0.00076$ for $E \times TO \times LS$). Effect sizes ($^{\mu}$ medium effect size ($d \geq 0.5$); $^{\sigma}$ small effect size ($d \geq 0.2$)) are shown for the significant differences. Detailed statistics are displayed in Appendix B. N = newton; *Trunk Orient = Trunk orientation;* HOR_{50} = 50th percentile of the horizontal force; HOR_{90} = 90th percentile of the horizontal force; $VERT_{50}$ = 50th percentile of the vertical force; $VERT_{90}$ = 90th percentile of the vertical force; ipsi = *ipsilateral*; front = *frontal*; cont = *contralateral*.

3.1. Static Task

In the static work task, *Exoskeleton* had no significant main effect on HOR_{50}. However, there was a significant interaction effect for $E \times TO$ ($p < 0.001$; $\eta_p^2 = 0.496$), including a significant pairwise comparison for the *contralateral* side ($p < 0.001$; $d = -0.912$), which showed a reduction when using the *EXO* (−126.4%) (Cf. Appendix B).

The main effect of *Exoskeleton* was significant for $VERT_{50}$ ($p = 0.011$; $\eta_p^2 = 0.209$); the acting force increased (1%) when using the *EXO*. There was no significant interaction effect for $E \times TO$ on $VERT_{50}$ (Cf. Table 1 and Appendix B).

3.2. Dynamic Task

Performing the dynamic work task, *Exoskeleton* had a significant main effect on HOR_{50} ($p = 0.012$; $\eta_p^2 = 0.205$) with significant interaction effects for $E \times TO$ ($p < 0.001$; $\eta_p^2 = 0.455$), $E \times LS$ ($p < 0.001$; $\eta_p^2 = 0.471$), and $E \times TO \times LS$ ($p = 0.002$; $\eta_p^2 = 0.201$). Pairwise comparisons for $E \times TO$ were significant only for *contralateral* ($p < 0.001$; $d = -0.493$). Pairwise comparisons for $E \times LS$ was significant only for *Squat* ($p < 0.001$; $d = -0.261$). Pairwise comparisons for $E \times TO \times LS$ were significant for $E \times$ *ipsilateral* $\times$ *Squat* ($p < 0.001$; $d = -0.195$), for $E \times$ *frontal* $\times$ *Stoop* ($p < 0.001$; $d = 0.597$), for $E \times$ *contralateral* $\times$ *Squat* ($p < 0.001$; $d = -0.487$), and for $E \times$ *contralateral* $\times$ *Stoop* ($p < 0.001$; $d = -0.717$). (Cf. Appendix B) *EXO* decreased HOR_{50} when performing the task in *Squat style* in all directions (−61.1–−19.8%), and increased HOR_{50} when performing the *Stoop style* in *ipsilateral* and *frontal* (+13.2; +20.6%) and decreased HOR_{50} when performing the *Stoop style* in *contralateral* (−85.5%) (Cf. Table 3).

Exoskeleton had no significant main effect on HOR_{90}. However, there was a significant interaction effect for $E \times TO$ ($p < 0.001$; $\eta_p^2 = 0.292$) and $E \times LS$ ($p = 0.006$; $\eta_p^2 = 0.236$), but without reaching statistical significance in the relevant pairwise comparisons and without interaction effects for the threefold interaction $E \times TO \times LS$ (Cf. Appendix B).

Exoskeleton had a statistically significant main effect on $VERT_{50}$ ($p < 0.001$; $\eta_p^2 = 0.376$) without any significant interaction effects (Cf. Appendix B). $VERT_{50}$ slightly increased when using the *EXO* ($\leq 7\%$) (Cf. Table 3).

Using the *EXO* had no significant effect on $VERT_{90}$ (Cf. Appendix B).

3.3. Support Moment

Descriptive information about the 50th and 90th percentile support moment of the exoskeleton while performing the work tasks is provided in Table 4.

Table 4. Median values and corresponding interquartile ranges (IQR) showing the support moment provided by the exoskeleton.

Support Moment [Nm]	Trunk Orient	Static Task		Squat Lifting		Stoop Lifting	
		Median	(IQR)	Median	(IQR)	Median	(IQR)
50th Percentile	ipsi	22.72	(7.26)	19.94	(13.21)	19.05	(16.21)
	front	23.24	(4.81)	20.79	(15.19)	20.93	(16.90)
	cont	22.72	(7.26)	19.94	(13.21)	19.05	(16.21)
90th Percentile	ipsi	NA	NA	29.15	(11.97)	30.25	(10.43)
	front	NA	NA	32.04	(10.61)	32.23	(11.09)
	cont	NA	NA	29.15	(11.97)	30.25	(10.43)

Trunk Orient = *Trunk orientation*; Nm = Newtonmeter; ipsi = *ipsilateral*; front = *frontal*; cont = *contralateral*.

4. Discussion

Numerous studies have evaluated the use of occupational BSEs on short-term changes in physical stress and strain parameters in the body region supported by the exoskeleton. Only a few studies also investigated potential side effects of using occupational BSEs [6]. Therefore, the present study includes the evaluation of biomechanical knee joint loading when using a BSE. Using the Laevo® exoskeleton had a variable influence on the antero-posterior acting horizontal forces, which seems to depend on the work task execution (e.g., lifting style) or posture (e.g., trunk orientation). Yet it remains unclear, whether the occurring changes are relevant in terms of knee joint health. Furthermore, vertical acting forces slightly increased due to the exoskeleton's weight itself.

When performing the static sorting task in a forward bent static upper body posture with lateral trunk orientation, the ipsilateral knee was heavily loaded and the contralateral knee was almost unloaded. With respect to the horizontally acting forces on the femoral part of the knee joint, only the contralateral knee was significantly influenced by wearing the *EXO*. Without the *EXO*, the force mainly acted in anterior direction (*Static-Control-contralateral:* 20.7 ± 23.4 N), and with the *EXO* in a more posterior direction (*Static-EXO-contralateral*: −5.5 ± 48.3 N). The mechanical principle of transmitting load from the back to the leg pads via smart joints induced a translation force directed backwards onto the thighs [12], causing a posteriorly directed knee force.

Performing the dynamic work task using the *EXO* had an overall influence on HOR_{50}. The major effect for work direction was observed on the *contralateral* side, reducing the anteriorly directed HOR_{50} for both *Lifting styles* (*Squat-contralateral*: −61.1%; *Stoop-contralateral*: −85.5%), while still being anteriorly directed (*Squat-EXO-contralateral:* 19.6 ± 69.5 N; *Stoop-EXO-contralateral*: 4.3 ± 58.6 N). Within the *E* × *LS* interaction, only the *Squat style* had a significant effect, reducing the anteriorly directed HOR_{50} even during frontally directed work and on the ipsilateral side during lateral work. In contrast, HOR_{50} tended to increase when performing *Stoop style* lifts during frontally directed work and during laterally directed work on the ipsilateral side, similar to our findings for the static work task. Both tasks were performed while maintaining almost extended knee postures compared to the *Squat style* (median flexion in *Static*: 19.7°; median and peak flexion in *Dynamic_Stoop*: 17.7°, 31.8°; median and peak flexion in *Dynamic_Squat:* 39.2°, 73.7° (0° flexion referring to fully extended knees)). Therefore, it is most likely that the effects of using the Laevo®

exoskeleton on horizontal knee forces depend on the wearer's body posture (i.e., the knee flexion angle).

Shear force magnitudes and directions (anteriorly vs. posteriorly directed) have been shown to vary depending on knee flexion angles in isokinetic knee extension tasks [37,38]. As described in two associated publications [11,16], using the *EXO* led to more flexed knee joints in the static and dynamic tasks. The changes were most prominent in those tasks that included stoop postures (*Static*; *Dynamic_Stoop*), particularly *contralateral* (+95% in *Static*; +78.8% in *Dynamic_Stoop*) where we also detected most HOR_{50} changes when using the *EXO*. Accompanying the knee joint angle changes, the hip joints were also more flexed by the subjects when using the *EXO*, particularly in those tasks including stoop postures and observing the *contralateral* side [11,16]. Further, the support moment of the Laevo® has been shown to depend strongly on the flexion angle of the smart joints which are located close by the hip pivot points [13]. Therefore, the leg pad pressure acting on the thighs must depend on the hip flexion angle, further influencing the horizontally acting knee forces.

Using the *EXO* had no effect on HOR_{90}. It is likely that the EXO does not substantially alter peak horizontal forces when lifting and lowering a load in *Stoop* and *Squat Lifting styles*. Therefore, the Laevo® presumably does not induce high peak horizontal loads on the knee joint. However, substantial time spent on knee straining work tasks, including those tasks without substantial force peaks (e.g., holding a posture), has been reported to be an important risk factor for musculoskeletal disorders in the knee [39,40]. Whether exoskeleton-induced changes in HOR_{50} can increase the risk for MSD is beyond the findings of the present study.

To our knowledge, there is no evidence on quantitatively reported knee forces in industrial work tasks and on potential changes induced by workplace interventions. Further, existing evaluations of knee forces, e.g., during daily activities, have been evaluated using different methods (i.e., in vivo measurements via telemetry, different biomechanical models) [41], which makes comparisons difficult. However, in previous studies, anteriorly directed knee forces evaluated during activities of daily living (i.e., walking, ascending and descending stairs, rising from or sitting down in a chair, single or two-legged stance) were reported to range from 0.04–1.6 times body weight (×BW) (peak) [37,42–46] and 0.09–0.18 × BW (mean) [43], and during squatting from 0.11–0.15 × BW (peak) and 0.02 × BW (mean) [42,43]. Posteriorly directed horizontal forces were reported to range from 0.23–1.7 × BW (peak) and 0.12–0.34 × BW (mean) [37,43,44] during daily activities, and from 0.2–3.6 × BW (peak) [37,47] during squatting. Neglecting bias due to insufficient comparability between methods and roughly approximating our data into a multiple body weight (×BW) metric (by dividing each measured force value [N] by the mean body weight of all included subjects (722.02 N)), we obtained the following forces when using the *EXO*: Anteriorly directed horizontal knee forces of ≤0.12 × BW (median) for static work tasks and ≤0.20 × BW (median), and ≤0.67 × BW (peak) for dynamic work tasks. Posteriorly directed horizontal knee forces of <0.01 × BW (median) only for the static task. This is within the force ranges reported for the common activities of daily living, although we included straining postures and additional loads. Therefore, it is possible that using the Laevo® does not exert horizontal forces on the knee joints exceeding typical loads. However, the risk of developing degenerative MSD, such as osteoarthritis in the knee joint, has been shown to be related to cumulative loading over prolonged durations [40,48–50]. In Germany, osteoarthritis of the knee and meniscal lesions are listed as occupational diseases for which cumulative knee exposure is an important factor for their recognition [51]. In this context, future research should address a possible negative contribution of BSE use on cumulative loading of the knee joint.

Using the *EXO* had medium to large significant effects on $VERT_{50}$. The force increased in the static work task by 0.9–13.7% (8.2–74.2 N) and up to 7.0% (58.1N) in the dynamic work task, without being influenced by *Trunk orientation* or *Lifting style*. *EXO* had no effect on $VERT_{90}$. It can be assumed that the increases in $VERT_{50}$ were mainly caused by the exoskeleton's own weight (39 N; including the inbuilt force sensor), but probably not by any additional load transfer from the back to the legs.

Vertical acting knee forces have been reported to range between 1.0–10.0 × BW (peak) for activities of daily living [37,44,46,52–55], and to range between 0.3–5.6 × BW (peak) for squat tasks [37,47,54–56]. In the present study, when approximating the data into ×BW metrics, the vertical forces with using the *EXO* resulted in 0.48–1.25 × BW (median) for the static task, with 0.54–1.58 × BW (median), and 1.2–2.57 × BW (peak) for the dynamic work tasks. Similar to HOR, this lies within the range of the reported vertical forces when neglecting bias due to insufficient comparability between methods. However, in terms of cumulative knee loading as a risk factor for MSD of the knee, the weight of a BSE may represent a relevant additional load on the musculoskeletal system of the lower limbs. While the weight with 2.8 kg of the Laevo® exoskeleton is rather light, other commercially available BSEs weigh up to 7 kg [57].

Until now, mainly muscle activity has been observed to estimate possible side effects of using BSEs [6]. The loading of the knee joints is highly influenced by forces exerted by the knee extensor and flexor muscles [58]. Therefore, it is likely that changes in occurring knee forces are accompanied by a changed activity of these muscle groups. Previous studies have reported that the knee extensor muscles are only slightly influenced by the use of the Laevo® exoskeleton [9,11,16,18,59]. However, the activity of the gastrocnemius medialis muscle (GM) increased in all dynamic *contralateral* conditions, possibly due to postural changes [11], and the activity of the biceps femoris muscle (BF) decreased across all conditions as reported in two associated publications [11,16], possibly due to the supporting nature of the EXO for hip extension [11,12,16]. It has been reported that antagonistic coactivation of the hamstring is one important knee joint stabilizing factor which also influences forces acting on the knee joint [58]. Both GM and BF contribute to the antagonistic muscle activity with respect to the knee joint during the tasks observed here. Although a BSE may provoke changes in musculoskeletal strain (e.g., muscle activity) by addressing a specific joint (e.g., supporting hip extension), these changes also affect adjacent joints, such as the knee joint. In the present study, changing the activity of BF and GM by using the *EXO* may have produced secondary effects, such as changes of the knee joint forces. This is consistent with the assumptions of Park et al. (2022), who evaluated a BSE during walking and discussed an accompanying reduction in knee flexion torque along with a reduction in hip extension torque due to the hip extension support of the BSE, which may be caused by reduced BF muscle activity [60].

Although this was not explored further in the presented experiment, it is most likely that possible side effects are nearly proportional to the support provided by the device, which is caused by the load-transferring character of the BSE. According to our associated papers, the Laevo® exoskeleton seems to provide a rather low back-relieving effect [11,16]. Consequently, side effects may also occur only slightly. Subsequently, using a BSE that provides a greater amount of support to the user may also cause more accompanying side effects. Further, mechanical differences of different devices may lead to different (side) effects due to the respective mechanical load transfer. For example, Alabdulkarim et al. (2019) compared three exoskeleton designs of upper body support exoskeletons during simulated overhead drilling. The findings demonstrated significant differences between the three exoskeleton designs in muscle activation of the supported area but also different muscle activation in non-target region which can be considered as side effects [61]. Therefore, before implementing a BSE, it is crucial to assess side effects that may occur for each individual device in its current version.

4.1. Limitations

Several limitations need to be address for the current study. First, the study population consisted of healthy male subjects aged 19 to 38 years, which does not reflect the general working population, also including female, aging, and physically impaired persons. Therefore, our results cannot be generalized. Second, seven out of originally 36 included subjects had to be excluded for the knee force calculations, resulting in a sample size of

29. Data had to be excluded due to technical issues while synchronizing the data for the first seven subjects. However, the body side that was prepared with the measurement equipment was still counterbalanced (in 14 subjects on the left, in 15 subjects on the right). Third, the Laevo® exoskeleton is only partially adaptable to its wearer's proportions. The distance between the hip joint and the chest was chosen between two available sizes (S, L), resulting in a lever arm of 405 mm or 435 mm. Only one of the 29 subjects used the S-sized model. The distance between the hip joint and the leg pad was not adjustable for the Laevo®, so the leg pads were not always placed exactly as specified by the manufacturer (i.e., lower than instructed for shorter subjects). Variations in exoskeleton placement on the body of the wearer can easily occur when such devices are applied in the field and must be minimized. Similarly, the exoskeleton cannot always be prevented from shifting during all movements. However, in our experiments, the fit of the Laevo® was highly controlled by the examiners. Fourth, all subjects underwent a one-hour familiarization session, which might be too short to fully adapt to a routine exoskeleton use. Fifth, this experiment included three highly controlled simulated work tasks (e.g., on working posture). A real working environment, therefore, was not reflected, and possible variations of the exoskeletons' effects are not known. Therefore, field studies under randomized, controlled conditions are needed to complement laboratory studies, which only provide initial insights into the acute possible effects of using an exoskeleton. Sixth, this study focused on acute effects of wearing an exoskeleton. Effects induced by regular long-term and full-shift use remain unclear and need to be investigated by long-term studies. Seventh, we used a self-developed biomechanical inverse quasi-static model for calculating moments and forces acting on the joints. The model includes some simplifications that might cause deviations from the actual occurring knee joint forces. Generally, in quasi-static models the dynamic movements are neglected [30] which could have biased the calculated forces in the dynamic lifting task. A comparison of a quasi-static vs. a dynamic model by Hariri et al., (2021) showed an underestimation of peak (19.7%) and cumulative spinal moments (3.6%) when not including the dynamic movements into the model in manual material handling tasks [30]. In particular, the 90th percentile knee forces could have been underestimated in this experiment. Further, only the vertical but not the horizontal components of the ground reaction force were included into the model. Some simplifications regarding the joint mechanics were adopted (i.e., neglecting torsional forces, assuming the pivot point being central and without shifting, treating joints like pure hinge joints, neglecting forces induced by antagonist muscles). The length of some body segments which were used for the model was estimated in relation to the respective body length. Only one leg was prepared with the measurement equipment (i.e., position sensors). Therefore, the force which was generated by the exoskeleton and acted onto the thighs was distributed onto both legs to be 50% loaded each. (Cf. Appendix A for detailed information about the model and its limitations.) Eighth, possible specific effects on the patellofemoral joint could not be assessed by our analysis. Those effects may be induced by the pressure of the exoskeleton's pad onto the anterior upper leg muscles.

4.2. Key Points

- The changes detected for HOR and VERT seem rather small and may not exceed typical ranges. However, it remains unclear what additional effect even small increases in acting knee joint forces have on musculoskeletal knee joint health, considering the contribution of cumulative loads to MSD of the knee.
- This evaluation shows that the side effects of using an exoskeleton depend on the work task executed (i.e., knee and trunk postures). Therefore, the decision to implement a BSE or not needs to depend on the individual work tasks.
- Back-support exoskeletons should be as light as possible, as their own weight seems to directly increase the vertical forces acting on the knee joint.
- Potential side effects, such as changes in knee joint forces, should be considered early in the development of a BSE.

5. Conclusions

When developing, evaluating, and applying a BSE, it is crucial to also focus on potential side effects that might occur when using the device during occupational tasks. We found task and posture-related changes in the loading characteristics of the knee joints when using the Laevo® exoskeleton using our biomechanical model. Conclusions regarding the impact on musculoskeletal health risk for the knee would be beyond the present study. However, due to the cumulative nature of MSD, potential negative effects on the knee joints when using BSEs should be considered by future research.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Ethics Committee of the Medical Faculty of the University of Tübingen (617/2018BO2).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data are not publicly available due to data use restrictions contained in study participants' information material.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Inverse Quasi-Static Model Used for the Knee Force Calculations

Table A1. Selection of variables used for the model (forces, coordinates, angles, anthropometrics and segment measures of the subjects).

Ground reaction force (GRF) in three directions [N]: Horizontal¯mediolateral ($x-$ direction) ($F_{Floor.x}$) Horizontal¯anteroposterior ($y-$ direction) ($F_{Floor.y}$) vertical ($z-$ direction) ($F_{Floor.z}$)	Force plate system linked to a signal conditioner and digitizer (FP9090-15-1000; Analog and Digital Amplifier AM6800; resulting resolution 0.5 N and 125 ms in time; Overall maximum error $\leq$ 6 N *; Bertec Corporation, Columbus, OH, USA)
Ground reaction force vector coordinates (x, y) [mm] ($x_{F_{Floor.z}}$), ($y_{F_{Floor.z}}$)	$x_{F_{Floor.z}} = -M_y/F_z$ $y_{F_{Floor.z}} = M_x/F_z$

Table A1. *Cont.*

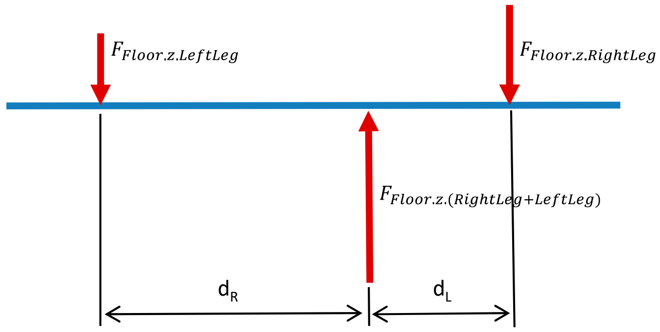
Distribution of the vertical ground reaction force ($F_{Floor.z}$) onto both feet [N]	The vertical ground reaction force vector on the force plate was recorded continuously, and the x and y coordinates of both ankle joints were kept constant during the experiments (see explanation above). The total ground reaction force was distributed over both feet using an equation estimating the proportion to the ground reaction force of each foot.  $F_{Floor.z.RightLeg} = \frac{F_{Floor.z(RightLeg+LeftLeg)} * d_L}{(d_R + d_L)}$ $F_{Floor.z.LeftLeg} = \frac{F_{Floor.z(RightLeg+LeftLeg)} * d_R}{(d_R + d_L)}$ Following, both legs (left and right) being considered separately in the model. To simplify, the terms $F_{Floor.z.LeftLeg}$ and $F_{Floor.z.RightLeg}$ will be omitted and only the formula $F_{Floor.z}$ will be used.
Coordinates (x, y) of both ankle joint centers of the subjects during the experiments standing on the force plate [mm] $(x_{F_{Ankle}})$, $(y_{F_{Ankle}})$	The position of both feet was measured and marked prior to the experiments and controlled to always stay in the preset position (Cf. manuscript Section 2.4 Experimental procedure and tasks and Figure 2). The y-position of both, the left and right forefoot was assured to be equal. The x- and y- coordinates of the lateral and medial malleolus were marked on the force plate and the midpoint of the tie line connecting these two points was calculated and used to estimate the x- and y-coordinates of the ankle joints.
Force of the Laevo® chest pad against the subject's sternum [μV] $(F_{Exo.Thorax})$	Measured by a force sensor manually integrated in the chest pad (diameter 38 × thickness 10 mm; Type KM38-1 kN, ME-Messsysteme GmbH, Henningsdorf, Germany), connected to a sampling and storage device (PS12-II; Resolution: 0.1 N; estimated typical error: 0.5 N; maximum error: 1 N) An occurring measurement error depends mainly on undesirable shear forces and undesirable moments acting on the sensor. Estimated typical and maximum measurement errors were determined using known applied forces, shear forces and moments. The shear forces and moments that actually occur during the test were estimated in a qualified manner.
Inclination angles of femur and tibia relative to the perpendicular [°] $(\varphi_{Femur.yz})$, $(\varphi_{Tibia.yz})$	Measured by gravimetric inclination sensors connected to a sampling and storage device (PS12-II with 2.5D-gravimetrical sensors; THUMEDI GmbH & Co. KG, resolution 0.1° and 125 ms in time; maximum static error 0.5°; maximum repetition error 0.2°)
Body mass [kg]	Measured with a scale prior to the experiment at the subjects' first visit in our lab; similar clothing was worn as in the experiment.
Body height [mm]	Measured during an upright stance with the back straight against a wall, feet hip width apart, facing straight ahead.
Partial foot length (distance of the medial sesamoid and malleolus) [mm] **	Measured between the most prominent points over the medial sesamoid and malleolus.
Shank length [mm] (l_{Shank}) **	Measured on the lateral outside of the shank between the knee joint gap and the malleolus.
Thigh length [mm] $\left(l_{Thigh}\right)$ **	Measured on the lateral outside of the thigh between the knee joint gap and the trochanter major.

Table A1. *Cont.*

Foot mass [kg] (m_{foot})	$Foot\ mass = body\ mass * 0.000069 + 0.47$ [33]
Foot + shoe mass [kg] ($m_{foot+shoe}$)	Five different sports shoes of different owners were weighed and their relative weight to the foot mass of the owners was calculated. The average relative shoe mass was 0.3229. To estimate the total mass of foot plus shoe, the previously estimated foot mass was multiplied by factor 1.3229.
Foot + shoe weight [N] ($F_{G.FootShoe}$)	$F_{G.FootShoe} = (Foot\ mass + shoe\ mass) * 9.81$
Shank weight [N] ($F_{G.Shank}$)	$F_{G.Shank} = (body\ mass * 0.0375 + 0.38) * 9.81$ [33]
Distance between the ankle joint center and the mass center of the shank [mm] ($l_{MassCenter.Shank}$)	$l_{MassCenter.Shank} = l_{Shank} * 0.56$ [32]
Distance between the ankle joint and the center of mass (COM) of the foot (including the shoe) [mm] ($l_{MassCenter.FootShoe}$)	$l_{MassCenter.FootShoe} = Partial\ foot\ length_{(malleolus-sesamoid)} * 0.5$ [32]
Radius ankle center to Achilles tendon [mm] ($r_{Achilles}$)	$\mathrm{r}_{\mathrm{Achilles}} = body\ height * 0.0271$ • The factor 0.0271 was estimated by taking measurements of ten male subjects: measuring the distance of the virtual tangent lines of the front- and backside of the ankle joint (on malleolus level). The distance was divided by 2 and relatively related to the individual subjects' body height. The average of the relative factor of the 10 subjects was calculated and used as factor.
Radius knee center to Patella [mm] ($r_{Patella}$)	$r_{Patella} = body\ height * 0.0358$ • The factor 0.0358 was estimated by taking measurements of ten male subjects: measuring the distance of a virtual tangent line of the Patella to a virtual tangent line of knee back side. The distance was divided by 2 and relatively related to the individual subjects' body height. The average of the relative factor of the 10 subjects was calculated and used as factor.
Relevant measures of the Laevo® exoskeleton	Distance smart joint to leg pad: 200 mm Distance smart joint to chest pad: 405 mm (S-size)/435 mm (L-size)

M = moment; F = force/ground reaction force; r = radius; l = length; d = distance; L = left; R = right. * The overall maximum error of GRF was estimated to be ≤ 6 N. Multiple tests were carried out during the measurement periods and always showed an error below 4 N. ** For all measurements of one individual segment (lower limbs), we measured either the left or the right body side, which was randomized to be evaluated and therefore prepared with the measurement equipment, i.e., inclination sensors, in each individual.

Appendix A.1. Description of the Model

Appendix A.1.1. Ankle Joint Forces

Forces and moments acting on the ankle joint are calculated, including the vertical and horizontal forces acting on the ankle joint ($F_{Ankle.z}$ and $F_{Ankle.y}$, respectively) and on the Achilles tendon ($F_{Achilles}$). Therefore, the y-coordinates of the vertical ground reaction force ($y_{F_{Floor.z}}$), the y-coordinates of both ankle joints ($y_{F_{Ankle}}$), the perpendicular distance between the pivot point of the ankle joint and the force vector of the Achilles tendon ($r_{Achilles}$) were used. The dead weight of the feet, including shoes ($F_{G.FootShoe}$), was considered to not contributing to the load on the ankle joint. To simplify the model, it is assumed that $F_{Achilles}$ acts parallel to the shank.

Table A2. Symbols with description and Equations as used for the model displayed in Figure A1.

Symbol	Description
$\varphi_{Tibia.yz}$	Angle between tibia and the perpendicular (in y/z-direction).
l_{Shank}	Shank length.
$F_{Achilles}$	Forces acting on the Achilles tendon.
$r_{Achilles}$	Radius of ankle joint center to Achilles tendon.
$F_{Ankle.z}$	Force acting on the ankle joint in z-direction.
$F_{Ankle.y}$	Force acting on the ankle joint in y-direction.
$F_{G.FootShoe}$	Segment weight of foot + shoe.
$F_{FloorVirt.Ankle.z}$	Virtual ground reaction force in z-direction, excluding foot + shoe mass.
$F_{Floor.z}$	Ground reaction force in z-direction.
$y_{F_{Ankle}}$	Y-position of the ankle joint.
$y_{F_{G.FootShoe}}$	Y-position of the force vector of the foot + shoe center of mass.
$y_{F_{FloorVirt.Ankle.z}}$	Y-position of the virtual ground reaction force vector, excluding foot + shoe mass.
$y_{F_{Floor.z}}$	Y-position of the total ground reaction force vector.
$l_{MassCenter.FootShoe}$	Distance between the ankle joint and the mass center of foot + shoe.
Symbol	**Equation**
$F_{FloorVirt.Ankle.z}$	$= F_{Floor.z} - F_{G.FootShoe}$
$y_{F_{FloorVirt.Ankle.z}}$	$= \frac{F_{Floor.z} \cdot y_{F_{Floor.z}} - F_{G.FootShoe} \cdot y_{F_{G.FootShoe}}}{F_{FloorVirt.Ankle.z}}$
$y_{F_{G.FootShoe}}$	$= y_{F_{Ankle}} + l_{MassCenter.FootShoe}$
$F_{Achilles}$	$= F_{FloorVirt.Ankle.z} \cdot \frac{y_{F_{FloorVirt.Ankle.z}} - y_{F_{Ankle}}}{r_{Achilles}}$
$F_{Ankle.z}$	$= F_{FloorVirt.Ankle.z} + cos\left(\varphi_{Tibia.yz}\right) \cdot F_{Achilles}$ $= F_{Floor.z} - F_{G.FootShoe} + cos\left(\varphi_{Tibia.yz}\right) \cdot F_{Achilles}$ $= F_{Floor.z} - F_{G.FootShoe} + cos\left(\varphi_{Tibia.yz}\right) \cdot (F_{Floor.z} - F_{G.FootShoe}) \cdot \frac{y_{F_{FloorVirt.Ankle.z}} - y_{F_{Ankle}}}{r_{Achilles}}$
$F_{Ankle.y}$	$= sin\left(\varphi_{Tibia.yz}\right) \cdot F_{Achilles}$ $= sin\left(\varphi_{Tibia.yz}\right) \cdot (F_{Floor.z} - F_{G.FootShoe}) \cdot \frac{y_{F_{FloorVirt.Ankle.z}} - y_{F_{Ankle}}}{r_{Achilles}}$
$F_{Ankle.y}$	$= sin\left(\varphi_{Tibia.yz}\right) \cdot F_{Achilles}$ $= sin\left(\varphi_{Tibia.yz}\right) \cdot (F_{Floor.z} - F_{G.FootShoe}) \cdot \frac{y_{F_{FloorVirt.Ankle.z}} - y_{F_{Ankle}}}{r_{Achilles}}$
$F_{Ankle.yz}$	$= \sqrt{F^2_{Ankle.z} + F^2_{Ankle.y}}$
$\varphi\_F_{Ankle.yz}$	$= arctan\left(\frac{F_{Ankle.y}}{F_{Ankle.z}}\right)$

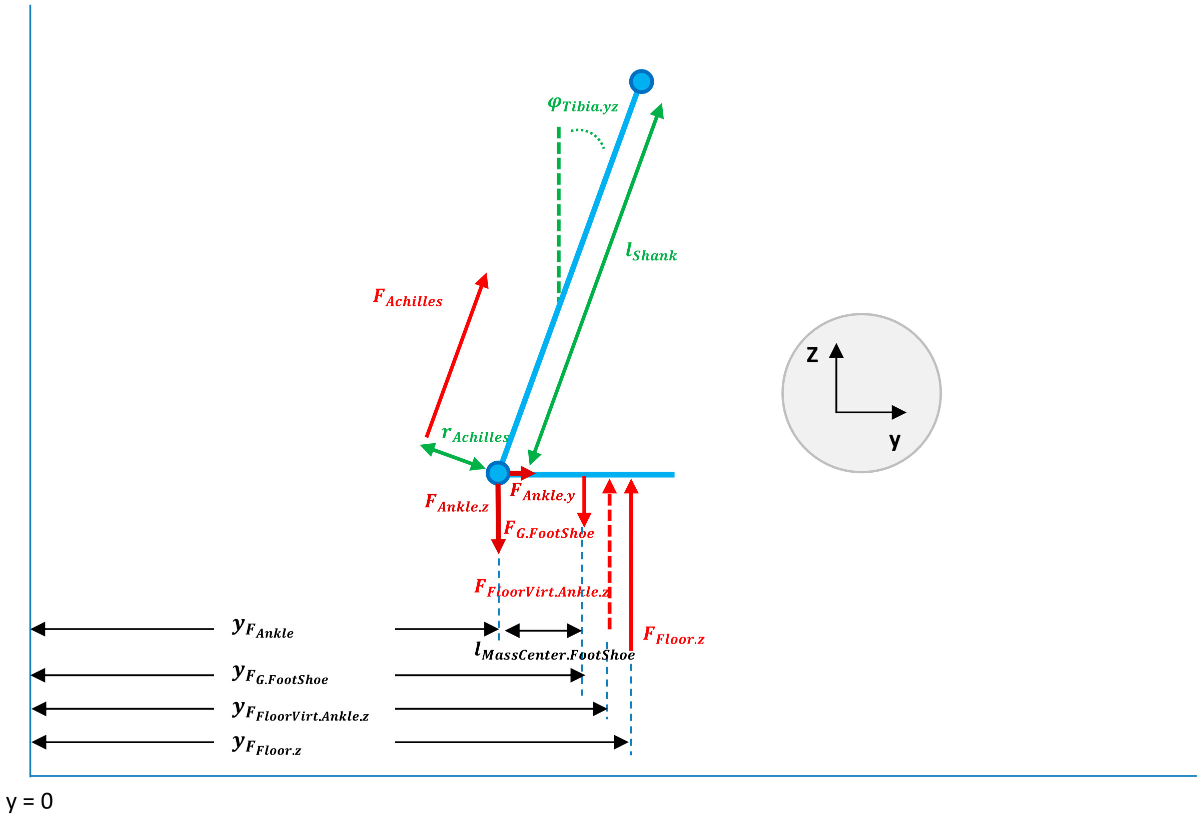


Figure A1. Calculation of ankle joint forces.

Appendix A.1.2. Knee Joint Forces

The ratio of the weight of the shanks contributing to its segment weight ($F_{G.Shank}$) and the coordinates of these force vectors ($y_{F_{G.Shank}}$) is calculated using the y-coordinates of the ankle joints ($y_{F_{Ankle}}$), the inclination angles of the tibia ($\varphi_{Tibia.yz}$), the shanks' weight and the distance between ankle and shanks' center of gravity ($l_{MassCenter.Shank}$). These force components should be considered because they act on the body below the knees and therefore do not contribute to the force acting on the knee joints.

A resulting "virtual ground reaction force vector", excluding shank, foot and shoe ($F_{FloorVirt.Knee.z}$), is of importance for the calculation of the forces and moments acting on the knee joints.

In a next step, the force acting on the quadriceps tendon (F_{Quad}) is calculated. For this purpose, the coordinates of the knee joints ($y_{F_{Knee}}$), which were estimated using the shank's inclination angle in the sagittal plane ($\varphi_{Tibia.yz}$) and the shank's length (l_{Shank}), the $F_{FloorVirt.Knee.z}$, and the distance between the patella and the rotation axis of the knee joint ($r_{Patella}$) were used for the model. To simplify the model, we assume $\vec{F}_{Quad}$ to act parallel to the shank. Further, the knee joint moments and the vertical ($F_{Knee.z}$), horizontal ($F_{Knee.y}$) and resulting total forces acting on the knee joints are calculated using the F_{Quad}, $F_{FlorVirt.Knee,z}$, and the inclination angle of the femur ($\varphi_{Femur.yz}$).

Table A3. Symbols with description and Equations as used for the model displayed in Figure A2.

Symbol	Description
$\varphi_{Femur.yz}$	= Angle between femur and the perpendicular (y/z-direction)
F_{Quad}	= Force acting at the Quadriceps tendon
$r_{Patella}$	= Radius of knee joint center to patella
$F_{Knee.z}$	= Force at the knee joint in z-direction (without exoskeleton)
$F_{Knee.y}$	= Force at the knee joint in y-direction (without exoskeleton)
$\varphi_{Tibia.yz}$	= Angle between tibia and the perpendicular (in y/z-direction)
l_{Shank}	= Shank length
$l_{MassCenter.Shank}$	= Distance between the ankle joint and the mass center of the shank
$F_{G.Shank}$	= Segment weight of the shank
$F_{FloorVirt.Knee.z}$	= Virtual ground reaction force in z-direction, excluding foot + shoe + shank mass
$F_{G.FootShoe}$	= Segment weight of foot + shoe
$F_{Floor.z}$	= Ground reaction force in z-direction
$y_{F_{Knee}}$	= Y-position of the knee joint
$y_{F_{G.Shank}}$	= Y-position of the force vector of the shank center of mass
$y_{F_{Ankle}}$	= Y-position of the ankle joint
$y_{F_{G.FootShoe}}$	= Y-position of the force vector of the foot + shoe center of mass
$y_{F_{FloorVirt.Knee.z}}$	= Y-position of the virtual ground reaction force vector, excluding foot + shoe and shank mass
$y_{F_{Floor.z}}$	= Y-position of the total ground reaction force vector
$l_{MassCenter.FootShoe}$	= Distance between the ankle joint and the mass center of foot + shoe
Symbol	**Equation**
$F_{FloorVirt.Knee.z}$	$= F_{FloorVirt.Ankle.z} - F_{G.Shank} = F_{Floor.z} - F_{G.FootShoe} - F_{G.Shank}$
$y_{F_{FloorVirt.Knee.z}}$	$= \frac{F_{Floor.z} \cdot y_{F_{Floor.z}} - F_{G.Shank} \cdot y_{F_{G.Shank}} - F_{G.FootShoe} \cdot y_{F_{G.FootShoe}}}{F_{FloorVirt.Knee.z}}$
$y_{F_{Knee}}$	$= y_{F_{Ankle}} + sin\left(\varphi_{Tibia.yz}\right) \cdot l_{Shank}$
$y_{F_{G.Shank}}$	$= y_{F_{Ankle}} + sin\left(\varphi_{Tibia.yz}\right) \cdot l_{MassCenter.Shank}$
$y_{F_{G.FootShoe}}$	$= y_{F_{Ankle}} + l_{MassCenter.FootShoe}$
F_{Quad}	$= F_{FloorVirt.Knee.z} \cdot \frac{y_{F_{Knee}} - y_{F_{FloorVirt.Knee.z}}}{r_{Patella}}$ $= (F_{Floor.z} - F_{G.FootShoe} - F_{G.Shank}) \cdot \ldots$ $\ldots$ $\frac{\lvert y_{F_{Ankle}} + sin\left(\varphi_{Tibia.yz}\right) \cdot l_{Shank} - \frac{F_{Floor.z} \cdot y_{F_{Floor.z}} - F_{G.Shank} \cdot \left(y_{F_{Ankle}} + sin\left(\varphi_{Tibia.yz}\right) \cdot l_{MassCenter.Shank}\right) - F_{G.FootShoe} \cdot \left(y_{F_{Ankle}} + l_{MassCenter.FootShoe}\right)}{F_{Floor.z} - F_{G.FootShoe} - F_{G.Shank}} \rvert}{r_{Patella}}$
$F_{Knee.z}$	$= F_{FloorVirt.Knee.z} + cos\left(\varphi_{Femur.yz}\right) \cdot F_{Quad}$ $= F_{Floor.z} - F_{G.FootShoe} - F_{G.Shank} + cos\left(\varphi_{Femur.yz}\right) \cdot F_{Quad}$
$F_{Knee.y}$	$= sin\left(\varphi_{Femur.yz}\right) \cdot F_{Quad}$
$F_{Knee.yz}$	$= \sqrt{F_{Knee.z}^2 + F_{Knee.y}^2}$
$\varphi\_F_{Knee.yz}$	$= arctan\left(\frac{F_{Knee.y}}{F_{Knee.z}}\right)$

Force acting on the knee joint is induced by the thigh muscles pulling on the anterior and posterior sides (simplified in this model); therefore, we calculated the absolute value of the "$y_{F_{Knee}} - y_{F_{FloorVirt.Knee.z}}$" within the "$F_{Quad}$"-calculation. Essential is that the most of the force is acting on the front side of the knee joint, being transmitted from the quadriceps muscle to the quadriceps tendon. Therefore, the designation "F_{Quad}" was chosen.

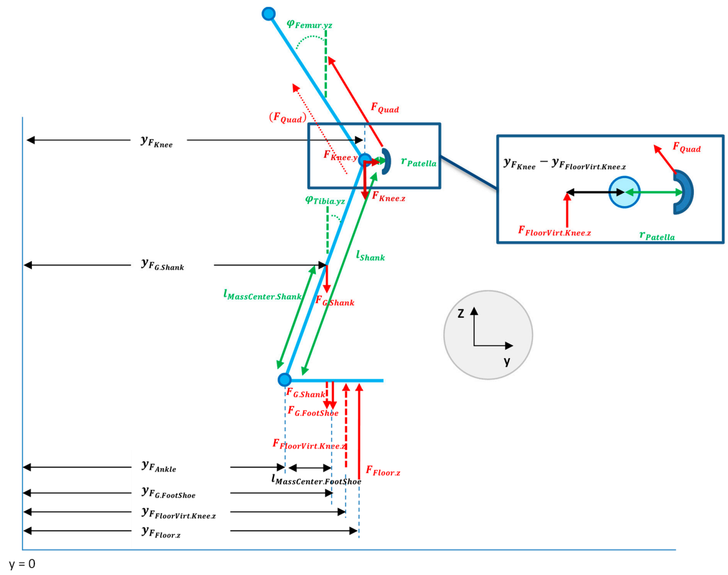


Figure A2. Calculation of knee joint forces.

Appendix A.1.3. Contribution of the Laevo®Exoskeleton

The Laevo® (Laevo®, Delft, The Netherlands) exoskeleton generates a moment about its rotation axis (“smart joint”) passing through the hip joints, assuming the rotating axis of the exoskeleton equals the axis which is passing through the rotation points of the hip joints. Therefore, the exoskeleton is loading the exoskeletons’ contact points, e.g., the chest at sternum level, the upper legs and the pelvis. The amount of force is determined by (1) the inclination angle of the exoskeletons “smart joint”, i.e., the angle between the trunk and the thighs, and by (2) the movement direction (e.g., upwards or downwards). The exoskeleton’s support moment (M_{Exo}) and the force acting on the thighs ($F_{Exo.Femur.sum}$) were recorded using the measurements of the force sensor that was integrated in the exoskeletons’ chest pad ($F_{Exo.Thorax}$) and the geometric dimensions of the exoskeleton’s structures ($l_{Exo.Thorax}$ and $l_{Exo.Thigh}$).

The forces related to the exoskeleton additionally act on the knee joints, being reduced by the thigh that acts as the lever arm. These exoskeleton-related forces were considered in the model as additively overlaying horizontal and vertical components of the forces acting on the knee joints.

Table A4. Symbols with description and Equations as used for the model displayed in Figure A3.

Symbol	Description
$l_{Exo.Thorax}$	= Distance between the smart joints and the chest pad
l_{Thigh}	= Thigh length
$l_{Exo.Thigh}$	= Distance between the smart joints and the leg pads
$\varphi_{Femur.yz}$	= Angle between femur and the perpendicular (y/z-direction)
$F_{Exo.Thorax}$	= Force acting on the chest pad
$F_{Exo.Thigh.sum}$	= Force acting on the leg pads
$F_{Exo.Knee}$	= Force acting on the knee induced by the exoskeleton
$F_{Exo.Knee.z}$	= Force acting on the knee induced by the exoskeleton in $z -$ direction
$F_{Exo.Knee.y}$	= Force acting on the knee induced by the exoskeleton in y-direction
$F_{KneeWithExo.z}$	= Total force at the knee joint in z-direction (exoskeleton included)
$F_{KneeWIthExo.y}$	= Total force at the knee joint in y-direction (exoskeleton included)

Table A4. *Cont.*

Symbol	Equation
M_{Exo}	$= F_{Exo.Thorax} \cdot l_{Exo.Thorax}$
$F_{Exo.Thigh.sum}$	$= \frac{F_{Exo.Thorax} \cdot l_{Exo.Thorax}}{l_{Exo.Thigh}} = \frac{M_{Exo}}{l_{Exo.Thigh}}$
$F_{Exo.Thigh}$	$= \frac{F_{Exo.Thigh.sum}}{2}$
$F_{Exo.Knee}$	$= \frac{F_{Exo.Thigh.\frac{l}{r}} \cdot l_{Exo.Thigh}}{l_{Thigh}} = \frac{F_{Exo.Thorax} \cdot l_{Exo.Thorax} \cdot l_{Exo.Thigh}}{l_{Exo.Thigh} \cdot l_{Thigh}} = \frac{F_{Exo.Thorax} \cdot l_{Exo.Thorax}}{l_{Thigh}} = \frac{M_{Exo}}{l_{Thigh}}$
$F_{Exo.Knee.z}$	$= \frac{F_{Exo.Thorax} \cdot l_{Exo.Thorax}}{l_{Thigh}} \cdot sin(\varphi_{Femur.yz}) = F_{Exo.Knee} \cdot sin(\varphi_{Femur.yz})$
$F_{Exo.Knee.y}$	$= -\frac{F_{Exo.Thorax} \cdot l_{Exo.Thorax}}{l_{Thigh}} \cdot cos(\varphi_{Femur.yz}) = -F_{Exo.Knee} \cdot cos(\varphi_{Femur.yz})$
$F_{KneeWithExo.z}$	$= F_{Floor.z} - F_{G.FootShoe} - F_{G.Shank} +$ $cos(\varphi_{Femur.yz}) \cdot F_{Thigh} \ldots + \frac{F_{Exo.Thorax} \cdot l_{Exo.Thorax}}{l_{Thigh}} \cdot sin(\varphi_{Femur.yz}) = F_{Knee.z} + F_{Exo.Knee.z}$
$F_{KneeWithExo.y}$	$= sin(\varphi_{Femur.yz}) \cdot F_{Thigh} - \frac{F_{Exo.Thorax} \cdot l_{Exo.Thorax}}{l_{Thigh}} \cdot cos(\varphi_{Femur.yz}) = F_{Knee.y} + F_{Exo.Knee.y}$
$F_{KneeWithExo.yz}$	$= \sqrt{F^2_{KneeWithExo.z} + F^2_{KneeWithExo.y}}$
$\varphi\_F_{KneeWithExo.yz}$	$= arctan\left(\frac{F_{KneeWithExo.y}}{F_{KneeWithExo.z}}\right)$

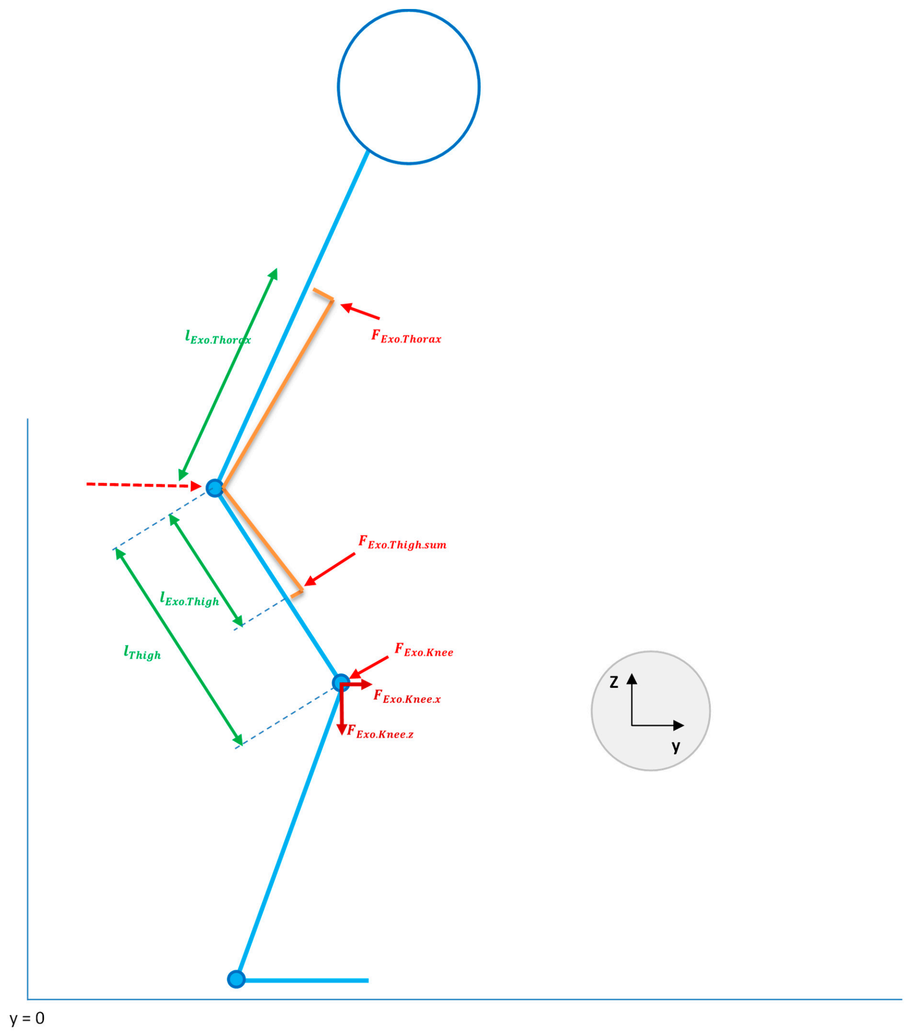


Figure A3. Calculations of knee joint forces including the contribution of the exoskeleton.

Appendix A.1.4. Limitations

Neglecting the dynamic movements

- Cf. Section 4.1 Limitations (manuscript)

Neglecting the horizontal ground reaction forces in this model:

- In this model, solely the vertical component (z-direction) of the ground reaction force is integrated; both horizontal acting components (x- and y-direction) of the ground reaction force are presumed to be extremely low in the here presented work tasks due to the experimental design. (No horizontal movements of the lower limbs and no fast movements have been included. Horizontal forces may only occur for short moments and to a small extent, due to the mass inertia during movement.)

Distribution of the exoskeleton's force acting onto the thighs

- The calculated sum of the force generated by the exoskeleton and acting on the subject's thighs was distributed onto both legs to be loaded by 50% each. This simplification of the model was applied instead of considering the individual angles between each upper leg and the trunk, because only one leg was prepared with the measurement equipment. Assuming that the subjects bent their trunk relative to their upper limbs similar between both body sides, the resulting division of the forces were exact. The expected error according to this simplification may be minimal since the main contribution to the knee joint loading is caused by the subjects' body weight and not by the exoskeleton.

Calculation of $r_{Achilles}$ and $r_{Patella}$

- We did not find any standard terms for calculating or estimating the $r_{Achilles}$ and $r_{Patella}$ in the available literature; therefore, we used own measurements for calculating an average ratio of the radius $r_{Achilles}$ and $r_{Patella}$ in relation to body size. Errors might result from this simplification in our model since the real individual distances were not considered. However, we used a within-subject-design, comparing the different conditions within each subject. Therefore, the relative changes between conditions can be used for comparison.

Joints and joint forces

- The ankle and knee joints were treated like a simple hinge joints; other aspects of the joint functions and movement variances were neglected.
- Torsional forces were neglected. However, the Laevo® is not designed to support torsional forces and is unable to absorb those. Therefore, the exoskeleton should not have any impact on torsional forces at the knee joints.
- The pivot point of a joint is not necessarily central which is assumed in this model. Further, when a body is moving the pivot point of a joint is shifting. The virtual pivot point of the joints is neglected in the model.
- The model includes forces which are produced by muscles responsible for the main movement in the work task (agonists). Forces which are induced by the antagonistic muscles (e.g., the biceps femoris) are not considered. Kellis and Baltzopoulos [58] showed an influence of including the antagonistic (hamstrings) muscle force into a two-dimensional tibiofemoral joint force model which increased the posteriorly directed shear and compression forces. In our force estimating model the antagonistic muscle force has only been partly included (calf muscle forces but not hamstrings), which could have biased the calculated knee forces.

Gravimetric position sensors

- Gravimetric positions sensors provide a very high precision in static postures and slower movements (standard error $\leq 0.5°$). In fast movements including high accelerations (which were not included in this experiments) these sensors are less precise; other techniques (i.e., motion capture systems) should then be applied.

Appendix B.

Table A5. *F*-values and *p*-values of the repeated measures ANOVAs with corresponding effect sizes (partial eta squared (η_p^2)). Main effects of the *Exoskeleton* condition (*E*) and the interaction effects for *E* with *Trunk orientation* (*E* × *TO*), *E* with *Lifting style* (*E* × *LS*) and *E* with *TO* and *LS* (*E* × *TO* × *LS*) for static and dynamic work tasks.

Task	Effect	HOR_{50}			HOR_{90}			$VERT_{50}$			$VERT_{90}$		
		F	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Static	*E*	0.16	0.696	0.006	-	-	-	7.41	**0.011**	**0.209**	-	-	-
	E × *TO*	27.60	**<0.001 ***	**0.496** $^{\lambda}$				1.19	0.313	**0.041**			
Dynamic	*E*	7.24	**0.012 ***	**0.205** $^{\mu}$	0.02	0.888	0.001	16.85	**<0.001 ***	**0.376** $^{\lambda}$	1.64	0.211	**0.054** $^{\sigma}$
	E × *TO*	23.34	**<0.001 ***	**0.455** $^{\lambda}$	11.90	**<0.001 ***	**0.292** $^{\lambda}$	1.02	0.368	**0.035** $^{\sigma}$	0.16	0.852	0.005
	E × *LS*	24.96	**<0.001 ***	**0.471** $^{\lambda}$	8.84	**0.006 ***	**0.236** $^{\mu}$	1.52	0.227	**0.052** $^{\sigma}$	4.06	0.053	**0.121** $^{\sigma}$
	E × *TO* × *LS*	7.04	**0.002 ***	**0.201** $^{\mu}$	1.52	0.227	**0.049** $^{\sigma}$	2.96	0.060	**0.096** $^{\sigma}$	2.60	0.083	**0.086** $^{\sigma}$

* Significant *p*-values ($\alpha \leq 0.05$); $^{\lambda}$ large effect size ($\eta_p^2 \geq 0.26$); $^{\mu}$ medium effect size ($\eta_p^2 \geq 0.13$); $^{\sigma}$ small effect size ($\eta_p^2 \geq 0.02$); HOR_{50} = 50th percentile of the horizontal force; HOR_{90} = 90th percentile of the horizontal force; $VERT_{50}$ = 50th percentile of the vertical force; $VERT_{90}$ = 90th percentile of the vertical force.

Table A6. Pairwise comparisons (*p*-values and Cohens'd (*d*)) for the relevant interactions between *E* × *TO*, *E* × *LS*, and *E* × *TO* × *LS* for variables with significant interaction effects for static and dynamic work tasks.

Task	Effect	Trunk Orient	Lifting Style	HOR_{50}		HOR_{90}	
				p	*d*	*p*	*d*
Stat	*E* × *TO*	ipsi		0.372	0.083	n.a.	n.a.
		front		0.091	**0.269** $^{\sigma}$	n.a.	n.a.
		cont		**<0.001 ***	**−0.912** $^{\lambda}$	n.a.	n.a.
Dyn	*E* × *TO*	ipsi		0.311	−0.045	0.981	−0.024
		front		0.834	0.018	0.028	**0.230** $^{\sigma}$
		cont		**<0.001 ***	**−0.493** $^{\sigma}$	0.013	**−0.244** $^{\sigma}$
	E × *LS*		Squat	**<0.001 ***	**−0.261** $^{\sigma}$	0.033	−0.139
			Stoop	0.276	0.072	0.050	0.145
	E × *TO* × *LS*	ipsi	Squat	**<0.001 ***	**−0.195**	–	–
			Stoop	0.024	0.166	–	–
		front	Squat	0.001	**−0.335** $^{\sigma}$	–	–
			Stoop	**<0.001 ***	**0.597** $^{\mu}$	–	–
		cont	Squat	**<0.001 ***	**−0.487** $^{\sigma}$	–	–
			Stoop	**<0.001 ***	**−0.717** $^{\mu}$	–	–

* Significant *p*-values ($\alpha \leq 0.00333$) for *E* × *TO*; ($\alpha \leq 0.00833$) for *E* × *LS*; ($\alpha \leq 0.00076$) for *E* × *TO* × *LS*; $^{\lambda}$ large effect size ($d \geq 0.8$); $^{\mu}$ medium effect size ($d \geq 0.5$); $^{\sigma}$ small effect size ($d \geq 0.2$); Trunk Orient = *Trunk orientation*; HOR_{50} = 50th percentile of the horizontal force; HOR_{90} = 90th percentile of the horizontal force; $VERT_{50}$ = 50th percentile of the vertical force; $VERT_{90}$ = 90th percentile of the vertical force.

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Chapter 6

Discussion and Conclusion

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This dissertation contributes knowledge of how using occupational exoskeletons—with a focus on passive back-support exoskeletons—may affect the musculoskeletal system of humans. It comprises of four publications (Chapters 2–5). One aspect, herein, is the determination of its positive effects, meaning a potential reduction of work-related stress or strain in the target body area, namely, the lower back. Another focus of this thesis is the detection and discussion of possible side-effects impacting areas outside of the target region. This discussion chapter will highlight key findings of the studies included in this doctoral thesis, summarize and discuss their contribution to the broader research context, derive practical implications regarding the use of occupational exoskeletons, and present recommendations for future research.

6.1 Effects of using occupational back-support exoskeletons

In Bär et al. (2021) we showed that using a BSE in work tasks has the potential to reduce physical strain parameters (e.g., muscle activity, perceived strain) in the back area, which has also been reported but not quantitatively investigated by other existing reviews within this research field (de Looze et al., 2016; Kermavnar et al., 2021; Theurel & Desbrosses, 2019). To date, there are only a few studies focusing on stress parameters, such as forces and moments, or on physiological strain, such as heart rate and energy expenditure, and the findings are inconclusive (Bär et al., 2021).

Physical stress and strain

As presented by Bär et al. (2022a) and Luger et al. (2021b), using the Laevo® exoskeleton in either a static holding or a dynamic lifting task (both being short-term performances) only slightly reduced muscle activity in the back area. Therefore, its beneficial effect on the lower back is questionable. Interestingly, hip extensor muscle activity (biceps femoris muscle) decreased when using this device (Bär et al., 2022a; Luger et al., 2021b), which is in line with other studies investigating passive BSEs (Bosch et al., 2016; Luger et al., 2021a). These findings indicate that the trunk extending character of a rigid BSE such as the Laevo® works due to an extension torque at the hip level than at the lower back level since the spring joint is located on the outside of the hip joint. Therefore, the designation of the Laevo® being a "hip-support exoskeleton" (ExR), rather than a BSE, might be more suitable.

Although the effects of using occupational BSEs are not yet confirmed, several literature reviews agree that reducing acute stress and strain in the back area may be one positive effect, and thus, reducing factors associated with WMSD and injury. However, the real impact of implementing an exoskeleton intervention on the true risk of developing WMSD or experiencing injury remains unknown (Bär et al., 2021; de Looze et al., 2016; Kermavnar et al., 2021; Theurel & Desbrosses, 2019). In this context, it is not clear which magnitude of the various acute stress and strain reductions has a positive effect on musculoskeletal health and to what extent. Furthermore, for an estimation of the exoskeleton's effects on WMSD risk, the detection of chronic effects is essential, since cumulative loading plays a substantial role in the development of WMSD (Coenen et al., 2013; Sandmark et al., 2000; Verbeek et al., 2017; Walzer & Thiede, 2016).

Energy expenditure, metabolism, and cardiovascular demands

Occupational exoskeletons aim to reduce the musculoskeletal load experienced in certain areas, but they may also affect other physiological processes, such as energy expenditure and cardiovascular and metabolic workload. In Bär et al. (2021) we showed inconclusive findings for using BSEs, including decreased (Alemi et al., 2020; Baltrusch et al., 2019; Baltrusch et al., 2020a; Lotz et al., 2009), unchanged (Godwin et al., 2009; Luger et al., 2021a), and increased (Baltrusch et al., 2019; Marino, 2019; Miura et al., 2018) metabolic and cardiovascular parameters. Using the Laevo® slightly reduced the heart rate, although it was not substantial (Bär et al., 2022a; Luger et al., 2021a, 2021b). Possible elevations in other devices may be caused by additional weight the exoskeleton user has to carry or changes in the user's usual movement pattern. However, this assumption is beyond the current knowledge. Most occupational exoskeleton research has focused on acute effects, and only a few studies have used endurance protocols (lasting 45min (Godwin et al., 2009) to 120min (Marino, 2019)), which are essential for the detection of metabolic and cardiovascular responses at work.

6.2 Side-effects of using occupational back-support exoskeletons

For a safe application of exoskeletons, potential side-effects need to be clarified before implementation. Within this new research field, many open questions remain, some of which were addressed in Chapters 2–5.

Physical stress and strain

As indicated by Bär et al. (2021), increasing stress and strain in non-target areas when using a BSE is the main concern of potentially occurring side-effects. Herein, muscle activity or perceived parameters have been evaluated most frequently (e.g., Alemi et al., 2019; Bosch et al., 2016; Luger et al., 2021a). However, there is no sufficient evidence whether using a BSE negatively affects its user or not (Bär et al., 2021). In Bär et al. (2022a) and Luger et al. (2021b), we confirmed previous findings that only minor changes in muscle activity of the non-target areas occur when performing either static sorting (Bär et al., 2022a; Bosch et al., 2016; Kim et al., 2020) or dynamic lifting (e.g., Alemi et al., 2019, 2020; Baltrusch et al., 2019; Frost et al., 2009; Luger et al., 2021b; Madinei et al., 2020a) work tasks using the Laevo®. Excluded from this was the biceps femoris muscle, whose function is mainly to provide a hip extension torque in the here evaluated motoric tasks and should therefore be considered as the target area of the exoskeleton.

In Bär et al. (2022b) we describe, as far as we are aware for the first time, the knee joint forces (horizontal-anteroposterior and vertical tibiofemoral joint forces) when using a BSE. Using the Laevo® during various work tasks resulted in increased vertical tibiofemoral joint forces, illustrating a clear impact of the device's weight on the musculoskeletal structures lying underneath. The influence of the Laevo® on horizontal tibiofemoral forces seems to depend on the performed work task and a certain maintained posture, which supports several previous studies evaluating muscle activity and posture when using BSEs (Bär et al., 2022a; Kim et al., 2020; Luger et al., 2021a, 2021b; Madinei et al., 2020a).

According to current literature, increased stress may be induced by a load transfer from one body area to another (Bosch et al., 2016; Frost et al., 2009; Steinhilber et al., 2020; Theurel & Desbrosses, 2019). Nevertheless, Zelik et al. (2022) warned against a common assumption that the load taken from a certain area is directly transferred to other areas. An exoskeleton functions via leverage: less force is needed than the musculoskeletal structures would need to perform the same task (Zelik, 2020). However, the occurrence and mechanism of load transfer or newly appearing load on the musculoskeletal system needs to be investigated in more depth.

Kinematic changes—body posture

Body posture was described previously to interact with exoskeleton effects and with musculoskeletal health. Bär et al. (2022a) and Luger et al. (2021b) show that using the Laevo® exoskeleton leads to increased hip and knee flexion angles, especially prominent in the hip joint where the exoskeleton torque applies. Simultaneously, spinal posture only changed slightly (Bär et al., 2022a; Luger et al., 2021b). This is in line with the results of investigating the Laevo® in less controlled simulated work tasks (Luger et al., 2021a), however, the effects of using BSEs on kinematics is conflicting across the literature to date and their impact on musculoskeletal health is not known.

An adjusted body posture might be taken by the users in order to adopt the most convenient posture to benefit from the exoskeleton's supportive torque, to maintain postural stability when performing a particular work task, or to take a comfortable posture (e.g., to avoid any discomfort induced by the device's structures). However, any kinematic changes may lead to further consequences along the involved postural chain. Even if an altered joint angle is judged to be positive (e.g., restricted lumbar flexion), it is associated with further adaptations of the locomotor system, such as inter-joint coordination (e.g., movement pattern across adjacent joints), inter-muscular coordination (e.g., co-contraction), intra-muscular coordination (e.g., muscle activity recruitment), muscle mechanics (e.g., muscle lengths), and centre of gravity shifts (Burgess-Limerick, 2003; Gallagher & Hamrick, 1991). This emphasizes the need for research, including the entire postural chain, when evaluating occupational exoskeletons (Theurel & Desbrosses, 2019). Except for single joint angles in a few investigations, other kinematic parameters such as movement velocity, acceleration, and joint range of motion have not been studied in detail (e.g., Baltrusch et al., 2020a; Koopman et al., 2020a; Madinei et al., 2020a; Simon et al., 2021).

Muscular co-activation

In Bär et al. (2022b) we discussed the aspect of antagonistic muscle co-contraction and its contribution to joint stability and joint forces for the knee joint, and the possible influence of using a BSE on it. Likewise, in the spine area, muscle co-contraction may be a significant risk factor for back disorders, e.g., resulting in LBP (Theurel & Desbrosses, 2019). When lifting, abdominal muscle activity contributes to the required amount of trunk stabilization (de Looze et al., 1999; Ivancic et al., 2002; Koopman et al., 2019) and may increase to take over while decreasing back muscle activity (de Looze et al., 1999), for example, in deep stoop trunk flexion when flexion-relaxation occurs (Frost et al., 2009; Koopman et al., 2019) or when taking advantage of the BSE support (Alemi et al., 2019; Frost et al., 2009). A disadvantage might be that the increased stiffness caused by abdominal muscle activity contributes to an elevated spinal compression force (de Looze et al., 1999). Mostly, this muscle group did not experience major changes when using a BSE (Bär et al., 2021, 2022a; Luger et al., 2021a, 2021b). In contrast, a few studies monitored increased abdominal muscle activity that appeared in some of the task executions, such as stoop lifting (Frost et al., 2009; Koopman et al., 2019), when the exoskeleton was set to a stiffer mode (Frost et al., 2009), and some results showed high inter-subject variabilities (Alemi et al., 2019; Koopman et al., 2019). The rationale behind the increased abdominal muscle activity in some cases (Frost et al., 2009), and the extent to which this may contribute to spinal compression (Koopman et al., 2019), is not clear yet. The possible contribution of muscular co-activity to the effects of using occupational exoskeletons should be considered instead of relying on evaluations of single muscles or muscle groups.

Balance impairment

A further concern that has been raised is the impairment of the wearers' balance by wearing an external structure (de Looze et al., 2016; Howard et al., 2020; Nussbaum et al., 2019; Zingman et al., 2017). The centre of gravity may shift (Howard et al., 2020; Zingman et al., 2017), which can lead to a loss of balance and consequently to an increase of falling risk (Holbein & Chaffin, 1997; Pollock et al., 2000). This requires special attention for work areas already including environmental hazard risks (e.g., heights, risk for slipping, etc.). The aspect of balance or postural control in occupational exoskeleton wearers has received very little attention so far. In a study by Alemi et al. (2020), the perceived balance remained unchanged in three out of four lifting task conditions and was improved in one when using the Laevo® V2.5 exoskeleton, while the balance was reported to remain unchanged in all conditions when using another passive BSE[7]. Wearing two lower body exoskeletons in occupational assembly tasks (Luger et al., 2019)

[7] BackX™ AC (US Bionics Inc., Berkeley, CA)

or for load carrying in a military context (Schiffman et al., 2008) resulted in changes in the centre of pressure trajectory. Changes in balance and postural control are most likely dependent on an individual exoskeleton design (e.g., the exoskeleton's individual mechanical properties) and should be individually estimated prior to an application.

Neuro–cognitive demands

Zhu et al. (2021) highlight possible enhancements of neuro–cognitive demands that, if substantial, may lead to alterations in muscle recruitment patterns and muscle co-activity. When lifting and lowering a load while performing an additional cognitive dual-task (mental arithmetic) they found neuromotor and cognitive adaptation efforts when using a passive BSE. The consequence could be an increased loading in several body areas. This may further diminish the original positive effect of reducing the physical load in an addressed area (e.g., lower back). Considering individual exoskeletons, this effect may increase with the complexity of the device in terms of use (Zhu et al., 2021). However, apart from this one study, the discussion is beyond the findings of the current literature.

Perceived strain

Perceived strain has been used as a predictor for the occurrence of musculoskeletal strain. Subjective perceptions such as perceived discomfort, exertion, and tension were reported to be increased in non-target areas when using a BSE (Alemi et al., 2020; Bosch et al., 2016; Gorsic et al., 2022; Kim et al., 2020). However, at present, the picture of increased, decreased, or unchanged perceived strain in the non-target areas is ambiguous (Bär et al., 2021). Importantly, negatively perceived subjective parameters do not necessarily indicate the hazardous nature of an exoskeleton itself. Remediable reasons could be responsible, such as subjects not being familiarized with wearing the exoskeleton, poor fit of the device (Zingman et al., 2017; e.g., not being correctly adjusted or no possibility to adjust the structures to the wearer), or incorrect use (e.g., through incorrect settings).

External hazards and repercussions

There are possible external hazards and repercussions that need to be considered before approving an exoskeleton for work. First, the aim of anthropomorphic exoskeletons is to mimic the user's anthropometry and align their joint rotation axis with the user's joints. Although many exoskeletons are constructed to be adjustable to the wearer's body, the alignment of structures may not coincide perfectly with the user. Poor compliance of the exoskeleton with the human's anthropometry and mechanics may cause additional, undesirable forces and subsequent discomfort or elevated injury risk (Huysamen et al., 2020; Toxiri et al., 2019). Second, mobility may be restricted by wearing an exoskeleton making fast movements difficult, e.g., in hazardous situations (Zingman et al., 2017). This may impair dodging an object, quickly escaping from a hazardous place, or regaining balance after stumbling. Third, the structures of the exoskeleton could get caught on passing or overhanging objects/structures or machinery (Kim et al., 2019), especially when being very expansive. Fourth, when falling, injury risk may be increased due to the structures around the body and the additional weight of the device (DGUV, 2019; Schick, 2018). Fifth, an exoskeleton may hinder accurately wearing a necessary PPE (e.g., fall arrest harness in hights) and might therefore diminish its protective function (BGHW, 2022; Kim, 2019). Sixth, hygiene issues may occur when exoskeletons are shared between several users and not cleaned appropriately (Kim, 2019; Zingman et al., 2017). Seventh, the exoskeleton may give its wearer a false sense of increased safety, and he or she might take more risks at work or overwork oneself (Kim, 2019; Lowe et al., 2016).

In conclusion, there are various aspects to consider when identifying possible side-effects and repercussions of using occupational exoskeletons. To date, evidence is lacking on whether exoskeleton applications adversely affect the musculoskeletal system of the wearer, especially in the long run. Caution is therefore required for promoting the application of occupational exoskeletons.

6.3 Factors influencing the effects of back-support exoskeleton use

Work task and execution technique dependency

When observing a certain task execution, including lifting styles and trunk orientation, the respective posture should be considered as it has been shown to interact with the (side-) effects of using the Laevo® exoskeleton on stress and strain parameters (Bär et al., 2022a, 2022b; Luger et al., 2021b). This is not surprising given the provided torque of an individual device probably depends on the device's joint angles and the wearer's posture, further supporting previous investigations (e.g., Kim et al., 2020; Madinei et al., 2020a, 2020b).

In realistic full- or part-time work shifts, a variety of work tasks need to be performed, and various task executions are possible dependent on the exoskeleton user or the environment. Several studies have shown that the effects—either positive or negative—of using a BSE depend on the work tasks performed and vary between distinct task executions. In lifting tasks, stress and strain parameters were influenced by lifting style (stoop, squat, freestyle; Bär et al., 2022b; Frost et al., 2009; Luger et al., 2021b), lifting distance (Koopman et al., 2020a), lifting symmetry (including trunk rotations; Bär et al., 2022b; Madinei et al., 2020a), and movement direction (up or down) as well as inclination angle within a lift–lower cycle (Schwartz et al., 2021). In manual assembly tasks, work hight, distance, and symmetry were determinants for the effects on stress or strain (Bär et al., 2022a; Kim et al., 2020; Madinei et al., 2020b), and in static trunk forward bending postures, the bending angles manipulated the effects (Koopman et al., 2019; Tetteh et al., 2022).

Exoskeletons are usually designed to support specific work tasks which directly serve a work goal, such as assembly tasks in industries or lifting objects in logistics (primary tasks). However, in between primary tasks, additional tasks need to be performed, such as climbing stairs or a ladder, lifting an object (if this is no regular task), rising from a chair, or simply walking (secondary tasks; BGHW, 2022; Glitsch, 2020). Using the Laevo® in several functional tasks was reported to increase perceived task difficulty, to mainly negatively alter task performance (e.g., prolonging task duration; Baltrusch et al., 2018; Luger et al., 2021a), and to increase discomfort, particularly in walking tasks and tasks requiring a high joint range of motion (the supportive torque either being switched on (Baltrusch et al., 2018), or off (Luger et al., 2021a)). Another passive BSE[8] was shown to alter gait parameters in simple walking, which may negatively affect walking energetics and fall risk (Park et al., 2022). This emphasizes the concern of negative effects occurring as a result of using exoskeletons in secondary tasks that the devices are not designed for.

Subject dependency

The heterogeneity of human anthropometrics has been described to be one key factor for the design and fit of anthropomorphic exoskeletons (Cenciarini & Dollar, 2011), and

[8] backX™ AC (US Bionics Inc., Berkeley, CA)

further personal characteristics such as sex, health status, and age may influence the effects of using the devices. Despite this, most of the current research has included rather young, healthy (Kermavnar et al., 2021), and male subjects (Bär et al., 2021; Kermavnar et al., 2021). For example, an exoskeleton may fit differently depending on its user. That is, it may not be adjustable according to the manufacturer's instruction (e.g., the leg pad position is dependent on thigh length; Bär et al., 2022a, 2022b), it may slip in some users when moving (e.g., a BSE-hip belt dependent on the individual pelvis shapes), it may induce increased pressure or discomfort (e.g., by the chest pad dependent on an individual's thorax size; Alemi et al., 2020; Kim et al., 2020), or users may receive a different amount of relative support (e.g., too little or too much torque, depending on body mass; Baltrusch et al., 2020a; Simon et al., 2021). A few studies have addressed possible interaction effects of sex with intervention and found different effects for males and females on some evaluated parameters, including perceived discomfort, perceived exertion, muscle activity in target and non-target areas, and performance when evaluating distinct BSEs (Alemi et al., 2020; Kim et al., 2020; Madinei et al., 2020a, 2020b; Ulrey & Fathallah, 2013a) or ULEs (Alabdulkarim et al., 2019; Alabdulkarim & Nussbaum, 2019). However, the nature of such differences is not clear yet. Anthropometric differences between males and females (e.g., differences in upper body mass) could be responsible for variations in postures and movements, and distinct exoskeleton design approaches need to reflect the specific needs of male and female users (e.g., in fit, or required torque; Alemi et al., 2020; Madinei et al., 2020a). Already in the developmental stage of an exoskeleton, individual technical requirements for the device of human characteristics (e.g., sex, anthropometrics, age, and musculoskeletal health) should be considered. Future research needs to focus on the detection of these.

Design dependency

Another factor that determines the effects of using occupational exoskeletons in work tasks is their individual design, e.g., their mechanical characteristics (Schwartz et al., 2021; Theurel & Desbrosses, 2019). To date, only a few studies have focused on comparing different BSE designs in occupational assembly tasks (Madinei et al., 2020b) or lifting tasks (Alemi et al., 2020; Madinei et al., 2020a) and found differences in stress and strain parameters between the devices[9] (working with rigid components). When comparing five different support settings by modulating the stiffness of the elastic elements in a soft BSE[10] (Frost et al., 2009) and when comparing two distinct support settings of a rigid BSE[11] (Koopman et al., 2020a; Koopman et al., 2019) distinct effects on stress and strain parameters between the setting conditions were identified. These differences interacted with the work task executions, such as the lifting style (Frost et al., 2009), lifting height (Koopman et al., 2020a), and trunk bending angle (Koopman et al., 2019).

6.4 Supportive torque characteristics

Upcoming research should focus on the level of physical support provided by the exoskeleton, as this has been poorly attended to so far (Glitsch, 2020; Huysamen et al., 2020; Steinhilber et al., 2020). Herein, it needs to be questioned how much supportive torque provided by an exoskeleton would reduce stress and strain (and to what extent) in the supported areas and, further, which level of stress and strain reduction would be effective in terms of reducing WMSD and injury risks. Furthermore, necessary support may vary across individuals. In a subject with less body mass, the absolute torque of an exoskeleton is relatively higher than that of a heavier person, and moreover, their personal force capacity may vary. For example, in a study that evaluated a passive BSE[12] that has a comparatively high supportive torque, one female participant had to be excluded because "the exoskeleton appeared to be too strong" for her (70 Nm vs 23–50 Nm in some other BSEs[13]; Baltrusch et al., 2019; Bär et al., 2022b; Koopman et al., 2019; Lamers, 2017; Simon et al., 2021). Further, for different work tasks, a different amount of supportive torque is required (Näf et al., 2018). Lifting style, for example, which depends on the particular lifting conditions (e.g., object size and height), is a determinant for lumbar spine moments (Kingma et al., 2010) and the necessary support is therefore individual (Näf et al., 2018).

[9] backX™ AC (US Bionics Inc., Berkeley, CA) and Laevo™ V2.5 (Laevo, Delft, The Netherlands)
[10] PLAD—personal lift assist device (Abdoli-Eramaki et al., 2006)
[11] Laevo (V2.4) (Laevo, Delft, The Netherlands)
[12] VT Lowe (Chang, 2021)
[13] PLAD—personal lift assist device (Abdoli-Eramaki et al., 2006), Laevo® V2.4/ V2.5 (Laevo ® Delft, Netherlands), Biomechanically-Assistive Garment (Lamers et al., 2017), and SPEXOR (Baltrusch et al., 2020)

In passive BSEs, the angle-force relationship is individual for each design, and different work tasks need certain force–angle relationships of the supportive torque. The Laevo® exoskeleton, for example, provides its highest support at a trunk forward flexion angle of around 40° and substantial supportive torque differences were found between trunk bending and extending movement (Koopman et al., 2019). The exoskeletons user may not benefit when holding a trunk forward bent posture differing from the optimal support angle. Furthermore, the relatively higher supportive torque in a dynamic movement (e.g., lifting) when bending down may produce additional negative side-effects, while the upward movement is sufficiently or too little supported.

Taken together, exoskeletons have different support characteristics, and the required support depends on the individual work tasks and the individuality of humans. Therefore, for safe and effective applications of BSEs, the optimal assistive torque needs to be determined for work situations. Unfortunately, there is little guidance regarding the necessary supportive torque magnitude for developers (Huysamen et al., 2020). In many studies, the supportive torque was not recorded, considered for the interpretations of the results, or reported.

6.5 Health-relevant considerations

Prevention of WMSD

The effectiveness of occupational exoskeletons with respect to their central aim to prevent WMSD must be verified before an application can be considered. The type of application is determined by three different stages of prevention based on the subject's health status. For a primary prevention, exoskeletons would be used regularly in healthy individuals with the goal of avoiding WMSDs. For a secondary prevention, exoskeletons would be used to reduce musculoskeletal symptoms or to prevent exacerbation in symptomatic individuals. For a tertiary prevention, exoskeletons would be used to delay the course of WMSDs or to help with the individual's reintegration (Steinhilber et al., 2020). Although it has been previously described that occupational exoskeletons can reduce parameters associated with WMSD risk, the authors of several reviews and overview papers agree that no preventive effects can yet be derived from the current state of research (Bär et al., 2021; Howard et al., 2020; Steinhilber et al., 2020; Theurel & Desbrosses, 2019). The majority of the available research to date has focused on healthy subjects. Therefore, the usefulness for symptomatic individuals—including secondary and tertiary prevention—cannot be estimated. To estimate all three types of prevention, a better knowledge of the long-term effects of using the devices under realistic working conditions is essential.

Appraisal for an application as personal protective equipment

A possible categorization of occupational exoskeletons as an emerging type of personal protective equipment (PPE) has been suggested, due to their characteristic similarities, such as their wearable nature and preventive intention (BGHW, 2022; DGUV, 2019; Lowe et al., 2019). A legal prerequisite for a PPE declaration is the conformity according to the Personal Protective Equipment Regulation (EU) 2016/425, including a risk assessment for the device (Regulation, 2016). Accordingly, conventional PPE is intended to protect the user from external hazards by providing a physical barrier (e.g., protective shoes, gloves, glasses; Howard et al., 2020; Lowe et al., 2019). However, experts in the field of occupational exoskeletons express concern that the body of evidence to promote exoskeletons being qualified does not yet exist (Howard et al., 2020; Kim et al., 2019; Nussbaum et al., 2019). Additionally, qualification and test standards are still lacking (Lowe et al., 2019).

In contrast to the idea of external protection, exoskeletons aim to prevent the user against the internal physical load of the musculoskeletal system or metabolic exertion. Quantifying the profit of using such a device is challenging, as it depends on various factors (e.g., physical composition and capacities of the individuals, work tasks, and exoskeleton design; Lowe et al., 2019), which were discussed in detail in section 6.4. As addressed in section 6.5, it is not clear how much supportive torque would be necessary for a certain situation and the extent of risk reduction this would lead to. Certainly, this information together with the knowledge of occurring side-effects—which was extensively discussed in section 6.2—should be the basis for the assessments proving occupational exoskeletons to be qualified as PPE.

6.6 Methodological approach of exoskeleton research

The main issue for a realistic evaluation of occupational exoskeletons, and related recommendations for practical applications, is the low methodological quality found in the literature: Studies that include various interrelated parameters, focus on the broad spectrum of possible side-effects, and long-term field studies are still missing (Bär et al., 2021).

Selection of evaluated parameters

An important thing to keep in mind is that primarily only muscle activity—which is indeed important to evaluate—has been observed without monitoring related parameters (Bär et al., 2021; Kermavnar et al., 2021; Theurel & Desbrosses, 2019). The relation of muscle activity to body posture was shown in two BSE evaluations, in which slight changes in spine postures led to major changes in back muscle activity (Koopman et al., 2019; Ulrey & Fathallah, 2013a). This may be due to a shift between active and passive structures (Koopman et al., 2019), as passive structures (such as ligaments and connective tissue) provide parts of the required torques for movements or holding postures (Fathallah, 2004; Gallagher & Hamrick, 1991). Especially in lower trunk forward bent postures, the back extensor muscle activity decreases and the load is absorbed by stretched passive structures, which then provide the extension torque. Both active and passive internal forces are responsible for spinal compressive and shear forces affecting the intervertebral discs (Fathallah, 2004). Therefore, a reduction in strain parameters (e.g., muscle activity) may accompany increased stress on other structures (e.g., joint forces). Thus, an interpretation of strain parameters without additionally monitoring the body posture and stress parameters should be done cautiously (Koopman et al., 2019).

Further, although many passive BSEs provide a supportive torque at the hip joint level, most BSE investigations have focussed on only back muscle activity (Bär et al., 2021). However, especially in stoop postures (which are frequently performed in several work fields), trunk extension is initiated and supported by pelvic de-rotation requiring the activity of the gluteal and hamstring muscles. The associated muscle stretch is further responsible for spinal compression forces (Gallagher & Hamrick, 1991). Nevertheless, only in some studies, the biceps femoris (e.g., Bär et al., 2022a; Bosch et al., 2016; Luger et al., 2021a, 2021b) and only in very few studies, the gluteus maximus (e.g., Baltrusch et al., 2020b; Frost et al., 2009; Hyun et al., 2020) muscle activity, has been monitored.

Comparison across study results

The comparison of exoskeleton effects across different studies remains challenging due to the heterogeneity of the testing protocols used. Standardizing testing protocols is one solution (Kermavnar et al., 2021), however it includes a trade-off with the actual work representativeness of the experimental design (De Bock et al., 2022). In the project "Exoworkathlon®", Fraunhofer IPA and IFF University of Stuttgart developed four work task courses for evaluating occupational exoskeletons (two for BSEs and two for ULEs) under conditions closer to industrial work lasting one hour each (Exoworkathlon, 2022; Kopp, 2022). Using these may be the next step toward a more realistic evaluation and thus better comparisons across occupational exoskeletons. However, the evaluation process remains dynamic as the technical development of devices is rapid. Further, as discussed previously, the application of devices is very individual regarding the users, work tasks required, and exoskeleton designs. Therefore, standardizing experimental protocols remains challenging and, with it, the comparison across study results.

6.7 Recommendations for research and practical implementation

Future research

This thesis emphasizes the need for further research in the field of exoskeleton investigation. First, starting with the main aim of occupational exoskeletons: the prevention of WMSD. For a realistic determination of exoskeleton effects, prospective interventional field studies over extended periods of time using both healthy and symptomatic workers are essential (Howard et al., 2020; Steinhilber et al., 2020). Second, in order to guarantee safe applications of occupational exoskeletons, the determination of possible side-effects or any health hazards requires further attention. Third, a critical selection of outcome parameters should be set for specific work tasks and the goal of using a certain exoskeleton. Herein, various interrelated parameters need to be assessed to better understand the background or reason for an adapting parameter. Fourth, exoskeleton research should include the individuality of humans (e.g., sex, anthropometrics). It further needs to consider the work task specificities and individualities across exoskeleton designs since the effects depend on these factors. Already in the developmental stage, these aspects need to be incorporated. Fifth, there is a need to determine which supportive torque characteristics are required, depending on the work task, individual user, and primary goal of using an exoskeleton. Since this aspect is not yet clear (Huysamen et al., 2020), it remains challenging to develop occupational exoskeletons. Sixth, before accepting an individual exoskeleton to be classified as PPE, it must be tested carefully to meet all legal and health-relevant requirements. Seventh, further aspects such as sociological questions (e.g., user acceptance) or adaptation barriers (Howard et al., 2020) should also be investigated. However, performing an extensive exoskeleton investigation before implementation remains challenging due to the rapid technical development in this field.

Practical implementation

Industrialists who consider implementing occupational exoskeletons as a workplace intervention should also confront further open points. For positive implementation and adoption, obstacles and facilitators such as user acceptance, cognitive requirements, cost–benefit relation, and others need to be identified (Kim, 2019). It is crucial to carefully choose the appropriate exoskeleton (e.g., individual support characteristics) related to the work tasks to be performed. The workplace, with its individual tasks, has to be assessed and risk assessments must be conducted in relation to each individual device (BGHW, 2022). Prior to use, users must obtain detailed instructions and participate in training sessions. An adaption period must be carried out as missing familiarization may cause negative effects such as postural changes (Gordon & Ferris, 2007; Simon et al., 2021). The introduction and regular use of occupational exoskeletons must be attended to and monitored by experts. In total, the decision to implement an occupational exoskeleton must be carefully considered, legal and workplace-specific regulations must be complied with, and specific monitoring must take place.

6.8 Strengths and limitations

This doctoral thesis contains a broad overview of the current exoskeleton research by way of an extensive systematic review with meta-analyses. It includes all types of occupational exoskeletons, various stress and strain-related outcome parameters, and an extensive quality assessment. The thesis further provides evidence of the various effects of using an exemplary commercially available BSE. Besides evaluating the intended effects, a major focus was on detecting negative side-effects—where a particularly high demand for research exists. This research is one of the first to include different work task executions (lifting style, trunk orientation), and additionally monitors body postures. Additionally, it is the first to focus on knee joint forces in a BSE evaluation. Beyond discussing the research results of this thesis (Chapters 2–5), associated discussion points are addressed, and related research gaps are identified. Moreover, current topics regarding the application of exoskeletons in occupational practice are addressed and discussed in light of the obtained knowledge and keeping in mind the main objective of promoting musculoskeletal health.

There are some limitations of the thesis to be noted, however, limitations regarding the single papers are not discussed in detail here. After evaluating the Laevo® V2.56 exoskeleton, no common conclusions can be drawn due to the high standardization of this controlled experiment, including a restricted population group and highly standardized simulated work tasks. However, the findings contribute to the knowledge that occurring (side-) effects depend on the individual work task performed and its execution or style and that they interact with body posture. From this research, no information about the effects of the Laevo® or any BSE on cumulative strains or muscular fatigue can be drawn as the presented experiments (Chapters 3–5) and most of the papers included in the systematic review (Chapter 2) investigated occupational exoskeletons using short-duration experimental tasks. The main challenge for the topicality of this research (e.g., the completeness of the systematic review and the main discussion) is the rapid development and technical improvement of exoskeletal devices and the associated delay of the research publications.

6.9 Conclusion

The aim of this doctoral thesis was to investigate positive and negative effects of using back-support exoskeletons on physical stress and strain in occupational tasks. This research reveals that using an occupational BSE has the potential to reduce acute musculoskeletal stress or strain in the back area. However, this was not clearly reproduced for the Laevo® V2.56 exoskeleton, which seems to support hip rather than back extension. Using BSEs may negatively affect the human musculoskeletal system occasionally, however, there is currently insufficient evidence to support this. Generally, the effects of using occupational BSEs depend on the individual work tasks and their execution (e.g., the body posture) and may be influenced by both human individuality and each exoskeleton's mechanical characteristics. This thesis emphasizes the need for further research investigating the effects and side-effects of using BSEs at work and possible influencing factors, by precisely and appropriately selecting and combining the various outcome parameters. Randomized controlled intervention studies in the field, including healthy and symptomatic professionals, are required for a realistic estimation of long-term effects relevant for musculoskeletal health. The preventive effects of BSEs on WMSDs are beyond the current research, therefore their application as a workplace intervention to prevent WMSDs cannot be recommended.

Summary

Exoskeletons are wearable, mechanical structures supporting the musculoskeletal system (e.g., in physical work) by generating torques which act on the human body. Recently, they have been introduced as a new prevention approach for work-related musculoskeletal disorders (WMSDs), receiving growing interest in various occupational areas and in research. However, their effectiveness on musculoskeletal health has not been proven, and possible negative effects impacting the musculoskeletal system have not been sufficiently investigated. Therefore, the aim of this doctoral thesis was to investigate the effects of using back-support exoskeletons (BSEs) on physical stress and strain during industrial tasks. Herein, the back, as the main target area, and other unsupported areas (e.g., the legs, shoulders, abdomen) are focused.

The thesis begins with a systematic review with several meta-analyses (Bär et al., 2021) outlining the effects of occupational exoskeletons on biomechanical, physiological, and subjectively perceived stress and strain. The meta-analyses revealed that using a BSE can potentially reduce the acute stress or strain in the back area during industrial tasks. Negative side-effects were not identified by the analyses for the BSEs, but occur occasionally. However, there is still not enough research on this aspect. Overall, research following high methodological standards and evaluating various health-relevant aspects is thoroughly lacking.

In response to the findings of Bär et al. (2021), an exploratory laboratory experiment was conducted to determine the influence of the commercially available passive BSE Laevo® V2.56 on physical stress and strain during simulated industrial tasks. Specifically, we investigated the effects of using the device on muscle activity in various body areas, spine and lower limb postures, and heart rate, focusing on a sorting task holding a static forward bent posture (including different trunk orientations; Bär et al., 2022a), and on a dynamic lifting task (including different lifting styles and trunk orientations; Luger et al., 2021b). Finally, Bär et al. (2022b) presents the exoskeleton’s effects on vertical and horizontal (anteroposterior) tibiofemoral joint forces during the static and the dynamic work tasks.

In Bär et al. (2022a) and Luger et al. (2021b) we found that using the Laevo® in simulated industrial tasks resulted in only minor, reductions of the back extensor muscle

activity (the erector spinae), but moderate support for hip extension (the biceps femoris). Meanwhile, minor changes in spinal posture and muscle activity in unsupported body areas occurred, and hip and knee flexion moderately increased. Thereby, the individual task executions (lifting style, trunk orientation) influenced the effects. Heart rate slightly decreased when using the Laevo® across all task executions (Bär et al., 2022a; Luger et al., 2021b). The vertical tibiofemoral joint forces generally increased with using the Laevo® without interacting with the task executions, while the device's effects on the horizonal (anteroposterior) tibiofemoral joint forces varied across the individual experimental conditions (Bär et al., 2022b).

This research shows that using a BSE may support either the back or hip extension and reduce acute stress or strain in target areas. However, changes of only single parameters (e.g., muscle activity) without monitoring associated musculoskeletal structures and functions (e.g., joint postures and forces) may prevent correct interpretations behind possible changes. Furthermore, negative side-effects may occur when using a BSE, which are insufficiently examined or not yet identified. The detection and further exclusion of negative side-effects is essential for the safe application of occupational exoskeletons. Various other factors may also codetermine any effects (either desired or undesired) associated with the use of occupational BSEs, e.g., individual work tasks and executions, mechanical characteristics of the device, and human individualities. Therefore, implementations of occupational exoskeletons at work should be preceded by individual assessments of the devices, with particular consideration of the various influencing factors. Overall, definitive conclusions in relation to musculoskeletal health is still beyond this dissertation and the current literature. Randomized controlled intervention studies in the field are critical for detecting long-term effects related to WMSD risk. They must include a well-thought selection and combination of various outcome parameters and body areas (e.g., relate various interacting stress and strain parameters, and include several interrelated musculoskeletal structures) and consider adherence to high methodological quality standards.

Zusammenfassung

Exoskelette sind tragbare, mechanische Strukturen, die das muskuloskelettale System, z.B. bei physischen Arbeitstätigkeiten, unterstützen, indem sie mit Kräften und Drehmomenten auf den menschlichen Körper einwirken. Kürzlich wurden sie als eine neue Präventionsmöglichkeit für arbeitsbezogene Muskelskeletterkrankungen vorgestellt und stoßen in verschiedenen Arbeitsfeldern und der Wissenschaft auf ein wachsendes Interesse. Eine positive Wirksamkeit von Exoskeletten in Bezug auf die muskuloskelettale Gesundheit wurde allerdings noch nicht erwiesen und mögliche, das Muskelskelettsystem negativ beeinflussende Parameter wurden noch nicht ausreichend untersucht. Daraus ergibt sich das Ziel dieser Doktorarbeit: die Erforschung von Auswirkungen einer Rücken-Exoskelett Nutzung bei industriellen Tätigkeiten auf die physische Belastung und Beanspruchung. Dabei werden zum einen der Rücken (als Zielregion) und zum anderen nicht vom Exoskelett unterstützte Körperregionen (z.B. Beine, Schultern, Bauch) fokussiert.

In Bär et al. (2021) wurden mittels eines systematischen Reviews mit mehreren Meta-Analysen die Effekte von arbeitsbezogenen Exoskeletten auf biomechanische, physiologische und subjektiv wahrgenommene Belastung und Beanspruchung untersucht. Die Meta-Analysen zeigen, dass die Nutzung eines rückenunterstützenden Exoskeletts während industrieller Tätigkeiten kurzfristig die Belastung oder Beanspruchung in der Rückenregion reduzieren kann. Für die Gruppe der rückenunterstützenden Exoskelette ergaben die Meta-Analysen keine statistisch signifikanten Nebeneffekte, welche aber in Einzelfällen auftraten. Dieser Aspekt wurde allerdings bislang noch nicht ausreichend in Studien untersucht. Insgesamt fehlt es an Forschung, die hohen methodischen Standards folgt und unterschiedliche gesundheitsrelevante Aspekte mit einbezieht.

Auf die Ergebnisse aus Bär et al. (2021) aufbauend wurde ein exploratives Laborexperiment durchgeführt, um den Einfluss des kommerziell erwerbbaren, passiven Rücken-Exoskeletts Laevo® V2.56 auf die physische Belastung und Beanspruchung während simulierter Arbeitstätigkeiten, wie sie im industriellen Umfeld vorkommen, zu ermitteln. Dazu wurde eine Sortiertätigkeit in statisch gehaltener Oberkörpervorbeugehaltung (einschließlich unterschiedlicher Rumpfausrichtungen; Bär

et al., 2022a) und eine dynamischen Hebetätigkeit (einschließlich unterschiedlicher Hebestile und Rumpfausrichtungen; Luger et al., 2021b) mit und ohne eine Verwendung des Exoskeletts durchgeführt. Die Muskelaktivität in verschiedenen Körperregionen, Körperhaltung in Wirbelsäule und unteren Extremitäten und die Herzfrequenz wurden dabei erfasst (Bär et al., 2022a; Luger et al., 2021b). Im Folgenden präsentieren Bär et al. (2022b) die Auswirkungen des Exoskeletts auf die vertikalen und horizontalen (anteroposterior) tibiofemoralen Gelenkkräfte während der statischen und der dynamischen Arbeitstätigkeiten.

Bär et al. (2022a) und Luger et al. (2021b) zeigen, dass die Nutzung des Laevo® in simulierten Industrietätigkeiten nur zu geringen, kurzfristigen Reduktionen der Rückenstreckermuskulatur (M. erector spinae) führte, dafür aber die Hüftextension (M. biceps femoris) unterstützte. Gleichzeitig zeigten sich nur geringe Veränderungen der Wirbelsäulenhaltung und der Muskelaktivität in den nicht unterstützten Körperregionen, die Hüft- und Knieflexion hingegen stiegen. Dabei wurden die Auswirkungen von der Tätigkeitsausführung (Hebestil, Rumpfausrichtung) beeinflusst. Die Herzfrequenz nahm mit Nutzung des Exoskeletts in allen Tätigkeitsausführungen leicht ab (Bär et al., 2022a; Luger et al., 2021b). Die vertikalen tibiofemoralen Gelenkkräfte stiegen insgesamt mit einer Exoskelett-Nutzung an, ohne eine Interaktion mit der Tätigkeitsausführung aufzuweisen. Dahingegen variierten die Effekte auf die horizontalen (anteroposterior) tibiofemoralen Gelenkkräfte in Abhängigkeit von der Tätigkeitsausführungen (Bär et al., 2022b).

Diese Forschungsarbeit zeigt, dass die Nutzung eines rückenunterstützenden Exoskeletts die Rücken- oder Hüftstreckung unterstützen und kurzfristig die Belastung und Beanspruchung in der Zielregion reduzieren kann. Allerdings könnte die Bewertung von alleinigen Parametern (z.B. Muskelaktivität), ohne eine Kontrolle der assoziierten muskuloskelettalen Strukturen und Funktionen (z.B. Gelenkkräfte, Körperhaltung), eine korrekte Interpretation möglicher Wirkungen erschweren. Darüber hinaus können bei einer Verwendung eines Exoskeletts negative Nebenwirkungen auftreten, die bislang unzureichend untersucht und womöglich noch nicht aufgedeckt wurden. Für eine sichere Anwendung der Systeme ist die Aufdeckung und der Ausschluss von negativen Nebenwirkungen ausschlaggebend. Zusätzlich können weitere Faktoren, die mit einer

Exoskelett-Nutzung in Zusammenhang stehenden Effekte (negativ oder positiv) mitbestimmen, darunter die jeweilige Arbeitstätigkeit und deren individuelle Ausführung, die mechanischen Eigenschaften eines Exoskeletts und die Individualität der nutzenden Person. Einem Exoskelett-Einsatz am Arbeitsplatz sollte daher eine individuelle Prüfung der Systeme unter der Beachtung aller Einflussfaktoren vorausgehen. Schlussfolgerungen bezüglich der muskuloskelettalen Gesundheit sind auf einer Grundlage dieser Dissertation und der aktuellen Literatur bislang nicht möglich. Für eine Feststellung von langfristigen Auswirkungen eines Exoskelett-Einsatzes auf das Risiko für arbeitsbezogene Muskelskelettbeschwerden sind randomisierte, kontrollierte Interventionsstudien in der Arbeitspraxis entscheidend. Dabei sollte eine sinnvolle Auswahl und Kombination verschiedener Messparameter und Körperregionen berücksichtigt werden (z.B. verschiedene miteinander interagierende Belastungs- und Beanspruchungsparameter und in Zusammenhang stehende muskuloskelettale Strukturen).

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Appendices

Table of contents

Appendix 1

Search strategy MEDLINE (PubMed)

#1 "exoskeleton device"[MeSH] OR "wearable electronic devices" [MeSH]

#2 exoskeleton*[tw] OR exosuit*[tw] OR "wearable robotic"[tw] OR "wearable robotics"[tw] OR "wearable robot system"[tw] OR "wearable robot systems"[tw] OR "human power assistive system"[tw] OR "human power assistive systems"[tw] OR "human-robot cooperation system"[tw] OR "human-robot cooperation systems"[tw] OR "human-robot interaction"[tw] OR "human-robot interactions"[tw] OR "wearable assistive device"[tw] OR "wearable assistive devices"[tw]

#3 orthosis [tw] OR orthoses[tw] OR "walking aid"[tw] OR "walking aids"[tw] OR "standing aid"[tw] OR "standing aids"[tw] OR "supportive system"[tw] OR "supportive systems"[tw]

#4 #1 OR #2 OR #3

#5 workplace [MeSH] OR work [MeSH] OR "work schedule tolerance"[MeSH]

#6 work*[tw] OR occupation*[tw] OR job [tw] OR jobs[tw] OR employee*[tw] OR industry[tw] OR industries[tw]

#7 #5 OR #6

#8 #4 AND #7

#9 (animals [MeSH] OR animal*[tw]) NOT (humans[MeSH] OR human*[tw])

#10 #8 NOT #9

Appendix 2

Search strategy CENTRAL

#1 [mh "exoskeleton device"] OR [mh "wearable electronic devices"]

#2 "exoskeleton":ti,ab,kw OR "exoskeletons":ti,ab,kw OR "exosuit":ti,ab,kw OR "exosuits":ti,ab,kw OR "wearable robotic":ti,ab,kw OR "wearable robotics":ti,ab,kw OR "wearable robot system":ti,ab,kw OR "wearable robot systems":ti,ab,kw OR "human power assistive system":ti,ab,kw OR "human power assistive systems":ti,ab,kw OR "human-robot cooperation system":ti,ab,kw OR "human-robot cooperation systems":ti,ab,kw OR "human-robot interaction":ti,ab,kw OR "human-robot interactions":ti,ab,kw OR "wearable assistive device":ti,ab,kw OR "wearable assistive devices":ti,ab,kw

#3 "orthosis":ti,ab,kw OR "orthoses":ti,ab,kw OR "walking aid":ti,ab,kw OR "walking aids":ti,ab,kw OR "standing aid":ti,ab,kw OR "standing aids":ti,ab,kw OR "supportive system":ti,ab,kw OR "supportive systems":ti,ab,kw

#4 #1 OR #2 OR #3

#5 [mh workplace] OR [mh work] OR [mh "work schedule tolerance"]

#6 work*:ti,ab,kw OR occupation*:ti,ab,kw OR job:ti,ab,kw OR jobs:ti,ab,kw OR employee*:ti,ab,kw OR industry:ti,ab,kw OR industries:ti,ab,kw

#7 #5 OR #6

#8 #4 AND #7

#9 ([mh animals] OR "animal*":ti,ab,kw) NOT ([mh humans] OR "human*":ti,ab,kw)

#10 #8 NOT #9

Search strategy EMBASE

#1 "exoskeleton device":de OR "wearable electronic devices":de

#2 "exoskeleton*":ti,ab OR "exosuit*":ti,ab OR "wearable robotic":ti,ab OR "wearable robotics":ti,ab OR "wearable robot system":ti,ab OR "wearable robot systems":ti,ab OR "human power assistive system":ti,ab OR "human power assistive systems":ti,ab

OR "human-robot cooperation system":ti,ab OR "human-robot cooperation systems":ti,ab OR "human-robot interaction":ti,ab OR "human-robot interactions":ti,ab OR "wearable assistive device":ti,ab OR "wearable assistive devices":ti,ab

#3 "orthosis":ti,ab OR "orthoses":ti,ab

#4 #1 OR #2 OR #3

#5 "workplace":de OR "work":de OR "work schedule":de

#6 "work*":ti,ab OR "occupation*":ti,ab OR "job":ti,ab OR "jobs":ti,ab OR "employee*":ti,ab OR "industry":ti,ab OR "industries":ti,ab

#7 #5 OR #6

#8 #4 AND #7

#9 ("animal":de OR "animal*":ti,ab) NOT ("human":de OR "human*":ti,ab)

#10 #8 NOT #9

Search strategy WOS

#1 TS="exoskeleton" OR TS="exoskeletons" OR TS="exosuit" OR TS="exosuits" OR TS="wearable robotic" OR TS="wearable robotics" OR TS="wearable robot system" OR TS="wearable robot systems" OR TS="human power assistive system" OR TS="human power assistive systems" OR TS="human-robot cooperation system" OR TS="human-robot cooperation systems" OR TS="human-robot interaction" OR TS="human-robot interactions" OR TS="wearable assistive device" OR TS="wearable assistive devices"

#2 TS="orthosis" OR TS="orthoses" OR TS="walking aid" OR TS="walking aids" OR TS="standing aid" OR TS="standing aids" OR TS="supportive system" OR TS="supportive systems"

#3 #1 OR #2

#4 TS="work*" OR TS="occupation*" OR TS="job" OR TS="jobs" OR TS="employee*" OR TS="industry" OR TS="industries"

#5 #3 AND #4

#6 TS="animal*" NOT TS="human*"

#7 #5 NOT #6

Search strategy ClinicalTrials.gov

#1 "exoskeleton" OR "exosuit" OR "wearable robotic" OR "wearable robotics" OR "human-robot interaction" OR "human-robot interactions" OR "wearable assistive device"

#2 "orthosis" OR "orthoses"

#3 #1 OR #2

#4 "work" OR "occupation" OR "job" OR "employee"

#5 #3 AND #4

Search strategy DRKS

#1 "exoskeleton" OR "exoskeletons" OR "exosuit" OR "exosuits" OR "wearable robotic" OR "wearable robotics" OR "wearable robot system" OR "wearable robot systems" OR "human power assistive system" OR "human power assistive systems" OR "human-robot cooperation system" OR "human-robot cooperation systems" OR "human-robot interaction" OR "human-robot interactions" OR "wearable assistive device" OR "wearable assistive devices"

#2 "orthosis" OR "orthoses" OR "walking aid" OR "walking aids" OR "standing aid" OR "standing aids" OR "supportive system" OR "supportive systems"

#3 #1 OR #2

#4 "work*" OR "occupation*" OR "job" OR "jobs" OR "employee*" OR "industry" OR "industries"

#5 #3 AND #4

Search strategy EU CTR

#1 "exoskeleton*" OR "exosuit*" OR "wearable robotic" OR "wearable robotics" OR "wearable robot system" OR "wearable robot systems" OR "human power assistive system" OR "human power assistive systems" OR "human-robot cooperation system"

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Search strategy ISRCTN

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#3 #1 OR #2

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#5 #3 AND #4

Search strategy WHO ICTRP

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#2 "orthosis" OR "ortheses" OR "walking aid" OR "walking aids" OR "standing aid" OR "standing aids" OR "supportive system" OR "supportive systems"

#3 #1 OR #2

#4 "rehabilitation" OR "therapy" OR "therapies" OR "prevention" OR "pain reduction" OR "musculoskeletal disorder" OR "musculoskeletal disorders" OR "musculoskeletal disease" OR "musculoskeletal diseases" OR "disease progression" OR "mobility" OR "patient" OR "patients" OR "low back pain" OR "anterior cruciate ligament injury" OR "ACL injury" OR "osteoarthritis" OR "arthrosis" OR "shoulder impingement syndrome" OR "shoulder impingement syndrom" OR "frozen shoulder" OR "tennis elbow" OR "carpal tunnel syndrom" OR "carpal tunnel syndrome" OR "epicondylitis" OR "ankle sprain"

#5 #3 AND #4

Appendix 3 *Study characteristics 1*

Table 2. Study setting, year, sample size and sex of the included participants - number of studies or subjects out if the included 63 studies.

Setting	**Laboratory**	**Field**		
[n of studies]	59	4		
Continent of realization	**North America**	**Europe**	**Asia**	**South America**
[n of studies]	27	22	13	1
Study duration [days]	**1**	**2**	**3**	**unknown**
[n of studies]	37	8	2	16
Year of publication	**2004-2017**	**2018-2020**		
[n of studies]	19	44		
Sex of included subjects	**male**	**female**	**unknown**	
[n of subjects]	496	165	39	
Sample size [n of subjects]	**1-5**	**6-10**	**11-20**	**21-45**
[n of studies]	15	14	31	3

Table 3. Exoskeleton characteristics - (1) number of exoskeletons out of the 44 different exoskeletons evaluated in the 63 included studies and (2) number of studies that evaluated these exoskeletons out of the 63 studies.

Type of exoskeleton	**passive**	**active**	**mix**		
[n of exoskeletons]	28	15	1		
[n of studies]	45	17	1		
Area of support	**back**	**lower limbs**	**upper limbs**	**wrist**	**ankle**
[n of exoskeletons]	16	9	13	4	2
[n of studies]	30	10	21	2	2

Table 4. Tasks, duration and outcomes - number of studies out of the included 63 studies.

Tasks	**Lifting and Carrying**	**Assembly**	**Static posture**	**Dynamic reaching**	**Walking**	**Isometric force exertion**	**Computer work**	**Painting**	**Snow shoveling**	**Laparo-scopy**
[n of studies]	25	18	9	8	6	3	1	1	1	1
Duration of the measures	**<60 sec**	**1-10 min**	**11-60 min**	**61-240 min**	**241-480 min**	**unknown**				
[n of studies]	10	13	7	1	2	30				
Outcomes	**Muscle activity**	**Shear and compression force**	**Joint moments**	**Heart rate**	**Energy expenditure**	**Blood pressure**	**Perceived outcomes**			
[n of studies]	47	4	7	12	12	1	26			

Appendix 4 *Study characteristics 2*

Study identification			Methods			Participants			Intervention				Notes	
First author	**Year**	**Ref**	**Study design**	**Study setting and duration**		**n (m/f)**	**Mean age ± SD/ range [y]**	**Ran**	**Exoskeleton (Manufacturer)**	**Active/ Passive & suppor-ting area**	**task dur-ation**	**Content of intervention & control conditions**	**Funding of study**	**Notable conflicts of Interest**
Abdoli-E	**2006**	**36**	Experimental randomized cross-over laboratory study	CA	1 day	9 (9/0)	23.9 ± 4.6	yes	PLAD (Biomechanics and Ergonomics Lab Kingston Canada)	Passive/ back	n/a	Lifting of 3 loads (5kg, 15kg, 25kg) in 3 styles (stoop, squat, free) in 3 directions (centre, right left) and with and without exoskeleton.	n/a	n/a
Abdoli-E	**2008**	**37**	Experimental randomized cross-over laboratory study	CA	1 day	9 (9/0)	23.9 ± 4.6	yes	PLAD (Biomechanics and Ergonomics Lab Kingston Canada)	Passive/ back	n/a	Lifting of 3 loads (5kg, 15kg, 25kg) in 3 styles (stoop, squat, free) in 3 directions (centre, right left) and with and without exoskeleton.	n/a	n/a
Agnew	**2008**	**38**	Experimental randomized cross-over laboratory study	CA	1 day	9 (9/0)	21.7 ± 0.9	yes	PLAD (Biomechanics and Ergonomics Lab Kingston Canada)	Passive/ back	n/a	Forward bending in 5 angles (15°, 30°, 45°, 60°, 75°) with 6 intervention conditions (without exoskeleton, with exoskeleton with 5 different stiffness levels K1-5).	n/a	n/a
Alabdul-karim	**2019 I**	**40**	Experimental cross-over laboratory study	USA	1 day	16 (8/8)	23.0 ± 2.0	no	1. FORTIS (Lockheed-Martin USA) 2. ShoulderX (SuitX USA) 3. Fawcett Exovest™ (The Tiffen Company USA)	Passive/ upper extremity	3 min	Repetitive overhead drilling task with 2 tool masses (~2kg, ~5kg), 2 work paces (16 holes/min, 2 holes/min) with 4 intervention conditions (without exoskeleton, with 3 different exoskeletons).	n/a	None declared.

Alabdul-karim	**2019 II**	**39**	Experimental cross-over laboratory study	USA	1 day	12 (7/5)	21.2 ± 4.9	no	3. Fawcett Exovest™ (The Tiffen Company USA) 2. EksoVest™ (Esko Bionics Company USA) 3. FORTIS™ (Lockheed-Martin USA)	Passive/ upper extremity	2 min	Repetitive overhead drilling task with 2 tool masses (~2kg, ~5kg) with 4 intervention conditions (without exoskeleton, with 3 different exoskeletons) at a fixed work pace (7 holes/min).	n/a	None declared.
Alemi	**2019**	**41**	Experimental cross-over laboratory study	USA	1 day	12 (12/0)	22.8 ± 4.3	no	VT-Lowe (AR Lab of Virginia Tech University USA)	Passive/ back	1 min	Lifting of 2 different loads (0% bodyweight, 20% bodyweight) in 4 lifting types (stoop, squat, freestyle, asymmetric) with and without exoskeleton at a work pace of 4 lifts/min.	SE Chang, J Geissinger, and AT Asbeck are co-authors on a patent for the exoskeleton which is currently licensed to Lowe's Inc. MM Alemi and AA Simon have no conflicts of interest.	This study was funded by Lowe's, Inc. The study sponsors had no involvement 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.
Alemi	**2020**	**42**	Experimental randomized cross-over laboratory study	USA	1 day (~5 h)	18 (9/9)	24.8 ± 4.1	yes	1. BackX™ model AC (SuitX USA) 2. Laevo (Laevo Delft Netherlands)	Passive/ back	5 min	Lifting of a 6.8kg wooden panel in 2 lifting directions (symmetric, asymmetric) and 2 lifting postures (standing, kneeling) in 3 intervention conditions (without exoskeleton, with 2 different exoskeletons) at a work pace of 5 lifts/min.	Funding for the study reported here was obtained from the Boeing Company. The sponsor had no involvement in data analysis, interpretation, or the decision for publication.	n/a
Baltrusch	**2018**	**122**	Experimental randomized cross-over laboratory study	NL	1 day	18 (18/0)	27.7 ± 5.1	yes	Laevo (Laevo Delft Netherlands)	Passive/ back	5 min	Two tasks (forward bending, one-handed back position) while performing a manual sorting task.	The work presented in this paper was supported by the European Union's Horizon 2020 research and innovation program under grant agreement No 687662 – SPEXOR.	n/a
Baltrusch	**2019**	**43**	Experimental cross-over laboratory study	NL	1 day	13 (13/0)	28.9 ± 4.4	no	Laevo (Laevo Delft Netherlands)	Passive/ back	5 min	Two tasks: walking in self-paced mode and repetitive lifting of a 10kg box at a fixed pace of 6 lifts/min.	The work presented in this paper was supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 687662 – SPEXOR.	No potential conflict of interest was reported by the authors.

Baltrusch	**2020**	**44**	Experimental randomized cross-over laboratory study	NL	1 day	10 (10/0)	47.4 ± 7.1	yes	SPEXOR (Spexor consortium EU)	Passive/ back	5 min	Lifting of a 10kg box from ankle to hip height at a fixed pace of 8 lifts/min.	The work presented in this paper was supported by the European Union's Horizon 2020 research and innovation program under Grant Agreement no. 687662-SPEXOR.	The authors declare that they have no conflict of interest.
Bosch	**2016**	**45**	Experimental cross-over laboratory study	NL	1 day	18 (9/9)	25.0 ± 8.0	no	Laevo (Laevo Delft Netherlands)	Passive/ back	vari-able	Two tasks: picking, placing and removing 10 pairs of pins in a fixed order with a fixed work pace of 2/3 Hz for 10 work cycles in a static 40° forward trunk flexion position; holding task in a 40° forward flexed trunk position until 2/10 on the CR10 Borg-scale was reached.	This research was supported by the European shared cost project Robo-Mate, funded under the Seventh Framework Program (FP7-2013-NMP-ICT-FOF).	n/a
Bougrinat	**2019**	**128**	Experimental cross-over laboratory study	CA	1 day	1 (1/0)	n/a	no	WAXO (Mechanical Engineering Department Montreal Canada)	Active/ ankle	5 or 7 min	Walking on a treadmill with a constant speed of 1.2m/s while without exoskeleton (5 min) and with exoskeleton (7 min).	The funding organization was not involved in any of these: study design; the collection, analysis and interpretation of data; the writing of the report; and in the decision to submit the article for publication.	None declared.
de Vries	**2019**	**46**	Experimental cross-over laboratory study	NL	1 day	12 (12/0)	25.0 ± 1.3	no	SkelEx (Skelex Rotterdam Netherlands)	Passive/ upper extremity	10 sec	Static arm position in 5 vertical elevation angles (30°, 60°, 90°, 120°, 150°) and 3 horizontal abduction angles (0°, 30°, 60°) with and without exoskeleton performed with both arms simultaneously.	This research was supported by Dutch Top sector of Life Sciences and Health (TKI-LSH-VT2017). The contents of this paper are solely the responsibility of the authors and do not necessarily represent the official views of Dutch Top sector of Life Sciences and Health.	n/a
Dezman	**2017**	**47**	Experimental randomized cross-over laboratory study	SI	1 day	4 (4/0)	30.0 ± 7.0	yes	Passive ankle exoskeleton (Humanoid and Cognitive Robotics Lab Ljubljana Slovenia)	Passive/ ankle	10 min	Walking on a horizontal treadmill at a constant speed of 4 km/h in 5 intervention conditions (without exoskeleton, with exoskeleton with 4 different spring characteristics [0, 5, 12, 20 N/mm).	n/a	n/a

Ferrigno	**2009**	**48**	Experimental cross-over laboratory study	BR	1 day	23 (10/ 13)	22.3 ± 1.9	no	1/A. Stiff thermoplastic orthosis (Department of Orthopedics and Traumatology Campinas Brazil (custom-made)) 2/B. Stiff palmar orthosis ("commercial")	Passive/ wrist	10 to 20 sec	Two tasks (typing task: 40-character sentence), mouse task: 10 clicks to color a geometrical figure) performed in 3 intervention conditions (without exoskeleton, with 2 different exoskeletons).	n/a	No commercial party having a direct financial interest in the results of the research supporting this article has or will confer a benefit on the authors or on any organization with which the authors are associated.
Frost	**2009**	**49**	Experimental cross-over laboratory study	CA	1 day	13 (13/0)	20.9 ± 3.8	no	PLAD (Biomechanics and Ergonomics Lab Kingston Canada)	Passive/ back	10 sec	Lifting of a 15kg box with open handles from floor height to a self-adjusted to individual ASIS height in 3 lifting styles (stoop, squat, freestyle) and with 6 intervention conditions (without exoskeleton, with exoskeleton with 5 stiffness coefficients 300, 550, 800, 1050, 1300 N/m) at a fixed pace of 30 lifts/min.	The authors would like to acknowledge the financial support of the Canadian Institutes of Health Research.	n/a
Gillette	**2019**	**50**	Experimental cross-over laboratory study	USA	1 day	6 (4/2)	41.0 ± 7.0	no	Levitate Airframe® (Levitate Technologies Inc. San Diego USA)	Passive/ upper extremity	10 min	Assessment of a part of a job task with and without exoskeleton.	The authors wish to thank Terry Butler for his assistance coordinating communications between Levitate Technologies and John Deere. The authors also wish to thank Dan Wisner, Chad Neumayer, and Bethany Henning of John Deere for their assistance organizing the on-site data collections.	Levitate Technologies provided the upper body exoskeletons that were tested during this study and paid a fee-for-service for the EMG assessment, but had no influence on the interpretation of the results, the contents of this article.
Godwin	**2009**	**51**	Experimental randomized cross-over laboratory study	CA	2 days (separ ated by a maxim um of 7 days)	12 (0/12)	30.0 ± 13.0	yes	PLAD (Biomechanics and Ergonomics Lab Kingston Canada)	Passive/ back	45 min	Lifting a 20%-back-extensor-strength-load wooden box from 18 cm above floor height to individual knuckle height with and without exoskeleton at a fixed pace of 12 lifts/min.	We would like to acknowledge the financial contribution of the Center for Research Expertise – Musculoskeletal Disorders (CREMSD), National Sciences and Engineering Research Council (NSERC) (Operating grant #327733) and Canadian Institute for Health Research (CIHR) (POP grant #67409) for financial support.	n/a

Graham	**2009**	**52**	Experimental randomized cross-over field study	CA	2 days (conse cutive)	10 (8/2)	n/a	yes	PLAD (Biomechanics and Ergonomics Lab Kingston Canada)	Passive/ back	full worki ng day	Assembly task including working on the dash from the left side of the car while being in a forward flexed position. The cycle time was 55 seconds (the time a new car came down the line), during which subjects bent forward into the car and slightly twisted to the left working on the dash for ~30s, and stood and walked to get new car parts from alongside the assembly line for ~25s.	We would like to acknowledge the financial contribution of Natural Sciences and Engineering Research Council (CGS-M Scholarship) and the Ontario Workplace Safety and Insurance Board (WSIB #07117 – Bridging the Gap Grant) for their financial support.	n/a
Groos	**2020 I**	**55**	Experimental randomized cross-over laboratory study	DE	1 day	17 (10/7)	26.7 ± 5.9	yes	Chairless Chair (noonee AG Switzerland)	Passive/ lower extremity	5 to 15 min	Three tasks: walking on a horizontal treadmill with 2.4 km/h for 10 min, screwing with a manual (5min) and electric (5min) screwdriver at a 50-55cm working height, assembling and disassembling of wooden and plastic components at 45-cm working height for 15 min. All tasks were performed without and with exoskeleton.	n/a	n/a
Groos	**2020 II**	**54**	Experimental randomized cross-over laboratory study	DE	1 day	20 (9/11)	31.9 ± 13.4	yes	Levitate Airframe® (Levitate Technologies Inc. San Diego USA)	Passive/ upper extremity	n/a	Three assembly tasks: screwing with both hands (right, left) of 6 screws; screwing with an electric screwdriver of 7 rows with 7 screws each; plugging with both hands (right, left) of 8 Lego-stones, all performed without and with exoskeleton.	n/a	n/a
Huysame n	**2018 I**	**57**	Experimental randomized cross-over laboratory study	CH	1 day	11 (11/0)	27.0 ± 2.0	yes	Robo-Mate (Robomate consortium EU)	Active/ back	n/a	Lifting and lowering a box of different weight (7.5 kg, 15 kg) from mid-shin height to waist height five times without a fixed work pace, performed without and with exoskeleton.	This research was performed under the Robomate project (www.robo-mate.eu) which received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement N° 608979.	n/a
Huysame n	**2018 II**	**56**	Experimental randomized cross-over laboratory study	IT	1 day	8 (4/4)	38.0 ± 10.0	yes	Iso-elastic upper limb exoskeleton (Institute of Mechatronic Systems Zurich Switzerland)	Passive/ upper extremity	30 sec	Overhead static reaching posture holding 2 loads (0kg, 2kg) for 30 seconds at a fixed height with their dominant hand performed without and with an exoskeleton.	This research was supported by funding from the European Commission under the Robomate FP7 project (contract number 608979).	n/a

Hyun	**2019**	**58**	Experimental cross-over laboratory study	KR	1 day	10 (10/0)	34.9 ± 4.0	no	H-VEX (Hyundai Motor Group)	Passive/ upper extremity	32 sec	A pointing task at 2 working heights (elbow at or above shoulder height) with 2 loads (0kg, 2kg) repeated twice, performed without and with an exoskeleton.	The authors declare that they have no known competing financial interests that could have appeared to influence the work reported in this paper.	The authors declare that they have no known competing personal relationships that could have appeared to influence the work reported in this paper.
Johans-son	**2004**	**123**	Experimental randomized cross-over laboratory study	SE	1 day	12 (6/6)	37.0 ± 6.8	yes	1. Stiff wrist orthosis (Department for Work and Health Stockholm Sweden (custom-made) 2. Flexible wrist orthosis (Clary's Trollhättan Sweden (commercial)	Passive/ wrist	64 sec	Gripping task containing a 4-sec gripping phase and a 4-sec relaxing phase repeated 8 times with 3 experimental conditions (without exoskeleton, with 2 wrist exoskeletons).	This work was supported by Grants from The Swedish Council for Working Life Research (Project No 96-0846).	n/a
Kim H.J.	**2019**	**88**	Experimental cross-over laboratory study	KR	1 day	1 (?/?)	n/a	no	Lower limb exoskeleton robot (Department of Mechanical Engineering Seoul Korea)	Passive/ lower extremity	3 to 4 min	Two tasks: transport operation with walking on a treadmill with 2 km/h carrying 3 different loads (0, 10, 20kg) for 4 min repeated twice; standing state holding a 5.5-kg grinder for 3min repeated twice; performed without and with exoskeleton.	n/a	n/a
Kim S.	**2019**	**59**	Experimental cross-over laboratory study	USA	1 day (2.5 h)	12 (6/6)	24.5 ± 3.3	no	EksoVest™ (Ekso Bionics Inc. USA)	Passive/ upper extremity	n/a	Two tasks at 2 different individual work heights (shoulder, overhead): repetitive drilling with 2 tools (light, heavy) at a work pace of 1 hole/10sec and a wiring task without work pace, performed without and with exoskeleton.	This work was supported by a grant from EksoBionics, Inc. However, the sponsor had no involvement in data analysis, interpretation, or the decision for publication.	The authors declare no conflict of interest.

Kim S.	**2018 I**	**60**	Experimental cross-over laboratory study	USA	1 day	12 (6/6)	27.5 ± 9.6	no	EksoVest™ (Ekso Bionics Inc. USA)	Passive/ upper extremity	n/a	2 tasks (drilling 4 times with 2 pneumatic drill loads (3.6, 5.9 kg), wiring 5 pairs of wires) at 2 different individual work heights (shoulder, overhead) performed without and with exoskeleton.	This work 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 had no involvement in data analysis/interpretation, or the decision for publication.	None declared.
Kim S.	**2018 II**	**61**	Experimental cross-over laboratory study	USA	1 day	12 (6/6)	27.5 ± 9.6	no	EksoVest™ (Ekso Bionics Inc. USA)	Passive/ upper extremity	n/a	2 tasks (drilling 4 times with 2 pneumatic drill loads (3.6, 5.9 kg), wiring 5 pairs of wires) at 2 different individual work heights (shoulder, overhead) performed without and with exoskeleton.	This work 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 had no involvement in data analysis/interpretation or the decision for publication.	None declared.
Knott	**2017**	**62**	Experimental cross-over laboratory study	DE	1 day	35 (22/ 13)	35.1 ± 11.1	no	Support system (Hebehilfe Consortium Germany)	Passive/ lower extremity	32 min?	Simulated order picking including lifting, lowering, carrying and walking of 3 different loads (0, 2.6, 6.5kg), performed without and with exoskeleton.	n/a	n/a
Koopman	**2019**	**63**	Experimental cross-over laboratory study	NL	1 day	11 (11/0)	24.1 ± 2.7	no	Laevo (Laevo Delft Netherlands)	Passive/ back	30 sec	Lifting at 5 different heights (100%, 75%, 50%, 25%, 0% floor height) while holding the knees as straight as possible, repeated 3 times and performed without and with 2 settings of the exoskeleton (low, high).	The authors would like to acknowledge the support of Laevo for unconditionally providing the exoskeleton for this research. This work was supported by the European Union's Horizon 2020 through the SPEXOR project, contract no. 687662.	The authors state that there is no conflict of interest to report.
Lee D.	**2020**	**65**	Experimental cross-over laboratory study	USA	2 days	12 (9/3)	22.6 ± 2.7	no	Robotic knee orthosis (Atlantic Pediatric Device Consortium USA)	Active/ lower extremity	~20 min	Walking on a 15% gradient incline and decline at 0.7 m/s performed without and with exoskeleton.	This work was partially funded by the FDA through the Atlantic Pediatric Device Consortium, a NextFlex NMMI grant under award PC3.6 – LMCO-GaTech and an NSF National Robotic Initiative grant under award # 1830215. (Corresponding Author: Dawit Lee).	n/a

Lee J.W.	**2019**	**87**	Experimental cross-over laboratory study	KR	2 days	1 (1/0)	37.0	no	LAD (Rehabilitation Engineering Research Institute Korea)	Passive and active/ back	5 sec	Lifting task with 3 load conditions (0, 10, 20kg) according to the lifting technique recommended by KOSHA, performed without and with exoskeleton and using a fixed work pace of 1 lift/5s.	This work was supported by Institute for Information & Communications Technology Promotion (IITP) Grant funded by the Korea government (MSIP) (No. 2016-0-00452, Development of creative technology based on complex 3D printing technology for labor, the elderly and the disabled).	The authors declare that they have no conflict of interest.
Liu	**2018**	**66**	Experimental cross-over field study	USA	2 days	7 (7/0?)	n/a	no	Levitate Airframe® (Levitate Technologies Inc. San Diego USA)	Passive/ upper extremity	full work-ing day	Attending 2 laparoscopic operating days, one performed without and one with exoskeleton.	S Liu, D Hemming, RB Luo, JC Delong, BJ Sandler, GR Jacobsen, and S Horgan have no financial ties to disclose.	S Liu, D Hemming, RB Luo, JC Delong, BJ Sandler, GR Jacobsen, and S Horgan have no conflicts of interest to disclose.
Lotz	**2009**	**67**	Experimental randomized cross-over laboratory study	CA	3 days	10 (10/0)	22.0 ± 3.8	yes	PLAD (Biomechanics and Ergonomics Lab Kingston Canada)	Passive/ back	45 min	Lifting and lowering of a box from floor to knuckle height at a rate of 12 efforts (6 lifts, 6 lowers) per minute for nine 5-min work periods, performed without and with exoskeleton.	We would like to acknowledge the financial contribution of NSERC (Operating Grant #327733) and CIHR (POP Grant #67409) for financial support.	n/a
Luger	**2019 I**	**20**	Experimental randomized cross-over laboratory study	DE	2 days	45 (45/0)	24.8 ± 2.9	yes	Chairless Chair (noonee AG Switzerland)	Passive/ lower extremity	21 min	Three assembling tasks including screwing (6 screws), clip fitting (10 clips) and cable mounting (3 coaxial sockets) at 3 different frontal work distances (optimal, far, too far) and in 3 different working heights (optimal, too low, too high) performed in 3 experimental conditions (without exoskeleton, with exoskeleton in 2 sitting heights [high, low]).	We would like to thank AUDI AG for their financial contribution to this study, for providing us two exoskeletons, and for their input in developing the study design.	The authors declare no conflict of interest.

Luger	**2019 II**	**68**	Experimental randomized cross-over laboratory study	DE	2 days	45 (45/0)	24.8 ± 2.9	yes	Chairless Chair (noonee AG Switzerland)	Passive/ lower extremity	21 min	Three assembling tasks including screwing (6 screws), clip fitting (10 clips) and cable mounting (3 coaxial sockets) at 3 different frontal work distances (optimal, far, too far) and in 3 different working heights (optimal, too low, too high) performed in 3 experimental conditions (without exoskeleton, with exoskeleton in 2 sitting heights [high, low]).	Timothy J. Cobb received the grant "Arbeit und Gesundheit" by Südwestmetall for his doctoral thesis that will be based on data from the present study. AUDI AG (Ingolstadt, Germany) provided a financial contribution to this study. The remaining work of the Institute of Occupational and Social Medicine and Health Services Research is supported by an unrestricted grant of the employers' association of the metal and electrical industry Baden-Württemberg (Südwestmetall; Germany).	The authors declare no conflict of interest.
MacLean	**2019**	**69**	Experimental randomized cross-over laboratory study	USA	3 days	4 (4/0)	29.6 ± 3.8	yes	Knee Stress Release Device^{TM} (B-Temia Inc, Canada)	Active/ lower extremity	~6 min	Walking on 3 different surfaces (horizontal treadmill, 15° inclined treadmill, 1.1-km outdoor course) at a preferred walking speed while wearing 2 loads (0, 18.1kg), performed without and with exoskeleton.	This work was funded by Lockheed Martin Corporation (http://www.lockheedmartin.com/).	n/a
Madinei	**2020**	**22**	Experimental cross-over laboratory study	USA	2 days	18 (9/9)	24.7 ± 3.7	no	1. BackX (SuitX USA) 2. Laevo (Laevo Delft Netherlands)	Passive/ back	n/a	Precision manual assembly task requiring picking and inserting pegs in a grooved pegboard as quickly as possible (1) without exoskeleton at 4 working heights (knee, below knee) and different pegboard locations resulting in a total of 6 conditions, or (2) with 2 different exoskeletons at 2 working heights (waist, knee, ankle, below-floor) and different pegboard locations resulting in a total of 20 conditions.	Funding for the study was obtained from the Boeing Company. The sponsor had no involvement in data analysis, interpretation, or the decision for publication.	n/a
Marino	**2019**	**70**	Experimental cross-over field study	USA	2 days	14 (11/3)	25.0 to 47.0	no	1. BackX (SuitX USA) 2. Levitate Airframe® (Levitate Technologies Inc. San Diego USA)	Passive/ upper extremity and back	2 h	Tracking of a back-supporting exoskeleton and shoulder-supporting exoskeleton during part of work shift among stockers and tire installers, who performed their work without and with an exoskeleton.	This research and paper was supported by funding from Briotix Health and its client. The contents of this paper are solely the responsibility of the author and do not necessarily represent the official views of Briotix Health, its clients, or any other involved parties.	The author declares no conflict of interest.

Maurice	**2020**	**71**	Experimental randomized cross-over laboratory study	FR	1 day	12 (12/0)	23.2 ± 1.2	yes	PAEXO (Ottobock Germany)	Passive/ upper extremity	12 min	Overhead pointing task holding a power drill in the right hand to point as fast as possible from a starting point to a target at an individually adjusted height (shoulder an elbow flexed at 90°), repeated for 5 blocks of 24 pointing movements (24 movements, based on 3 repetitions of 2 target sizes and 4 starting positions), performed without and with an exoskeleton.	This work has received funding from the European Union's H2020 research and innovation programme under grant agreement No. 731540 (An.Dy).	n/a
Kadone	**2017**	**74**	Experimental cross-over laboratory study	JP	1 day	9 (9/0)	26.0 to 44.0	no	HAL (CYBERDYNE Inc. Ibaraki Japan)	Active/ back	~3 to 6 min	Snow-shoveling in ~25-cm-deep snow around 20m² scooping up snow and throwing it to more than half their height as fast as possible with a fixed foot position and method of holding the shovel at the start of the simulation, performed without and with an exoskeleton.	This work was supported by an Industrial Disease Clinical Research Grant from the Ministry of Health Labor and Welfare, Japan (Grant No. 160401-01).	A commercial party having a direct financial interest in the results of the research supported by this article has conferred or will confer a financial benefit on one or more of the authors. Y. Sankai is a professor of University of Tsukuba, a founder, a shareholder, and the CEO of University venture company "CYBERDYNE Inc", Ibaraki, Japan. H Kawamoto is an associate professor of University of Tsukuba, a co-founder, a shareholder, and an outside director of University venture company "CYBERDYNE Inc". Cyberdyne, the manufacturer or HAL, was not directly involved in the study design, collection, analysis, or interpretation of the data, writing the report, of the decision to submit the paper for publication.

Miura	**2018 I**	**72**	Experimental cross-over laboratory study	JP	1 day	9 (9/0)	26.0 to 44.0	no	HAL (CYBERDYNE Inc. Ibaraki Japan)	Active/ back	~3 to 6 min	Snow-shoveling in ~25-cm-deep snow around 20m2 scooping up snow and throwing it to more than half their height as fast as possible with a fixed foot position and method of holding the shovel at the start of the simulation, performed without and with an exoskeleton.	This work was supported by an Industrial Disease Clinical Research Grant from the Ministry of Health Labour and Welfare, Japan (Grant No. 160401-01).	Cf. Kadone et al. 2017
Miura	**2018 II**	**73**	Experimental cross-over laboratory study	JP	1 day	18 (7/11)	31.0 ± 6.1	no	HAL (CYBERDYNE Inc. Ibaraki Japan)	Active/ back	~4 to 6 min	Lifting a 12-kg cardboard box with a fixed pace of 15 lifts/min until fatigue, performed without and with an exoskeleton.	This work was supported by an Industrial Disease Clinical Research Grant from the Ministry of Health Labour and Welfare, Japan (Grant No. 160401-01).	Cf. Kadone et al. 2017
Moyon	**2018**	**75**	Experimental cross-over field study	FR	n/a	2 (?/?)	n/a	no	SkelEx (Skelex Rotterdam Netherlands)	Passive/ upper extremity	n/a	n/a	The PAD chosen for further tests was selected by its ability to reduce upper body strain according to a study ordered by Skel-Ex and realized by an independent laboratory. Furthermore, this choice is imposed by a company's exclusive partnership framing the project.	n/a
Mura-matsu	**2013**	**127**	Experimental cross-over laboratory study	JP	1 day	3 (3/0?)	n/a	no	Back support muscle suit (Department of Mechanical Engineering Tokyo Japan)	Active/ back	2.5 sec	Lifting of a load, performed without and with exoskeleton.	n/a	n/a
Näf	**2018**	**124**	Experimental cross-over laboratory study	BE	1 day	3 (3/0)	30.0 (mean only)	no	SPEXOR (Spexor consortium EU)	Passive/ back	n/a	Range of motion task in 3 directions (flexion-extension, lateral bending, rotation) while holding the knees as straight as possible without locking the knees, performed in 4 different experimental conditions (without exoskeleton, with exoskeleton in 3 different setting [flex-slider, flex-no slider, rigid]).	This work has been funded by the European Commissions as part of the project SPEXOR under grant no. 687662. www.spexor.eu.	n/a

Naka-mura	**2017**	**125**	Experimental randomized cross-over laboratory study	JP	1 day	3 (3/0)	n/a	yes	Muscle suit (Department of Mechanical Engineering Tokyo Japan)	Active/ back	6 sec	Lifting and holding a 10-kg load in 2 postures (bent knees, straight knees), performed without and with an exoskeleton.	n/a	n/a
Naruse	**2005**	**90**	Experimental cross-over laboratory study	JP	1 day	1 (1/0)	24.0	no	Power assist device (Aizu-Wakamatsu Japan)	Active/ back	n/a	Lifting and holding an object with 2 loads (0, 20kg), 3 horizontal orientations (0, 30, 60°), 2 horizontal distances (0.4, 0.6m) and 2 location heights (0.0, 0.4m) without moving the right heel, performed without and with an exoskeleton.	n/a	n/a
Pillai	**2020**	**76**	Experimental randomized cross-over laboratory study	USA	1 day	15 (11/4)	n/a	yes	LegX (SuitX USA)	Passive/ lower extremity	n/a	(1) Panel work including holding a drill and aiming it at 2 different target positions (waist, knee height), performed without and with an exoskeleton in 2 different modes (with lock mode i.e. 110° knee flexion, lock & spring mode). (2) Sustained ground work including moving a rod between three markers on the floor placed at different distances using a self-selected starting location, performed without and with the exoskeleton in locking mode (110° knee flexion).	n/a	n/a
Rashedi	**2014**	**24**	Experimental cross-over laboratory study	USA	2 days	12 (12/0)	27.0 ± 2.6	no	Fawcett Exovest™ (The Tiffen Company USA)	Passive/ upper extremity	10 min	Overhead task of keeping a tool with both hands of 3 different masses (1.1, 3.4, 8.1kg) engaged with a hexagonal bolt that was oriented downward repeated for 20 cycles (50%-duty cycle; 30-s-cycle time; i.e., a set work pace), performed without and with an exoskeleton	This work was supported by a grant from Equipois, Inc., and in cooperation with Ford Motor Company and Boeing, Inc. These companies provided the WADE and/or initial information on overhead work characteristics in their worksites. However, they had minimal involvement in study design, and no involvement in data analysis and interpretation, or decision for publication. The contents of this paper are solely the responsibility of the authors and do not necessarily represent the official views of the sponsor.	n/a

Sado	**2019**	**77**	Experimental cross-over laboratory study	MY	1 day	5 (5/0?)	28.0 ± 5.0	no	Lower-body exoskeleton (Centre for Product Design and Manufacturing Kuala Lumpur Malaysia)	Active/ lower extremity	n/a	Lifting/squatting with a 4.3-kg box from the floor height for six consecutive times; carrying/walking with a 4.3-kg box from a set start to a set end location for three consecutive times; both tasks performed without and with an exoskeleton	The authors wish to acknowledge the support by University of Malaya under RU Operation Grant (RU016-2016) and Grant (GPF023A- 2018). The authors would also like to acknowledge the Ministry of Higher Education of Malaysia for the facility and equipment support under High Impact Research Grant UM.C/625/1/HIR/MOHE/ENG/41.	None declared.
Schmalz	**2019**	**78**	Experimental randomized cross-over laboratory study	DE	1 day	12 (6/6)	24.0 ± 3.0	yes	PAEXO (Ottobock Germany)	Passive/ upper extremity	n/a	Overhead work including 2 tasks (screwing nuts, drilling with an electric drill) at individually adjusted eye height, performed without and with an exoskeleton.	This research received no external funding.	T Schmalz, M Ernst, A Kannenberg, J Bornmann and B Schirrmeister work for the research department of Otto Bock SE & Co. KGaA, the manufacturer of the exoskeleton used in this study. The authors alone are responsible for the content and writing of the paper.
Spada	**2018**	**91**	Experimental cross-over laboratory study	IT	1 day	16 (16/0)	43.0 ± 11.1	no	MATE (COMAU Italy)	Passive/ upper extremity	at subj will	Three tasks: (1) holding a static posture with extended arms (90°) holding a 3.5-kg load with the forearms; (2) repeated manual handling task moving a 3.4-kg object between two positions of different heights with a work pace of 30 actions/min; (3) precision task tracing a continuous wavy line between two premarket traces on a paper fixed on a billboard while standing. All tasks performed without and with an exoskeleton.	n/a	n/a
Sylla	**2014**	**79**	Experimental cross-over laboratory study	FR	1 day	8 (8/0?)	24.0 ± 7.0	no	ABLE (CEA-LIST Interactive Robotics Unit France)	Active/ upper extremity	~8 to 13 sec	An overhead screwing task in 5 different intervention conditions (without exoskeleton, with exoskeleton in 4 different compensative torques [1.035, 1.335, 1.635, 1.935 kg·m]).	n/a	n/a

Thalman	**2018**	**129**	Experimental cross-over laboratory study	USA	1 day	1 (0/1)	23.0	no	Soft elbow exosuit (Polytechnic School Mesa USA)	Active/ upper extremity	n/a	Isometric contractions with 3 different loads (0.0, 1.5, 2.5kg) and range of motion tests from biceps full extension to full flexion; both tasks performed without and with an exoskeleton.	C.M. Thalman is funded by the National Science Foundation Graduate Research Fellowships Program.	n/a
Theurel	**2018**	**132**	Experimental randomized cross-over laboratory study	FR	1 day	8 (4/4)	32.0 ± 2.6	yes	EXHAUSS Stronger® (Exhauss France)	Passive/ upper extremity	n/a	Three tasks: (1) lifting/lowering a load (men 9kg, women 5kg) from a platform at low height (knee) to a platform at high height (shoulder) with a fixed work pace of 10 cycles/min for 3 min; (2) walking/carrying a load (men 15kg, women 8kg) over 30 m at a preferred walking speed repeated four times; (3) unstacking/stacking 4 boxes (men 15kg, women 8kg) for eight times without a set work pace for 5 min. All tasks were performed without and with an exoskeleton.	n/a	The authors report no conflicts of interest in this work.
Ulrey	**2013**	**81**	Experimental randomized cross-over laboratory study	USA	1 day	18 (11/7)	26.0 ± 8.9	yes	BNDR (Limbic Systems Inc. Ventura USA)	Passive/ back	15 to 20 sec	Lifting task of a standard office file box with 3 different loads (0.00, 4.54, 9.07 kg) repeated for three to four times, performed without and with an exoskeleton.	This work was supported by the Western Center for Agricultural Health and Safety, and the Henry A. Jastro and Peter J. Shields Graduate Research Scholarship, at the University of California, Davis.	n/a
Van Engel-hoven	**2019**	**82**	Experimental cross-over laboratory study	USA	1 day	14 (14/0)	37.0 ± 13.0	no	ShoulderX (SuitX USA)	Passive/ upper extremity	30 sec	Two tasks: (1) repetitive task inserting and removing a series of screws at an individually adjusted overhead working height (90° shoulder elevation and elbow flexion) using an electric drill with the dominant (right) hand; (2) sustained task tracing a series of lines with a colored pencil with the dominant (right) hand in 120° shoulder elevation. Both tasks were performed with 2 tool masses (0.45, 2.25kg), at 4 peak torque amplitude conditions (0, 5, 10, 15 Nm) and both without and with an exoskeleton.	This publication is supported in part by the Pilot Project Research Training Program of the Southern California NIOSH Education and Research Center (SERC), Grant Agreement Number T42 OH008412 from the Center for Disease Control and Prevention. Its contents are solely the responsibility of the authors and do not necessarily represent the official view of the CDC. This study is supported in part by the NSF National Robotics Initiative award #1317978.	Researchers L Van Engelhoven and H Kazerooni, hold a series of patents for the technology at UC Berkeley and US Bionics (dba suitX). The device is being commercialized by suitX. Researchers L Van Engelhoven, H Kazerooni, and N Poon have equity in suitX.

Von Glinski	**2019**	**83**	Experimental randomized cross-over laboratory study	DE	1 day	14 (14/0)	18.0 to 67.0	yes	HAL (CYBERDYNE Inc. Ibaraki Japan)	Active/ back	10 min	Symmetrical lifting/lowering a 17.05-kg box from ground level up to a table at a set work pace of 4 lifts/min with a self-selected lifting style and foot position, performed without and with an exoskeleton.	n/a	n/a
Wehner	**2013**	**130**	Experimental cross-over laboratory study	USA	1 day	1 (1/0)	42.0	no	Soft robotic exosuit (Wyss Institute for Biologically Inspired Engineering Boston USA)	Active/ lower extremity	8 to 10 min	Walking on a level treadmill at 1.5 m/s, performed in 8 different experimental conditions (without exoskeleton and with exoskeleton with 7 different actuator turn on times [unpowered, 10, 20, 30, 40, 50, 60%]).	This work is supported by the Wyss Institute for Biologically Inspired Engineering.	n/a
Wei	**2020**	**126**	Experimental randomized cross-over laboratory study	CN	1 day	8 (8/0)	24.0 ± 2.5	yes	MeBot-EXO (College of Optoelectronics Science and Engineering Suzhou China)	Passive/ back	30 sec5 min	Holding a static stoop position in 50-55° forward trunk flexion, repeated three times, performed without and with exoskeleton, during which muscle activity was recorded. Maintaining a static stoop position, performed without and with exoskeleton, during which metabolic cost was recorded.	This research is partly supported by Natural Science Research of Jiangsu Higher Education Institutions of China [16KJB510040].	No potential conflict of interest was reported by the authors.
Weston	**2018**	**84**	Experimental cross-over laboratory study	USA	1 day	12 (12/0)	25.3 ± 6.0	no	Fawcett Exovest™ (The Tiffen Company USA)	Passive/ upper extremity	n/a	Force exertion task performed in 3 different vertical exertion heights (50, 65, 100% subject height), in 2 orientations (symmetric feet at 0°, asymmetric feet at 45°), using 2 different tools mainly supported by the right hand (4.54-kg nut runner, 13.61-kg pneumatic impact wrench), performed without and with exoskeleton.	This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.	The authors have no competing interests or conflict of interest to declare.
Wijeguna-wardana	**2019**	**131**	Experimental cross-over laboratory study	LK	1 day	1 (1/0)	25.0	no	ChairX (Bionics Laboratory Moratuwa Sri Lanka)	Active/ lower extremity	80 sec	Holding 3 different forward-inclined postures (20, 40, 60°), performed without and with exoskeleton.	n/a	n/a
Yin	**2019**	**85**	Experimental cross-over laboratory study	CN	1 day	12 (12/0)	26.4 ± 5.1	no	WPAD (School of Mechanical and Automotive Engineering Guangzhou China)	Active/ back	15 min	Lifting task with the feet shoulder-width apart, adopting a stoop lifting technique in the sagittal plane moving a 10-kg wooden box from the ground to half the subject height at a set work pace of 6 lifts/min.	This work was supported by the Guangzhou Scientific and Technological Project (NO.grant number 201802010067). The authors have declared that no conflict of interest exists.	n/a

Yong	**2019**	**86**	Experimental cross-over laboratory study	CN	1 day	10 (10/0 ?)	26.0	no	Waist assist exoskeleton (Shenzhen Robotics Research Center Project China)	Active/ back	~15 sec	Lifting a box in a stooped posture from the ground to an upright posture and lowering it back to the ground, repeated for five times for each of 6 different loads (0, 5, 10, 15, 20, 25kg), performed without and with exoskeleton.	This work is partly supported by the Shenzhen Robotics Research Center Project, the National Natural Science Foundation of China (No. U1613219), the Shenzhen Overseas Innovation and Entrepreneurship Research Program, China (No. KQJSCX20170731164301774) and the National Key Research and Development Program of China (2017YFB1302303).	The authors declare no conflict of interest.
Zhang	**2016**	**89**	Experimental cross-over laboratory study	USA	1 day	3 (3/0?)	26.7 ± 3.3	no	Passive spine exoskeleton (Department of Mechanical and Industrial Engineering Amherst USA)	Passive/ back	120 sec	Two tasks: (1) dynamic test with three repetitions of spine flexion to 90° and spine extension back into a standing position in the sagittal plane with the arms crossed across the chest; (2) static test holding a flexed position in 3 individually adjusted positions (small, medium, full-range flexion). Both tests were performed without and with exoskeleton.	n/a	n/a

abbreviations

f	female	sec	second(s)	BE	Belgium	JP	Japan
m	male	min	minute(s)	BR	Brazil	KR	Croatia
n	number	h	hour(s)	CA	Canada	LK	Sri Lanka
n/a	not applicable	y	year(s)	CH	Switzerland	MY	Malaysia
Ran	randomized	Hz	hertz	CN	China	NL	the Netherlands
Ref	reference	Kg	kilogram	DE	Germany	SE	Sweden
SD	standard deviation	m/s	meter/second	FR	France	SI	Slovenia
Subj	subject	mm	Millimeter	IT	Italy	USA	United States of America
		N	Newton				
		Nm	Newton meter				

Appendix 5 *Study outcomes, tasks and results*

First author	Year	Ref	Exoskeleton	obj/ subj	Outcome [unit]/ area or direction	Task/Condition	Results: no Exo (±SD); Exo (±SD); mean difference; p-value
Abdoli-E	**2006**	**36**	**PLAD**	**obj**	Muscle activity [%MVC] LES	Lifting stoop	NE 2228.9 (±591.5); E 1891.8 (±523.9); MD -15.1%; p<0.05 [a]
					Muscle activity [%MVC] LES	Lifting squat	NE 2305.5 (±659); E 1930.3 (±576.8); MD: -16.3%; p<0.05 [a]
					Muscle activity [%MVC] LES	Lifting freestyle	NE 2150.1 (±610.2); E 1909.2 (±555.9); MD -11.2%; p<0.05 [a]
					Muscle activity [%MVC] TES	Lifting stoop	NE 1428.7 (±671.2); E 1060.4 (±665.9); MD -25.8%; p<0.05 [a]
					Muscle activity [%MVC] TES	Lifting squat	NE 1308.2 (±671.2); E 962.1 (±638.8); MD -26.5%; p<0.05 [a]
					Muscle activity [%MVC] TES	Lifting freestyle	NE 1301.3 (±622.8); E 945.7 (±575.9); MD -27.3%; p<0.05 [a]
					Muscle activity [%MVC] EO	Lifting stoop	NE 302.4 (±245.3); E 336.5 (±437.7); MD +11.3%; NS p<0.05 [a]
					Muscle activity [%MVC] EO	Lifting squat	NE 301.5 (±239.3); E 268.2 (±246.2); MD -11%; NS [a]
					Muscle activity [%MVC] EO	Lifting freestyle	NE 262.9 (±241.8); E 220.2 (±268.6); MD -16.2%; NS [a]
					Muscle activity [%MVC] RA	Lifting stoop	NE 72.1 (±41.7); E 90.8 (±61.8); MD +26%; NS [a]
					Muscle activity [%MVC] RA	Lifting squat	NE 69.9 (±47.5); E 61.6 (±42.4); MD -11.9%; NS [a]
					Muscle activity [%MVC] RA	Lifting freestyle	NE 62.3 (±46); E 70.8 (±60.9); MD 13.7%; NS [a]
Abdoli-E	**2008**	**37**	**PLAD**	**obj**	Joint moment L4/L5 a/p	Lifting freestyle	NE 4734.7 (±489.8); E 3959.2 (±489.8); MD -16.4%; p<0.001 [a]
					Joint moment L4/L5 lat	Lifting freestyle	NE 3256.3 (± 408.2); E 2979.6 (± 571.4); MD -8.8%; p<0.001 [a]
					Joint moment L4/L5 twist	Lifting freestyle	NE 371.6 (± 58); E 272.7 (± 68.2); MD -26.6%; p<0.001 [a]
Agnew	**2008**	**38**	**PLAD**	**obj**	Muscle activity [%MVC] Trunk extensors (LAT, TES, LES, MULT)	Static forward bending	NE 6.5 (±3.2); E 3.9 (±2.3); MD -41%; p=nd [a]
					Muscle activity [%MVC] Trunk flexors (RA, EO, IO)	Static forward bending	NE 1.8 (±0.7); E 2 (±0.6); MD +15.4%; p=nd [a]
					Compression force [N] L4/L5	Static forward bending	NE 2061.3 (±414.8); E 1807.8 (±1109); MD -12.3%; p=nd [a]
					Shear force [N] L4/L5 a/p	Static forward bending	NE -9 (±52.7); E -33.3 (±96.4); MD +268.7%; p=nd [a]
Alabdul-karim	**2019 I**	**40**	**FORTIS**	**obj**	Muscle activity [%MVC] DA	Drilling Overhead	NE 4.6 (±4.6); E 8.1 (±5.8); MD +75.7%; p=nd
					Muscle activity [%MVC] DM	Drilling Overhead	NE 4.2 (±2.9); E 8.6 (±7.2); MD +104.9%; p=nd
					Muscle activity [%MVC] TRI	Drilling Overhead	NE 4.4 (±2.8); E 4.5 (±2.8); MD +1%; p=nd
					Muscle activity [%MVC] ILL	Drilling Overhead	NE 2.6 (±2); E 4.1 (±4.2); MD +54.5%; p=nd
				subj	Perceived discomfort [Borg CR-10 scale] hands/ wrists	Drilling Overhead	NE 3.4 (±1.7); E 2.5 (±1.5); MD -27.7%; p<0.05
					Perceived discomfort [Borg CR-10 scale] upper arms	Drilling Overhead	NE 4.2 (±1.8); E 3.2 (±1.8); MD -25.5%; p<0.05
					Perceived discomfort [Borg CR-10 scale] shoulders	Drilling Overhead	NE 3.9 (±1.5); E 3.4 (±1.9); MD -11.9%; NS
					Perceived discomfort [Borg CR-10 scale] neck	Drilling Overhead	NE 4 (±1.7); E 2.9 (±1.8); MD -27.6%; p=nd
					Perceived discomfort [Borg CR-10 scale] lower back	Drilling Overhead	NE 3 (±1.8); E 2.8 (±1.7); MD -6.4%; p=nd
					Perceived discomfort [Borg CR-10 scale] thighs	Drilling Overhead	NE 1.7 (±0.8); E 2.6 (±1.8); MD +55%; p<0.05
					Perceived discomfort [Borg CR-10 scale] lower leg/ feet	Drilling Overhead	NE 2 (±1.1); E 4.2 (±2.3); MD +106.2%; p<0.05

			Fawcett Exovest™	**obj**	Muscle activity [%MVC] DA	Drilling Overhead	NE 4.6 (±4.6); E 6.8 (±4.1); MD +47.3%; p=nd
					Muscle activity [%MVC] DM	Drilling Overhead	NE 4.2 (±2.9); E 6.4 (±4.4); MD +52.2%; p=nd
					Muscle activity [%MVC] TRI	Drilling Overhead	NE 4.4 (±2.8); E 4.1 (±3.2); MD -6.7%; p=nd
					Muscle activity [%MVC] ILL	Drilling Overhead	NE 2.6 (±2); E 4.1 (±3.7); MD +56.2%; p=nd
				subj	Perceived discomfort [Borg CR-10 scale] hands/ wrists	Drilling Overhead	NE 3.4 (±1.7); E 2.8 (±1.9); MD -19.2%; NS
					Perceived discomfort [Borg CR-10 scale] upper arms	Drilling Overhead	NE 4.2 (±1.8); E 3.4 (±1.7); MD -19.6%; p<0.05
					Perceived discomfort [Borg CR-10 scale] shoulders	Drilling Overhead	NE 3.9 (±1.5); E 3.8 (±1.8); MD -1.2%; NS
					Perceived discomfort [Borg CR-10 scale] neck	Drilling Overhead	NE 4 (±1.7); E 3.5 (±1.9); MD -14.3%; p=nd
					Perceived discomfort [Borg CR-10 scale] lower back	Drilling Overhead	NE 3 (±1.8); E 3.2 (±1.6); MD +7%; p=nd
					Perceived discomfort [Borg CR-10 scale] thighs	Drilling Overhead	NE 1.7 (±0.8); E 1.6 (±0.8); MD -3.7%; NS
					Perceived discomfort [Borg CR-10 scale] lower leg/ feet	Drilling Overhead	NE 2 (±1.1); E 1.9 (±1); MD -3.5%; NS
			ShoulderX	**obj**	Muscle activity [%MVC] DA	Drilling Overhead	NE 4.6 (±4.6); E 3.6 (±2.5); MD -22.2%; p=nd
					Muscle activity [%MVC] DM	Drilling Overhead	NE 4.2 (±2.9); E 3.6 (±2); MD -15.4%; p=nd
					Muscle activity [%MVC] TRI	Drilling Overhead	NE 4.4 (±2.8); E 5.1 (±3.5); MD +15.6%; p=nd
					Muscle activity [%MVC] ILL	Drilling Overhead	NE 2.6 (±2); E 2.5 (±2.1); MD -3.4%; p=nd
				subj	Perceived discomfort [Borg CR-10 scale] hands/ wrists	Drilling Overhead	NE 3.4 (±1.7); E 3.1 (±2); MD -8.2%; NS
					Perceived discomfort [Borg CR-10 scale] upper arms	Drilling Overhead	NE 4.2 (±1.8); E 3.5 (±1.5); MD -17.3%; p<0.05
					Perceived discomfort [Borg CR-10 scale] shoulders	Drilling Overhead	NE 3.9 (±1.5); E 4.2 (±1.9); MD +9.6%; NS
					Perceived discomfort [Borg CR-10 scale] neck	Drilling Overhead	NE 4 (±1.7); E 3.3 (±1.8); MD -17.8%; p=nd
					Perceived discomfort [Borg CR-10 scale] lower back	Drilling Overhead	NE 3 (±1.8); E 2.2 (±0.9); MD -26%; p=nd
					Perceived discomfort [Borg CR-10 scale] thighs	Drilling Overhead	NE 1.7 (±0.8); E 1.6 (±0.9); MD -7.3%; NS
					Perceived discomfort [Borg CR-10 scale] lower leg/ feet	Drilling Overhead	NE 2 (±1.1); E 1.8 (±0.9); MD -10.9%; NS
Alabdul-karim	**2019 II**	**39**	**Fawcett Exovest™**	**obj**	Muscle activity [%MVC] DA	Drilling Overhead	NE 5.9 (±4.3); E 6.2 (±3.9); MD +5%; p=nd
					Muscle activity [%MVC] ILL	Drilling Overhead	NE 1.7 (±0.8); E 3.6 (±2.1); MD +107.4%; p=nd
					Muscle activity [%MVC] RA	Drilling Overhead	NE 1.7 (±1.5); E 1.7 (±1.7); MD -0.9%; p=nd
				subj	Perceived exertion [Borg CR-10 scale] hands/ wrists	Drilling Overhead	NE 3.1 (±1); E 3.2 (±1.1); MD 4.5%; p=nd
					Perceived exertion [Borg CR-10 scale] upper arms	Drilling Overhead	NE 4.1 (±1.4); E 3.8 (±1.4); MD -7.1%; NS
					Perceived exertion [Borg CR-10 scale] shoulders	Drilling Overhead	NE 4.4 (±1.6); E 4.4 (±1.6); MD -0.9%; NS
					Perceived exertion [Borg CR-10 scale] neck	Drilling Overhead	NE 1.9 (±0.9); E 1.8 (±0.7); MD -2.9%; NS
					Perceived exertion [Borg CR-10 scale] lower back	Drilling Overhead	NE 3 (±1.2); E 3.5 (±1.5); MD +16%; p<0.05
					Perceived exertion [Borg CR-10 scale] thighs	Drilling Overhead	NE 1.9 (±0.8); E 2.9 (±1.3); MD +48.6%; NS
					Perceived exertion [Borg CR-10 scale] lower leg/ feet	Drilling Overhead	NE 2.1 (±1); E 3.4 (±1.9); MD +59.1%; p=nd
			Eksoworks	**obj**	Muscle activity [%MVC] DA	Drilling Overhead	NE 5.9 (±4.3); E 6.8 (±4.2); MD +15.6%; p=nd
					Muscle activity [%MVC] ILL	Drilling Overhead	NE 1.7 (±0.8); E 2.8 (±1.8); MD +60.8%; p=nd
					Muscle activity [%MVC] RA	Drilling Overhead	NE 1.7 (±1.5); E 1.9 (±1.8); MD +9.1%; p=nd
				subj	Perceived exertion [Borg CR-10 scale] hands/ wrists	Drilling Overhead	NE 3.1 (±1); E 3 (±1.3); MD -4.1%; p=nd
					Perceived exertion [Borg CR-10 scale] upper arms	Drilling Overhead	NE 4.1 (±1.4); E 3.8 (±1.1); MD -8.5%; p<0.05
					Perceived exertion [Borg CR-10 scale] shoulders	Drilling Overhead	NE 4.4 (±1.6); E 4.2 (±1.3); MD -5.9%; p<0.05

					Perceived exertion [Borg CR-10 scale] neck	Drilling Overhead	NE 1.9 (±0.9); E 2.1 (±0.8); MD +8%; NS
					Perceived exertion [Borg CR-10 scale] lower back	Drilling Overhead	NE 3 (±1.2); E 3.9 (±1.8); MD +27.9%; p<0.05
					Perceived exertion [Borg CR-10 scale] thighs	Drilling Overhead	NE 1.9 (±0.8); E 2.3(±1.1); MD +17.1%; NS
					Perceived exertion [Borg CR-10 scale] lower leg/ feet	Drilling Overhead	NE 2.1 (±1); E 2.3 (±1.2); MD +9.7%; p=nd
			FORTIS	**obj**	Muscle activity [%MVC] DA	Drilling Overhead	NE 5.9 (±4.3); E 4.4 (±3.4); MD -25.7%; p=nd
					Muscle activity [%MVC] ILL	Drilling Overhead	NE 1.7 (±0.8); E 1.9 (±0.9); MD +9.3%; p=nd
					Muscle activity [%MVC] RA	Drilling Overhead	NE 1.7 (±1.5); E 1.9 (±1.4); MD -7.3%; p=nd
				subj	Perceived exertion [Borg CR-10 scale] hands/ wrists	Drilling Overhead	NE 3.1 (±1); E 2.9 (±1.1); MD -5%; p=nd
					Perceived exertion [Borg CR-10 scale] upper arms	Drilling Overhead	NE 4.1 (±1.4); E 3.2 (±1.3); MD -22.4%; NS
					Perceived exertion [Borg CR-10 scale] shoulders	Drilling Overhead	NE 4.4 (±1.6); E 3.2 (±1.3); MD -27.5%; NS
					Perceived exertion [Borg CR-10 scale] neck	Drilling Overhead	NE 1.9 (±0.9); E 1.7 (±0.6); MD -11.7%; NS
					Perceived exertion [Borg CR-10 scale] lower back	Drilling Overhead	NE 3 (±1.2); E 2.2 (±1.1); MD -26.9%; NS
					Perceived exertion [Borg CR-10 scale] thighs	Drilling Overhead	NE 1.9 (±0.8); E 1.7 (±0.6); MD -12.1%; p<0.05
					Perceived exertion lower leg/ feet	Drilling Overhead	NE 2.1 (±1); E 2.1 (±1); MD -3.2%; p=nd
Alemi	**2019**	**41**	**VT-Lowe**	**obj**	Muscle activity [%MVC] EO	Lifting stoop	NE 0.027 (±0.104); E 0.034 (±0.080); MD +25.9%; p=nd
					Muscle activity [%MVC] EO	Lifting squat	NE 0.031 (±0.105); E 0.037 (±0.079); MD +19.2%; p=nd
					Muscle activity [%MVC] EO	Lifting freestyle	NE 0.028 (±0.098); E 0.031 (±0.073); MD +9.9%; p=nd
					Muscle activity [%MVC] EO	Lifting asymmetric	NE 0.035 (±0.066); E 0.042 (±0.047); MD +17.7%; p=nd
					Muscle activity [%MVC] LES	Lifting stoop	NE 0.188 (±0.096); E 0.143 (±0.071); MD -24.0%; p=nd
					Muscle activity [%MVC] LES	Lifting squat	NE 0.193 (±0.094); E 0.142 (±0.073); MD -26.4%; p=nd
					Muscle activity [%MVC] LES	Lifting freestyle	NE 0.180 (±0.089); E 0.131 (±0.067); MD -27.0%; p=nd
					Muscle activity [%MVC] LES	Lifting asymmetric	NE 0.123 (±0.049); E 0.087 (±0.034); MD -30.0%; p=nd
					Muscle activity [%MVC] ILL	Lifting stoop	NE 0.112 (±0.082); E 0.078 (±0.070); MD -30.7%; p=nd
					Muscle activity [%MVC] ILL	Lifting squat	NE 0.108 (±0.081); E 0.078 (±0.073); MD -27.7%; p=nd
					Muscle activity [%MVC] ILL	Lifting freestyle	NE 0.111 (±0.076); E 0.068 (±0.064); MD -38.7%; p=nd
					Muscle activity [%MVC] ILL	Lifting asymmetric	NE 0.085 (±0.058); E 0.058 (±0.048); MD -30.0%; p=nd
					Muscle activity [%MVC] MUL	Lifting stoop	NE 0.204 (±0.083); E 0.170 (±0.066); MD -17.0%; p=nd
					Muscle activity [%MVC] MUL	Lifting squat	NE 0.196 (±0.085); E 0.159 (±0.068); MD -18.8%; p=nd
					Muscle activity [%MVC] MUL	Lifting freestyle	NE 0.186 (±0.079); E 0.153 (±0.061); MD -17.9%; p=nd
					Muscle activity [%MVC] MUL	Lifting asymmetric	NE 0.142 (±0.049); E 0.118 (±0.036); MD -16.6%; p=nd
					Muscle activity [%MVC] BF	Lifting stoop	NE 0.083 (±0.093); E 0.068 (±0.081); MD -17.6%; p=nd
					Muscle activity [%MVC] BF	Lifting squat	NE 0.068 (±0.086); E 0.063 (±0.079); MD -6.8%; p=nd
					Muscle activity [%MVC] BF	Lifting freestyle	NE 0.073 (±0.079); E 0.060 (±0.078); MD -17.6%; p=nd
					Muscle activity [%MVC] BF	Lifting asymmetric	NE 0.076 (±0.064); E 0.062 (±0.059); MD -19.0%; p=nd
					Muscle activity [%MVC] VL	Lifting stoop	NE 0.055 (±0.084); E 0.042 (±0.078); MD -23.9%; p=nd
					Muscle activity [%MVC] VL	Lifting squat	NE 0.146 (±0.083); E 0.134 (±0.082); MD -7.7%; p=nd
					Muscle activity [%MVC] VL	Lifting freestyle	NE 0.109 (±0.080); E 0.094 (±0.071); MD -14.4%; p=nd
					Muscle activity [%MVC] VL	Lifting asymmetric	NE 0.051 (±0.060); E 0.045 (±0.055); MD -11.8%; p=nd

Alemi	**2020**	**42**	**BackX™ model AC**	**obj**	Relative energy expenditure [kcal/kg/min]	Lifting	NE 0.0756 (±0.0197); E 0.0685 (±0.0181); MD -3.3%; p<0.05 [a]
				subj	Perceived exertion [Borg CR-10 scale] shoulder	Lifting	NE 2.4 (±1.4); E 2.0 (±1.5); MD -7.2%; p=nd [a]
					Perceived exertion [Borg CR-10 scale] lower back	Lifting	NE 3.2 (±1.4); E 2.2 (±1.5); MD -7.5%; p=nd [a]
					Perceived exertion [Borg CR-10 scale] legs	Lifting	NE 0.9 (±0.6); E 0.9 (±0.7); MD +26.7%; p=nd [a]
			Laevo	**obj**	relative energy expenditure [kcal/kg/min]	Lifting	NE 0.0756 (±0.0197); E 0.0709 (±0.0197); MD -6.2%; p<0.05 [a]
				subj	Perceived exertion [Borg CR-10 scale] shoulder	Lifting	NE 2.4 (±1.4); E 2.2 (±1.6); MD -9.8%; p=nd [a]
					Perceived exertion [Borg CR-10 scale] lower back	Lifting	NE 3.2 (±1.4); E 2.2 (±1.3); MD -31.6%; p=nd [a]
					Perceived exertion [Borg CR-10 scale] legs	Lifting	NE 0.9 (±0.6); E 0.7 (±0.6); MD -26.8%; p=nd [a]
Baltrusch [b]	**2018**	**122**	**Laevo**				
Baltrusch	**2019**	**43**	**Laevo**	**obj**	Metabolic cost [J/min/kg]	Walking	NE 2.4 (±0.5); E 2.8 (±0.4); MD +14.6%; p=nd
					Metabolic cost [W/kg]	Lifting	NE 4.1 (±1.4); E 3.9 (±1.1); MD -3.9%; p=nd
Baltrusch	**2020**	**44**	**SPEXOR**	**obj**	Metabolic cost [W/kg]	Lifting	NE 5.3 (±1.3); E 4.6 (±1.4); MD -17.6%; p=0.000
					Muscle activity [%MVC] TES	Lifting	NE 19.4 (±7.1); E 17.4 (±5.5); MD -10.2%; p=0.03
					Muscle activity [%MVC] ILL	Lifting	NE 22.7 (±11.3); E 19.0 (±8.6); MD -16.4%; p=0.01
					Muscle activity [%MVC] LES	Lifting	NE 26.2 (±9.0); E 22.6 (±5.9); MD -14.0%; p=0.04
					Muscle activity [%MVC] RA	Lifting	NE 7.1 (±3.6); E 6.8 (±3.6); MD -4.9%; NS
					Muscle activity [%MVC] EO	Lifting	NE 3.6 (±1.8); E 3.2 (±2.1); MD -10.1%; NS
Bosch	**2016**	**45**	**LAEVO**	**obj**	Muscle activity [%MVC] ILL	Assembly	NE 7.8 (±5.2); E 4.7 (±4); MD -39.4%; p<0.001 [a]
					Muscle activity [%MVC] LES	Assembly	NE 10.7 (±6.4); E 6.9 (±4.5); MD -35.1%; p<0.001 [a]
					Muscle activity [%MVC] TR-A	Assembly	NE 8 (±3.5); E 4.5 (±2.2); MD -44.1%; p<0.001 [a]
					Muscle activity [%MVC] BF	Assembly	NE 11.5 (±5.2); E 9.2 (±4.1); MD -20.4%; p=0.006 [a]
					Muscle activity [%MVC] OA	Assembly	NE 3.1 (±3.1); E 2.9 (±3.2); MD -3.8%; NS [a]
					Muscle activity [%MVC] RA	Assembly	NE 0.8 (±0.8); E 0.8 (±0.7); MD 0%; NS [a]
					Muscle activity [%MVC] ILL	Static forward bending	NE 7.4 (±4); E 4.2 (±2.5); MD -43.3%; p<0.001 [a]
					Muscle activity [%MVC] LES	Static forward bending	NE 10.6 (±5.2); E 6.7 (±3.5); MD -37.2%; p<0.001 [a]
					Muscle activity [%MVC] TR-A	Static forward bending	NE 6.2 (±3); E 3 (±1.9); MD -52%; p<0.001 [a]
					Muscle activity [%MVC] BF	Static forward bending	NE 10.5 (±4.9); E 7.9 (±3.7); MD -24.7%; p<0.001 [a]
					Muscle activity [%MVC] OA	Static forward bending	NE 2.5 (±2.7); E 2.7 (±2.7); MD +10%; NS [a]
					Muscle activity [%MVC] RA	Static forward bending	NE 1 (±0.7); E 0.7 (±0.7); MD -25%; NS [a]
				subj	Perceived discomfort [LPD 0-10 scale] back	Assembly	NE 2 (±1.9); E 0.9 (±1.8); MD -54.5%; p=0.021 [a]
					Perceived discomfort [LPD 0-10 scale] legs	Assembly	NE 1.1 (±1); E 1.4 (±2); MD +29.2%; p=0.023 [a]
					Perceived discomfort [LPD 0-10 scale] chest	Assembly	NE 0 (±0); E 0.45 (±0.73); MD n/a; p=n/a [a]

Bougrinat	**2019**	**128**	**WAXO**	**obj**	Muscle activity [%MVC] GAS	Walking	NE 0.162 (±0.067); E 0.090 (±0.024); MD -44.3%; NS [a]
					Muscle activity [%MVC] SOL	Walking	NE 0.388 (±0.085); E 0.245 (±0.053); MD -37.0%; NS [a]
de Vries	**2019**	**46**	**SkelEx**	**obj**	Muscle activity [%MVC] DP	Static arm holding	NE 11.2 (±11.3); E 10.8 (±11.1); MD -3.7%; NS
					Muscle activity [%MVC] DA	Static arm holding	NE 18.1 (±12.4); E 10.4 (±10.6); MD -42.9%; p=0.002
					Muscle activity [%MVC] TR-D	Static arm holding	NE 16.9 (±9.8); E 10.0 (±7.7); MD -40.7%; p<0.001
					Muscle activity [%MVC] TR-A	Static arm holding	NE 8.4 (±6.1); E 6.7 (±5.7); MD -20.7%; p=0.012
					Muscle activity [%MVC] LAT	Static arm holding	NE 15.6 (±17.3); E 10.4 (±5.4); MD -33.3%; NS
					Muscle activity [%MVC] BB	Static arm holding	NE 6.0 (±6.2); E 5.0 (±6.9); MD -17.1%; NS
					Moments (subj) [Nm] shoulder	Static arm holding	NE 8.1 (±2.6); E 4.5 (±1.7); MD -43.9%; p<0.001
Dezman	**2017**	**47**	**Passive ankle exo-skeleton**	**obj**	Oxygen consumption [ml/min]	Walking	NE 1061,4 (±82); E 1100 (±68.1); MD +3.6%; p=nd
					Respiratory volume [l/min]	Walking	NE 22 (±0.9); E 22.9 (±2.4); MD +4.4%; p=nd
					Heart rate [bpm]	Walking	NE 92.6 (±8.4); E 97.7 (±4.5); MD +5.5%; p=nd
Ferrigno	**2009**	**48**	**Stiff thermoplastic wrist orthosis**	**obj**	Muscle activity [%MVC] TR-D	Keyboard typing	NE 14.4 (±15.9); E 25.7 (±22.8); MD +78.6%; p=0.000
					Muscle activity [%MVC] TR-D	Mouse	NE 8.0 (±12.4); E 18.9 (±18.0); MD +135.5%; p=0.000
					Muscle activity [%MVC] FDS	Keyboard typing	NE 7.9 (±3.6); E 8.8 (±4.9); MD +11.5%; NS
					Muscle activity [%MVC] FDS	Mouse	NE 5.8 (±3.5); E 8.8 (±6.7); MD +51.4%; p<0.05
					Muscle activity [%MVC] ECU	Keyboard typing	NE 20.8 (±12.0); E 20.8 (±12.7); MD -0.4%; NS
					Muscle activity [%MVC] ECU	Mouse	NE 13.0 (±7.6); E 14.6 (±8.6); MD +13.1%; p<0.05
			Stiff palmar wrist orthosis	**obj**	Muscle activity [%MVC] TR-D	Keyboard typing	NE 14.4 (±15.9); E 18.4 (±15.7); MD +27.6%; p=nd
					Muscle activity [%MVC] TR-D	Mouse	NE 8.0 (±12.4); E 12.3 (±14.8); MD +53.8%; p=nd
					Muscle activity [%MVC] FDS	Keyboard typing	NE 7.9 (±3.6); E 7.5 (±3.7); MD -4.6%; p=nd
					Muscle activity [%MVC] FDS	Mouse	NE 5.8 (±3.5); E 6.8 (±5.1); MD +16.6%; p=nd
					Muscle activity [%MVC] ECU	Keyboard typing	NE 20.8 (±12.0); E 20.7 (±12.3); MD -0.5%; p=nd
					Muscle activity [%MVC] ECU	Mouse	NE 13.0 (±7.6); E 14.7 (±8.9); MD +13.4%; p=nd
Frost	**2009**	**49**	**PLAD**	**obj**	Moment L4/L5 flexion-extension [Nm%lift]	Lifting stoop	NE 8762 (±1413); E 7224.2 (±1450.2); MD -17.6%; p=nd
					Moment L4/L5 flexion-extension [Nm%lift]	Lifting squat	NE 7331 (±734); E 5404.8 (±3566.1); MD -26.3%; p=nd
					Moment L4/L5 flexion-extension [Nm%lift]	Lifting freestyle	NE 7964 (±1229); E 6847.2 (±1698.7); MD -14%; p=nd
					Muscle activity [%MVC%lift] LAT	Lifting stoop	NE 266.9 (±309); E 325.8 (±309.2); MD +22.1%; p=nd [a]
					Muscle activity [%MVC%lift] LAT	Lifting squat	NE 169.3 (±117.2); E 166.7 (±163.5); MD -1.5%; p=nd [a]
					Muscle activity [%MVC%lift] LAT	Lifting freestyle	NE 163 (±108.7); E 195.7 (±185.5); MD +20%; p=nd [a]
					Muscle activity [%MVC%lift] TES	Lifting stoop	NE 1404.5 (±646.1); E 957.9 (±498.7); MD -31.8%; p=nd [a]
					Muscle activity [%MVC%lift] TES	Lifting squat	NE 1653.6 (±846.4); E 1268.2 (±639.8); MD -23.3%; p=nd [a]
					Muscle activity [%MVC%lift] TES	Lifting freestyle	NE 1467.4 (±570.7); E 1127.7 (±479.6); MD -23.1%; p=nd [a]
					Muscle activity [%MVC%lift] LES	Lifting stoop	NE 1853.9 (±505.6); E 1446.6 (±333.5); MD -22%; p=nd [a]
					Muscle activity [%MVC%lift] LES	Lifting squat	NE 1979.2 (±481.8); E 1455.7 (±353.2); MD -26.4%; p=nd [a]
					Muscle activity [%MVC%lift] LES	Lifting freestyle	NE 1970.1 (±489.1); E 1481 (±395.5); MD -24.8%; p=nd [a]
					Muscle activity [%MVC%lift] RA	Lifting stoop	NE 56.2 (±70.2); E 84.3 (±92.3); MD +50%; p=nd [a]
					Muscle activity [%MVC%lift] RA	Lifting squat	NE 130.2 (±130.2); E 166.7 (±243.8); MD +28%; p=nd [a]

					Muscle activity [%MVC%lift] RA	Lifting freestyle	NE 40.8 (±40.8); E 35.3 (±35.4); MD -13.3%; p=nd [a]
					Muscle activity [%MVC%lift] EO	Lifting stoop	NE 154.5 (±182.6); E 306.2 (±185.5); MD +98.2%; p=nd [a]
					Muscle activity [%MVC%lift] EO	Lifting squat	NE 260.4 (±208.3); E 221.4 (±199.9); MD -15%; p=nd [a]
					Muscle activity [%MVC%lift] EO	Lifting freestyle	NE 190.2 (±231); E 179.3 (±201.2); MD -5.7%; p=nd [a]
					Muscle activity [%MVC%lift] GLUT	Lifting stoop	NE 351.1 (±140.4); E 224.7 (±81.9); MD -36%; p=nd [a]
					Muscle activity [%MVC%lift] GLUT	Lifting squat	NE 338.5 (±169.3); E 333.3 (±136.8); MD -1.5%; p=nd [a]
					Muscle activity [%MVC%lift] GLUT	Lifting freestyle	NE 394 (±190.2); E 323.4 (±133.8); MD -17.9%; p=nd [a]
					Muscle activity [%MVC%lift] BF	Lifting stoop	NE 927 (±491.6); E 640.4 (±381.2); MD -30.9%; p=nd [a]
					Muscle activity [%MVC%lift] BF	Lifting squat	NE 468.8 (±182.3); E 359.4 (±180.8); MD -23.3%; p=nd [a]
					Muscle activity [%MVC%lift] BF	Lifting freestyle	NE 597.8 (±326.1); E 426.6 (±286.3); MD -28.6%; p=nd [a]
					Muscle activity [%MVC%lift] RF	Lifting stoop	NE 112.4 (±56.2); E 126.4 (±66.5); MD +12.5%; p=nd [a]
					Muscle activity [%MVC%lift] RF	Lifting squat	NE 859.4 (±481.8); E 1117.2 (±580.3); MD +30%; p=nd [a]
					Muscle activity [%MVC%lift] RF	Lifting freestyle	NE 462 (±285.3); E 785.3 (±449.8); MD +70%; p=nd [a]
Gillette	**2019**	**50**	**Levitate Airframe®**	**obj**	Muscle activity [%MVC] DA	job cycle - elevated arms	NE 19.4 (±6.7); E 15.8 (±5.6); MD -18.8%; p=0.02
					Muscle activity [%MVC] BB	Job cycle -arms elevated	NE 12.4 (±4.5); E 11.2 (±4.0); MD -10.1%; NS
					Muscle activity [%MVC] TR-D	Job cycle -arms elevated	NE 14.6 (±4.5); E 13.0 (±2.8); MD -10.4%; NS
					Muscle activity [%MVC] LES	Job cycle -arms elevated	NE 13.3 (±5.2); E 11.8 (±3.7); MD -11.4%; NS
Godwin	**2009**	**51**	**PLAD**	**obj**	Muscle activity [%RVE] TES	Lifting session	NE 1.566 (±0.172); E 1.107 (±0.172); MD -29.3%; p=nd
					Muscle activity [%RVE] LES	Lifting session	NE 1.568 (±0.112); E 1.143 (±0.112); MD -27.1%; p=nd
					Heart rate [%HRR]	Lifting session	NE 41.5 (±3.7); E 42.1 (±3.7); MD +1.6%; p=nd
				subj	Perceived exertion [Borg 6-20 scale]	Lifting session	NE 14.1 (±0.4); E 13.8 (±0.4); MD -2.5%; p=nd
Graham	**2009**	**52**	**PLAD**	**obj**	Muscle activity [%RVE] TES	Assembly	NE 25.4 (±12.8); E 18.1 (±6.1); MD -28.7%; p<0.05
					Muscle activity [%RVE] LES	Assembly	NE 30.1 (±17.8); E 25.8 (±15.2); MD -14.3%; p<0.05
					Muscle activity [%RVE] RA	Assembly	NE 61.6 (±33.2); E 62.2 (±24.8); MD +1%; NS
				subj	Perceived exertion [Borg 6-20 scale]	Assembly	NE 9.7 (±2.8); E 8.4 (±2.4); MD -13.9%; p=0.006
Groos	**2020 I**	**55**	**Chairless Chair**	**subj**	Perceived tension [0-4 scale] shoulders	Screwing	NE 0.250 (±0.699); E 0.221 (±0.595); MD -11.8%; p=nd
					Perceived tension [0-4 scale] shoulders	Assembly	NE 0.103 (±0.306); E 0.338 (±0.784); MD +228.6%; p=nd
					Perceived tension [0-4 scale] neck	Screwing	NE 0.706 (±1.047); E 0.588 (±1.121); MD -16.7%; p=nd
					Perceived tension [0-4 scale] neck	Assembly	NE 0.824 (±0.951); E 1.294 (±1.312); MD +57.1%; p=nd
					Perceived tension [0-4 scale] thighs	Screwing	NE 0.412 (±0.777); E 0.265 (±0.507); MD -35.7%; p=nd
					Perceived tension [0-4 scale] thighs	Assembly	NE 1.206 (±1.399); E 0.574 (±0.779); MD -52.4%; p=nd
					Perceived tension [0-4 scale] hips/ bottom	Screwing	NE 0.176 (±0.529); E 0.235 (±0.562); MD +33.3%; p=nd
					Perceived tension [0-4 scale] hips/ bottom	Assembly	NE 0.471 (±0.874); E 0.294 (±0.686); MD +37.5%; p=nd
					Perceived tension [0-4 scale] shanks	Screwing	NE 0.412 (±0.609); E 0.441 (±0.960); MD +7.1%; p=nd

					Perceived tension [0-4 scale] shanks	Assembly	NE 0.471 (±0.861); E 0.588 (±0.783); MD +25.0%; p=nd
					Perceived tension [0-4 scale] knees	Screwing	NE 0.059 (±0.243); E 0.118 (±0.485); MD +100.0%; p=nd
					Perceived tension [0-4 scale] knees	Assembly	NE 0.176 (±0.529); E 0.118 (±0.332); MD -33.2%; p=nd
					Perceived tension [0-4 scale] upper back	Screwing	NE 0.588 (±0.870); E 0.353 (±0.702); MD -40.0%; p=nd
					Perceived tension [0-4 scale] upper back	Assembly	NE 1.059 (±1.519); E 0.412 (±0.870); MD -61.1%; p=nd
					Perceived tension [0-4 scale] lower back	Screwing	NE 1.176 (±1.334); E 0.353 (±0.606); MD -70.0%; p=nd
					Perceived tension [0-4 scale] lower back	Assembly	NE 2.706 (±1.312); E 0.529 (±0.800); MD -80.4%; p=nd
					Perceived tension [0-4 scale] upper arm	Screwing	NE 0.206 (±0.538); E 0.088 (±0.379); MD -57.1%; p=nd
					Perceived tension [0-4 scale] upper arm	Assembly	NE 0.000 (±0.000); E 0.059 (±0.239); MD n/a; p=nd
					Perceived tension [0-4 scale] elbow	Screwing	NE 0.000 (±0.000); E 0.000 (±0.000); MD n/a; p=nd
					Perceived tension [0-4 scale] elbow	Assembly	NE 0.000 (±0.000); E 0.000 (±0.000); MD n/a; p=nd
					Perceived tension [0-4 scale] lower arm	Screwing	NE 0.500 (±0.826); E 0.235 (±0.554); MD -52.9%; p=nd
					Perceived tension [0-4 scale] lower arm	Assembly	NE 0.000 (±0.000); E 0.000 (±0.000); MD n/a; p=nd
					Perceived tension [0-4 scale] ankles	Screwing	NE 0.059 (±0.243); E 0.176 (±0.529); MD +200.0%; p=nd
					Perceived tension [0-4 scale] ankles	Assembly	NE 0.000 (±0.000); E 0.235 (±0.562); MD n/a; p=nd
					Perceived tension [0-4 scale] feet	Screwing	NE 0.059 (±0.243); E 0.235 (±0.664); MD +300.0%; p=nd
					Perceived tension [0-4 scale] feet	Assembly	NE 0.353 (±0.702); E 0.353 (±0.702); MD +0.0%; p=nd
Groos	**2020 II**	**54**	**Levitate Airframe®**	**obj**	Working heart rate [bpm]	Screwing manual overhead	NE 31.4 (±1.7); E 30.1 (±1.1); MD -4.1%; p=nd
					Working heart rate [bpm]	Screwing tool overhead	NE 25.7 (±2.5); E 25.0 (±2.2); MD -2.7%; NS
					Working heart rate [bpm]	Sticking overhead	NE 25.6 (±1.7); E 22.9 (±1.3); MD -10.7%; NS
					Muscle activity [sEA] TR-D	Screwing manual overhead	NE 17.0 (±1.6); E 11.6 (±1.0); MD -32.1%; p=nd
					Muscle activity [sEA] TR-D	Screwing tool overhead	NE 19.7 (±1.6); E 15.3 (±1.0); MD -22.3%; p=nd
					Muscle activity [sEA] TR-D	Sticking overhead	NE 14.8 (±3.9); E 10.0 (±2.5); MD -32.5%; p=nd
					Muscle activity [sEA] DA	Screwing manual overhead	NE 19.8 (±3.7); E 15.3 (±3.2); MD -22.7%; p=nd
					Muscle activity [sEA] DA	Screwing tool overhead	NE 23.1 (±2.8); E 17.4 (±2.5); MD -24.7%; p=nd
					Muscle activity [sEA] DA	Sticking overhead	NE 14.0 (±5.2); E 9.0 (±3.3); MD -35.5%; p=nd
					Muscle activity [sEA] DM	Screwing manual overhead	NE 12.4 (±2.6); E 8.1 (±1.9); MD -34.7%; p=nd
					Muscle activity [sEA] DM	Screwing tool overhead	NE 12.4 (±1.4); E 7.5 (±0.9); MD -39.5%; p=nd
					Muscle activity [sEA] DM	Sticking overhead	NE 8.1 (±3.3); E 5.2 (±1.9); MD -36.4%; p=nd

					Muscle activity [sEA] LAT	Screwing manual overhead	NE 5.9 (±1.6); E 4.0 (±1.4); MD -31.9%; p=nd
					Muscle activity [sEA] LAT	Screwing tool overhead	NE 6.6 (±2.1); E 6.4 (±1.4); MD -3.0%; p=nd
					Muscle activity [sEA] LAT	Sticking overhead	NE 5.0 (±1.2); E 5.2 (±1.0); MD +4.0%; p=nd
Huysamen	**2018 I**	**57**	**Robo-Mate**	**obj**	Muscle activity [%MVC] RA	Lifting	NE 7.9 (±7.5); E 7.9 (±5.9); MD -0.8%; p=nd
					Muscle activity [%MVC] LES	Lifting	NE 48.5 (±26.6); E 34 (±13.2); MD -29.3%; p=nd
					Muscle activity [%MVC] BF	Lifting	NE 21.9 (±6.7); E 16.5 (±6.8); MD -24.8%; p=nd
				subj	Perceived exertion [Borg CR-10 scale] trunk	Lifting	NE 3.2 (±1.5); E 2.2 (±1); MD -32.4%; p=nd
					Perceived exertion [Borg CR-10 scale] legs	Lifting	NE 3.8 (±2.1); E 3.2 (±1.1); MD -16.6%; p=nd
Huysamen	**2018 II**	**56**	**Iso-elastic upper limb exoskeleton**	**obj**	Muscle activity [%RVC] BB	Static arm overhead holding	NE 34 (±26.2); E 23 (±24.2); MD -32.4%; p=nd
					Muscle activity [%RVC] DM	Static arm overhead holding	NE 41.5 (±14.4); E 29 (±16.7); MD -30.1%; p=nd
					Muscle activity [%MVC] TES	Static arm overhead holding	NE 11.5 (±4.4); E 14 (±6.8); MD +21.7%; p=nd
					Muscle activity [%MVC] LES	Static arm overhead holding	NE 7.5 (±3.5); E 9 (±3.6); MD +20%; p=nd
					Muscle activity [%MVC] RA	Static arm overhead holding	NE 3.5 (±2); E 3 (±1.9); MD -14.3%; p=nd
					Muscle activity [%MVC] BF	Static arm overhead holding	NE 3.05 (±2); E 2.8 (±2); MD -9.8%; p=nd
					Muscle activity [%MVC] TIB	Static arm overhead holding	NE 1.7 (±1); E 1.9 (±1); MD +12.1%; p=nd
					Muscle activity [%MVC] GAS	Static arm overhead holding	NE 7 (±4.7); E 7 (±2.7); MD 0%; p=nd
					Muscle activity [%MVC] RF	Static arm overhead holding	NE 2.6 (±2.5); E 2.4 (±1.9); MD -7.8%; p=nd
				subj	Perceived exertion [Borg CR-10 scale] arms	Static arm overhead holding	NE 2.1 (±0.9); E 1.4 (±1); MD -35.7%; p=nd
					Perceived exertion [Borg CR-10 scale] trunk	Static arm overhead holding	NE 0.6 (±0.9); E 0.9 (±1.2); MD +50%; p=nd
					Perceived exertion [Borg CR-10 scale] legs	Static arm overhead holding	NE 0.3 (±0.4); E 0.6 (±0.8); MD +83.3%; p=nd
Hyun	**2019**	**58**	**H-VEX**	**obj**	Muscle activity [%MVC] CB	Static arm overhead holding	NE 11.1 (±3.1); E 5.3 (±2.3); MD -51.8%; p=nd
					Muscle activity [%MVC] DA	Static arm overhead holding	NE 16.5 (±3.2); E 9.3 (±4.2); MD -43.6%; p=nd

					Muscle activity [%MVC] DM	Static arm overhead holding	NE 14.5 (±3.8); E 6.5 (±3.7); MD -55.5%; p=nd
					Muscle activity [%MVC] BB	Static arm overhead holding	NE 3.8 (±2.1); E 2.3 (±1.5); MD -38.2%; p=nd
					Muscle activity [%MVC] TM	Static arm overhead holding	NE 11.2 (±6.1); E 7.1 (±4.9); MD -36.3%; p=nd
					Muscle activity [%MVC] ES	Static arm overhead holding	NE 3.2 (±0.8); E 5.1 (±0.9); MD +56.4%; p=nd
Johansson	**2004**	**123**	**Stiff wrist orthosis**		Muscle activity [%MVC] FCU	Gripping	NE 20.3 (nd); E 27.2 (nd); MD +33.8%; p=nd
					Muscle activity [%MVC] FDS	Gripping	NE 6.3 (nd); E 9.0 (nd); MD +41.6%; p=nd
					Muscle activity [%MVC] ECR	Gripping	NE 10.3 (nd); E 14.3 (nd); MD +38.5%; p=nd
					Muscle activity [%MVC] ECU	Gripping	NE 20.3 (nd); E 25.4 (nd); MD +25.1%; p=nd
			Flexible wrist orthosis		Muscle activity [%MVC] FCU	Gripping	NE 20.3 (nd); E 21.4 (nd); MD +5.2%; p=nd
					Muscle activity [%MVC] FDS	Gripping	NE 6.3 (nd); E 6.2 (nd); MD -1.6%; p=nd
					Muscle activity [%MVC] ECR	Gripping	NE 10.3 (nd); E 10.1 (nd); MD -1.9%; p=nd
					Muscle activity [%MVC] ECU	Gripping	NE 20.3 (nd); E 19.5 (nd); MD -4.1%; p=nd
Kim	**2018 I**	**88**	**EksoVestTM**	**obj**	Muscle activity [%MVC] DA	Drilling	NE 0.167 (±0.131); E 0.136 (±0.112); MD -19%; p=nd
					Muscle activity [%MVC] DA	Wiring	NE 0.091 (±0.067); E 0.034 (±0.022); MD -62.9%; p=nd
					Muscle activity [%MVC] DM	Drilling	NE 0.107 (±0.107); E 0.065 (±0.06); MD -39.5%; p=nd
					Muscle activity [%MVC] DM	Wiring	NE 0.053 (±0.056); E 0.022 (±0.078); MD -59.1%; p=nd
					Muscle activity [%MVC] TR-D	Drilling	NE 0.184 (±0.103); E 0.139 (±0.064); MD -24.3%; p=nd
					Muscle activity [%MVC] TR-D	Wiring	NE 0.076 (±0.062); E 0.048 (±0.033); MD -37.8%; p=nd
				subj	Perceived discomfort [Borg CR-10 scale] neck	Drilling	NE 1.1 (±1.6); E 1.1 (±1.4); MD +0.4%; p=nd
					Perceived discomfort [Borg CR-10 scale] neck	Wiring	NE 0.6 (±1.2); E 0.8 (±1.2); MD +47.4%; p=nd
					Perceived discomfort [Borg CR-10 scale] shoulder	Drilling	NE 2.2 (±2.1); E 2.1 (±1.6); MD -4.2%; p=nd
					Perceived discomfort [Borg CR-10 scale] shoulder	Wiring	NE 0.7 (±0.9); E 0.9 (±1); MD +30%; p=nd
					Perceived discomfort upper [Borg CR-10 scale] back	Drilling	NE 1.5 (±1.8); E 1.5 (±1.7); MD -2.4%; p=nd
					Perceived discomfort upper [Borg CR-10 scale] back	Wiring	NE 0.6 (±1); E 1 (±1.6); MD +53.7%; p=nd
					Perceived discomfort lower [Borg CR-10 scale] back	Drilling	NE 1.7 (±2.1); E 1.7 (±1.7); MD +3.7%; p=nd
					Perceived discomfort lower [Borg CR-10 scale] back	Wiring	NE 0.9 (±1.4); E 1 (±1.5); MD +18.3%; p=nd
					Perceived discomfort [Borg CR-10 scale] legs	Drilling	NE 1.4 (±1.6); E 1.2 (±1.5); MD -14.7%; p=nd
					Perceived discomfort [Borg CR-10 scale] legs	Wiring	NE 0.8 (±1.1); E 0.7 (±1); MD -16.9%; p=nd
					Perceived discomfort [Borg CR-10 scale] upper arms	Drilling	NE 2.5 (±2.1); E 2.3 (±1.8); MD -7.6%; p=nd
					Perceived discomfort [Borg CR-10 scale] upper arms	Wiring	NE 0.8 (±1.1); E 0.8 (±1.1); MD -10.2%; p=nd
					Perceived discomfort [Borg CR-10 scale] lower arms	Drilling	NE 2 (±1.9); E 1.2 (±1.2); MD -37.4%; p=nd
					Perceived discomfort [Borg CR-10 scale] lower arms	Wiring	NE 0.5 (±0.8); E 0.5 (±0.8); MD -0.4%; p=nd
Kim	**2018 II**	**59**	**EksoVestTM**	**obj**	Shear force median [N] lateral	Drilling	NE 264.6 (±214.9); E 214.6 (±163.1); MD -18.9%; p=nd
					Shear force median [N] lateral	Wiring	NE 119 (±66.8); E 107.7 (±90.1); MD -9.5%; p=nd

					Shear force median [N] a/p	Drilling	NE 1190.8 (±575.6); E 994.5 (±499.9); MD -16.5%; p=nd
					Shear force median [N] a/p	Wiring	NE 756.6 (±369.8); E 789.1 (±409); MD -4.3%; p=nd
					Compression force median [N]	Drilling	NE 105.6 (±102.3); E 131 (±102.6); MD +24.1%; p=nd
					Compression force median [N]	Wiring	NE 34.1 (±46.5); E 61.1 (±37.8); MD +79.3%; p=nd
Kim	**2019**	**60**	**EksoVestTM**	**obj**	Muscle activity [%MVC] DA	Drilling	NE 0.149 (±0.094); E 0.080 (±0.046); MD -46.5%; p=nd
					Muscle activity [%MVC] DA	Wiring	NE 0.135 (±0.069); E 0.056 (±0.023); MD -58.6%; p=nd
					Muscle activity [%MVC] IF	Drilling	NE 0.130 (±0.070); E 0.074 (±0.035); MD -43.2%; p=nd
					Muscle activity [%MVC] IF	Wiring	NE 0.102 (±0.055); E 0.049 (±0.024); MD -51.9%; p=nd
					Muscle activity [%MVC] ES	Drilling	NE 0.050 (±0.066); E 0.041 (±0.043); MD -18.1%; p=nd
					Muscle activity [%MVC] ES	Wiring	NE 0.039 (±0.057); E 0.036 (±0.038); MD -7.6%; p=nd
					Muscle activity [%MVC] SA	Drilling	NE 0.122 (±0.079); E 0.077 (±0.039); MD -37.3%; p=nd
					Muscle activity [%MVC] SA	Wiring	NE 0.104 (±0.064); E 0.064 (±0.043); MD -37.9%; p=nd
					Muscle activity [%MVC] EO	Drilling	NE 0.046 (±0.028); E 0.036 (±0.020); MD -21.1%; p=nd
					Muscle activity [%MVC] EO	Wiring	NE 0.034 (±0.021); E 0.030 (±0.018); MD -12.0%; p=nd
					Muscle activity [%MVC] RA	Drilling	NE 0.040 (±0.026); E 0.036 (±0.024); MD -8.8%; p=nd
					Muscle activity [%MVC] RA	Wiring	NE 0.033 (±0.021); E 0.033 (±0.020); MD -0.4%; p=nd
					Muscle activity [%MVC] LAT	Drilling	NE 0.047 (±0.026); E 0.041 (±0.021); MD -12.9%; p=nd
					Muscle activity [%MVC] LAT	Wiring	NE 0.036 (±0.019); E 0.030 (±0.014); MD -17.7%; p=nd
				subj	Perceived discomfort [Borg CR-10 scale] neck	Drilling	NE 1.7 (±1.4); E 1.0 (±1.2); MD -37.7%; p=nd
					Perceived discomfort [Borg CR-10 scale] neck	Wiring	NE 1.1 (±1.1); E 0.6 (±0.8); MD -49.1%; p=nd
					Perceived discomfort [Borg CR-10 scale] shoulders	Drilling	NE 2.6 (±1.6); E 1.9 (±1.5); MD -28.5%; p=nd
					Perceived discomfort [Borg CR-10 scale] shoulders	Wiring	NE 1.5 (±1.3); E 1.1 (±1.0); MD -25.4%; p=nd
					Perceived discomfort [Borg CR-10 scale] upper arms	Drilling	NE 2.8 (±1.6); E 2.1 (±1.5); MD -24.4%; p=nd
					Perceived discomfort [Borg CR-10 scale] upper arms	Wiring	NE 1.4 (±1.3); E 1.1 (±0.9); MD -27.9%; p=nd
					Perceived discomfort [Borg CR-10 scale]	Drilling	NE 2.1 (±1.5); E 1.4 (±1.2); MD -31.9%; p=nd
					Perceived discomfort [Borg CR-10 scale] lower arms	Wiring	NE 1.0 (±1.3); E 0.6 (±0.8); MD -42.0%; p=nd
					Perceived discomfort [Borg CR-10 scale] lower arms	Drilling	NE 1.6 (±1.7); E 1.1 (±1.6); MD -33.3%; p=nd
					Perceived discomfort [Borg CR-10 scale] lower back	Wiring	NE 1.1 (±1.3); E 0.8 (±0.9); MD -29.1%; p=nd
					Perceived discomfort [Borg CR-10 scale] legs	Drilling	NE 1.6 (±1.8); E 1.5 (±1.6); MD -8.9%; p=nd
					Perceived discomfort [Borg CR-10 scale] legs	Wiring	NE 1.3 (±1.8); E 1.2 (±1.4); MD -3.3%; p=nd
Kim	**2020**	**61**	**Lower limb exoskeleton robot**	**obj**	Oxygen consumption VO_2 [ml/min]	Walking	NE 1099.1 (nd); E 1263.2 (nd); MD +14.9%; p=nd
					Oxygen consumption VO_2 [ml/min]	Standing	NE 887.0 (nd); E 715.5 (nd); MD -19.3%; p=nd
Knott	**2017**	**62**	**Prototype lifting support system**	**obj**	Heart rate [bpm]	Lifting and carrying	NE 111.3 (±17.6); E 112.7 (±19.1); MD +1.3%; p=nd
					VO_2/kg [ml/min/kg]	Lifting and carrying	NE 14.5 (±2.6); E 15.3 (±3.1); MD +5.5%; p=nd
				subj	Perceived exertion [Borg 6-20 scale]	Lifting and carrying	NE 10.6 (±2.9); E 11.1 (±2.8); MD +4.6%; p=nd
Koopman	**2019**	**63**	**Laevo**	**obj**	Moment L4/L5 flexion-extension [Nm]	Static forward bending	NE 82.2 (±38.8); E 70.6 (±33.6); MD -14.1%; p<0.01

					Muscle activity [%MVC] ILL	Static forward bending	NE 6.3 (±3.6); E 5.3 (±3.6); MD -15.2%; p=nd
					Muscle activity [%MVC] LL	Static forward bending	NE 8.5 (±4.6); E 7.4 (±4.9); MD -12.8%; p=nd
					Muscle activity [%MVC] RA	Static forward bending	NE 3.6 (±4.2); E 3.3 (±3.3); MD -7.1%; p=nd
					Muscle activity [%MVC] EO	Static forward bending	NE 2.6 (±1.5); E 7.5 (±9.4); MD +193.2%; p=nd
					Muscle activity [%MVC] IO	Static forward bending	NE 5.1 (±4.5); E 5.1 (±4.4); MD -0.5%; p=nd
Lee D.	**2020**	**65**	**Robotic knee orthosis**	**obj**	Metabolic cost [W/kg]	Walking	NE 3.3 (±1.6); E 3.3 (±1.6); MD -0.5%; p=na
Lee J.W. [b]	**2019**	**87**	**LAD**				
Liu	**2018**	**66**	**Levitate Airframe®**	**subj**	Perceived pain [1-5 scale] neck	Laparoscopic operating	NE 0.714 (±1.113); E 0.000 (±0.000); MD -100.0%; NS
					Perceived pain [1-5 scale] shoulders	Laparoscopic operating	NE 1.143 (±0.900); E 0.143 (±0.378); MD -87.5%; p=0.019
					Perceived pain [1-5 scale] upper back	Laparoscopic operating	NE 0.286 (±0.756); E 0.143 (±0.378); MD -50.0%; p=nd
					Perceived pain [1-5 scale] lower back	Laparoscopic operating	NE 0.714 (±1.113); E 0.571 (±1.134); MD -20.0%; p=nd
					Perceived pain [1-5 scale] upper arms	Laparoscopic operating	NE 0.143 (±0.378); E 0.000 (±0.000); MD -100.0%; p=nd
					Perceived pain [1-5 scale] wrists	Laparoscopic operating	NE 0.143 (±0.378); E 0.000 (±0.000); MD -100.0%; p=nd
					Perceived pain [1-5 scale] knees	Laparoscopic operating	NE 0.286 (±0.756); E 0.000 (±0.000); MD -100.0%; p=nd
					Perceived pain [1-5 scale] feet	Laparoscopic operating	NE 0.143 (±0.378); E 0.000 (±0.000); MD -100.0%; p=nd
Lotz	**2009**	**67**	**PLAD**	**obj**	Muscle activity [%RVC] TES	Lifting session	NE 1.5 (±0.2); E 0.9 (±0.2); MD -41.9%; p=nd [a]
					Muscle activity [%RVC] LES	Lifting session	NE 1.4 (±0.2); E 0.9 (±0.2); MD -33.6%; p=nd [a]
					Heart rate [%HRmax]	Lifting session	NE 38 (±3.8); E 34 (±3.8); MD -10.5%; p=nd [a]
				subj	Perceived exertion [Borg 6-20 scale]	Lifting session	NE 14 (±0.4); E 13 (±0.4); MD -7.1%; p=nd
Luger	**2019**	**20**	**Chairless Chair**	**subj**	Perceived discomfort [Borg CR-10 scale]	Assembly	NE 0.621 (±1.077); E 1.302 (±1.505); MD +109.3%; p=nd
Luger	**2019**	**68**	**Chairless Chair**	**obj**	Muscle activity [%RVE] TR-D	Assembly	NE 22.4 (±12.1); E 23.8 (±11.5); MD +6.0%; p<0.0001
					Muscle activity [%RVE] LES	Assembly	NE 10.9 (±4.0); E 10.5 (±6.4); MD -3.3%; p=nd
					Muscle activity [%RVE] VL	Assembly	NE 14.1 (±13.6); E 29.1 (±24.5); MD +106.9%; p=nd
					Muscle activity [%RVE] GAS-med	Assembly	NE 70.5 (±59.7); E 17.6 (±14.9); MD -75.0%; p=nd

MacLean	**2019**	**69**	**Knee Stress Release Device™**	**obj**	Metabolic cost [W/kg]	Walking	NE 5.0 (±2.5); E 5.1 (±2.2); MD +2.1%; p=nd
Madinei	**2020**	**22**	**Laevo**	**obj**	Muscle activity [%MVC] ES	Assembly kneeling	NE 0.123 (±0.073); E 0.120 (±0.071); MD -2.6%; p=nd
					Muscle activity [%MVC] ES	Assembly sitting	NE 0.145 (±0.072); E 0.131 (±0.074); MD -9.8%; p=nd
					Muscle activity [%MVC] ILL	Assembly kneeling	NE 0.087 (±0.068); E 0.079 (±0.062); MD -9.2%; p=nd
					Muscle activity [%MVC] ILL	Assembly sitting	NE 0.093 (±0.066); E 0.074 (±0.059); MD -20.8%; p=nd
					Muscle activity [%MVC] RA	Assembly kneeling	NE 0.033 (±0.027); E 0.032 (±0.026); MD -3.9%; p=nd
					Muscle activity [%MVC] RA	Assembly sitting	NE 0.028 (±0.023); E 0.028 (±0.022); MD -1.6%; p=nd
					Muscle activity [%MVC] EO	Assembly kneeling	NE 0.047 (±0.042); E 0.048 (±0.048); MD +2.8%; p=nd
					Muscle activity [%MVC] EO	Assembly sitting	NE 0.039 (±0.035); E 0.045 (±0.042); MD +15.8%; p=nd
				subj	Perceived exertion [Borg CR-10 scale]	Assembly kneeling	NE 1.4 (±1.2); E 1.6 (±0.1); MD -13.4%; p=nd
					Perceived exertion [Borg CR-10 scale]	Assembly sitting	NE 1.3 (±1.2); E 1.3 (±1.1); MD +6.6%; p=nd
			BackX	**obj**	Muscle activity [%MVC] ES	Assembly kneeling	NE 0.123 (±0.073); E 0.102 (±0.059); MD -16.8%; p=nd
					Muscle activity [%MVC] ES	Assembly sitting	NE 0.145 (±0.072); E 0.094 (±0.056); MD -34.8%; p=nd
					Muscle activity [%MVC] ILL	Assembly kneeling	NE 0.087 (±0.068); E 0.066 (±0.051); MD -23.7%; p=nd
					Muscle activity [%MVC] ILL	Assembly sitting	NE 0.093 (±0.066); E 0.052 (±0.043); MD -43.7%; p=nd
					Muscle activity [%MVC] RA	Assembly kneeling	NE 0.033 (±0.027); E 0.033 (±0.028); MD +0.3%; p=nd
					Muscle activity [%MVC] RA	Assembly sitting	NE 0.028 (±0.023); E 0.030 (±0.025); MD +6.4%; p=nd
					Muscle activity [%MVC] EO	Assembly kneeling	NE 0.047 (±0.042); E 0.047 (±0.046); MD +0.4%; p=nd
					Muscle activity [%MVC] EO	Assembly sitting	NE 0.039 (±0.035); E 0.040 (±0.033); MD +1.5%; p=nd
				subj	Perceived exertion [Borg CR-10 scale]	Assembly kneeling	NE 1.3 (±1.2); E 1.1 (±1.1); MD -19.5%; p=nd
					Perceived exertion [Borg CR-10 scale]	Assembly sitting	NE 1.3 (±1.2); E 1.4 (±1.0); MD +8.5%; p=nd
Marino	**2019**	**70**	**BackX**	**obj**	Heart rate [bpm]	Work shift	NE 91.7 (±1.9); E 98.0 (±6.1); MD +6.9%; p=nd
			Levitate Airframe®	**obj**	Heart rate [bpm]	Work shift	NE 99.1 (±9.0); E 91.0 (±6.1); MD -8.2%; p=nd
Maurice	**2020**	**71**	**PAEXO**	**obj**	Muscle activity [%peak] DA	Pointing overhead	NE 0.258 (±0.101); E 0.122 (±0.054); MD -52.6%; p<0.001
					Muscle activity [%peak] LES	Pointing overhead	NE 0.015 (±0.002); E 0.028 (±0.044); MD +84.9%; NS
					Oxygen consumption [ml/kg/min]	Pointing overhead	NE 11.5 (±3.5); E 8.9 (±3.1); MD -22.3%; p<0.001
					Heart rate [bpm]	Pointing overhead	NE 111.1 (±18.5); E 105.2 (±15.8); MD -5.3%; p<0.001
					Physical demand [NASA-TLX]	Pointing overhead	NE 70.4 (±20.1); E 49.6 (±23.8); MD -29.5%; p<0.001
Kadone	**2017**	**74**					
Miura	**2018 I**	**72**	**HAL**	**obj**	Heart rate [bpm]	Snow shoveling	NE 112.0 (±24.5); E 123.0 (±32.6); MD +9.8%; p=nd
					Systolic blood pressure [mmHg]	Snow shoveling	NE 174.0 (±22.2); E 163.0 (±28.6); MD -6.3%; p=nd
				subj	Perceived fatigue [VAS - 100mm] lumbar back	Snow shoveling	NE 75.4 (±8.9); E 39.8 (±15.0); MD -47.2%; p<0.0001
Miura	**2018 II**	**73**	**HAL**	**subj**	Perceived fatigue [VAS - 100mm] lumbar back	Snow shoveling	NE 68.0 (±14.0); E 51.0 (±23.0); MD -25.0%; p<0.05
Moyon	**2018**	**75**	**SkelEx**	**obj**	Heart rate [bpm]	Manual handling	NE 93.8 (±12.4); E 86.5 (±10.6); MD -7.7%; p=nd

Muramatsu [b]	**2013**	**127**	**back support muscle suit**				
Näf [b]	**2018**	**124**	**SPEXOR**				
Nakamura [b]	**2017**	**125**	**active back muscle suit**				
Naruse [b]	**2005**	**90**	**active back assist device**				
Pillai	**2020**	**76**	**LegX**	**obj**	Muscle activity [%MVC] RF	Panel work	NE 19.8 (±3.7); E 12.6 (±4.7); MD -36.2%; p=nd [a]
					Muscle activity [%MVC] RF	Ground work	NE 16.1 (±4.7); E 7.0 (±2.8); MD -56.5%; p<0.05 [a]
					Muscle activity [%MVC] ST	Panel work	NE 4.5 (±1.1); E 3.8 (±1.0); MD -16.6%; p=nd [a]
					Muscle activity [%MVC] ST	Ground work	NE 2.8 (±0.6); E 2.3 (±0.5); MD -16.5%; NS [a]
					Muscle activity [%MVC] GAS-lat	Panel work	NE 4.5 (±1.1); E 4.4 (±1.1); MD -2.1%; p=nd [a]
					Muscle activity [%MVC] GAS-lat	Ground work	NE 4.0 (±0.9); E 3.3 (±0.5); MD -17.5%; NS [a]
					Muscle activity [%MVC] TIB	Panel work	NE 9.1 (±2.6); E 7.0 (±1.3); MD -22.9%; p=nd [a]
					Muscle activity [%MVC] TIB	Ground work	NE 10.7 (±3.3); E 7.0 (±1.4); MD -34.8%; NS [a]
					Muscle activity [%MVC] LES	Panel work	NE 24.9 (±4.0); E 23.2 (±3.3); MD -6.8%; p=nd [a]
					Muscle activity [%MVC] LES	Ground work	NE 15.4 (±3.7); E 14.0 (±2.6); MD -9.3%; NS [a]
					Muscle activity [%MVC] TES	Panel work	NE 15.3 (±3.4); E 12.1 (±3.1); MD -21.0%; p=nd [a]
					Muscle activity [%MVC] TES	Ground work	NE 11.9 (±2.3); E 9.8 (±2.3); MD -17.6%; NS [a]
Rashedi	**2014**	**24**	**Fawcett Exovest™**	**obj**	Muscle activity [%RVE] DA	Holding overhead	NE 2.6 (±2.9); E 1.1 (±1.2); MD -56.4%; p=nd
					Muscle activity [%RVE] DM	Holding overhead	NE 2.8 (±4.8); E 2.2 (±3.1); MD -21.7%; p=nd
					Muscle activity [%RVE] TRI	Holding overhead	NE 5.8 (±4.1); E 4.5 (±3.5); MD -23.4%; p=nd
					Muscle activity [%RVE] ILL	Holding overhead	NE 1.5 (±1.1); E 1.8 (±1.4); MD +21.4%; p=nd
				subj	Perceived discomfort [Borg CR-10 scale] upper arms	Holding tool overhead	NE 2.4 (±1.4); E 1.1 (±0.8); MD -55.9%; p<0.0001
					Perceived discomfort [Borg CR-10 scale] shoulders	Holding tool overhead	NE 2.7 (±1.8); E 1.6 (±1.1); MD -42.1%; p=0.0069
					Perceived discomfort [Borg CR-10 scale] back	Holding tool overhead	NE 2.1 (±1.3); E 2.8 (±1.6); MD +29.9%; NS
Sado	**2019**	**77**	**Active lower-body exoskeleton**	**obj**	Muscle activity [%peak] VI[c]	Lifting	NE 0.687 (±0.270); E 0.407 (±0.155); MD -40.8%; p=nd
					Muscle activity [%peak] VI[c]	Carrying	NE 0.631 (±0.219); E 0.342 (±0.112); MD -45.8%; p=nd
					Muscle activity [%norm] GAS	Lifting	NE 0.338 (±0.137); E 0.185 (±0.037); MD -45.3%; p=nd
					Muscle activity [%norm] GAS	Carrying	NE 0.593 (±0.159); E 0.379 (±0.190); MD -36.1%; p=nd
Schmalz	**2019**	**78**	**PAEXO**	**obj**	Oxygen rate [ml/min*kg]	Screwing	NE 5.8 (±0.7); E 5.2 (±6.6); MD -10.3%; p<0.01 [a]
					Oxygen rate [ml/min*kg]	Drilling	NE 7.4 (±1.3); E 0.4 (±0.5); MD -94.2%; p<0.01 [a]
					Heart rate [bpm]	Screwing	NE 103.0 (±21.7); E 98.0 (±18.3); MD -4.9%; p<0.05 [a]

					Heart rate [bpm]	Drilling	NE 99.0 (±21.7); E 93.0 (±20.0); MD -6.1%; p<0.05 [a]
Spada [b]	**2018**	**91**	**SPADA**				
Sylla	**2014**	**79**	**ABLE**	**obj**	joint torque [N/kg*m] arm	Screwing overhead	NE 0.070 (±0.038); E 0.200 (±0.346); MD +185.7%; p=nd
Thalman [b]	**2018**	**129**	**Soft ellbow exosuit**				
Theurel	**2018**	**132**	**EXHAUSS Stronger®**	**obj**	Muscle activity [%MVE] DA	Lifting	NE 12.8 (±4.0); E 5.9 (±3.1); MD -53.9%; p<0.01
					Muscle activity [%MVE] DA	Carrying	NE 3.0 (±2.6); E 1.8 (±1.7); MD -40.0%; NS
					Muscle activity [%MVE] DA	Stacking	NE 12.0 (±3.8); E 3.3 (±1.5); MD -72.5%; p<0.001
					Muscle activity [%MVE] TRI-l	Lifting	NE 3.8 (±2.7); E 7.4 (±2.2); MD +94.7%; p<0.05
					Muscle activity [%MVE] TRI-l	Carrying	NE 2.8 (±1.5); E 1.1 (±0.7); MD -60.7%; p<0.05
					Muscle activity [%MVE] TRI-l	Stacking	NE 3.8 (±2.4); E 8.2 (±2.7); MD +115.8%; p<0.01
					Muscle activity [%MVE] TIB	Lifting	NE 3.8 (±1.5); E 8.0 (±2.1); MD +110.5%; p<0.001
					Muscle activity [%MVE] TIB	Carrying	NE 11.9 (±2.9); E 10.6 (±2.9); MD -10.9%; NS
					Muscle activity [%MVE] TIB	Stacking	NE 8.2 (±3.8); E 9.1 (±2.2); MD +11.0%; NS
					Muscle activity [%RVE] LES	Lifting	NE 51.9 (±18.1); E 57.0 (±19.1); MD +9.8%; NS
					Muscle activity [%RVE] LES	Carrying	NE 39.7 (±20.1); E 61.5 (±26.1); MD +54.9%; NS
					Muscle activity [%RVE] LES	Stacking	NE 57.0 (±22.7); E 54.7 (±16.1); MD -4.0%; NS
					Cardiac cost [bpm]	Lifting	NE 52.1 (±5.4); E 59.3 (±8.2); MD +13.8%; NS
					Cardiac cost [bpm]	Carrying	NE 49.3 (±9.7); E 46.0 (±4.5); MD -6.7%; NS
					Cardiac cost [bpm]	Stacking	NE 66.6 (±5.2); E 67.0 (±7.4); MD +0.6%; NS
				subj	Perceived exertion [Borg 6-20 scale]	Lifting	NE 13.4 (±1.1); E 12.9 (±1.4); MD -3.7%; NS
					Perceived exertion [Borg 6-20 scale]	Carrying	NE 13.6 (±1.5); E 11.2 (±2.2); MD -17.6%; p<0.05
					Perceived exertion [Borg 6-20 scale]	Stacking	NE 13.3 (±1.2); E 12.8 (±1.7); MD -3.8%; NS
Ulrey	**2013**	**81**	**BNDR**	**obj**	Muscle activity [%peak] LES	Lifting stooped phase	NE 22.5 (±23.0); E 18.7 (±17.4); MD -17.0%; NS
					Muscle activity [%peak] TES	Lifting stooped phase	NE 25.4 (±23.5); E 22.9 (±17.9); MD -9.6%; NS
					Muscle activity [%peak] RA	Lifting stooped phase	NE 30.0 (±28.1); E 28.7 (±23.0); MD -4.3%; NS
					Muscle activity [%peak] BF	Lifting stooped phase	NE 44.1 (±10.3); E 36.6 (±10.0); MD -17.1%; p<0.0001
					Muscle activity [%peak] TIB	Lifting stooped phase	NE 16.7 (±14.0); E 80.0 (±15.9); MD +7.4%; NS
Van Engelhoven	**2019**	**82**	**ShoulderX**	**obj**	Muscle activity median [%MVC] TR-D	Drilling overhead light tool	NE 13.9 (±5.8); E 10.3 (±6.1); MD -25.7%; p=nd [a]
					Muscle activity median [%MVC] DA	Drilling overhead light tool	NE 16.8 (±7.0); E 7.3 (±4.8); MD -55.4%; p=nd [a]

					Muscle activity median [%MVC] BB	Drilling overhead light tool	NE 2.3 (±1.2); E 1.9 (±1.2); MD -15.9%; p=nd [a]
					Muscle activity median [%MVC] LAT	Drilling overhead light tool	NE 5.0 (±1.9); E 4.7 (±2.5); MD -6.7%; p=nd [a]
					Muscle activity median [%MVC] DP	Drilling overhead light tool	NE 3.1 (±1.7); E 2.0 (±1.3); MD -34.4%; p=nd [a]
					Muscle activity median [%MVC] TRI	Drilling overhead light tool	NE 1.7 (±1.2); E 3.0 (±3.4); MD +76.5%; p=nd [a]
					Muscle activity median [%MVC] IF	Drilling overhead light tool	NE 8.2 (±4.7); E 6.5 (±3.2); MD -20.7%; p=nd [a]
					Muscle activity median [%MVC] FL-D	Drilling overhead light tool	NE 5.4 (±3.3); E 4.4 (±2.4); MD -17.9%; p=nd [a]
				subj	Perceived exertion [Borg CR-10 scale] neck	Drilling overhead light tool	NE 1.1 (±1.0); E 0.9 (±0.9); MD -14.2%; p=nd [a]
					Perceived exertion [Borg CR-10 scale] post shoulder	Drilling overhead light tool	NE 1.5 (±1.0); E 0.9 (±0.8); MD -37.4% p=nd [a]
					Perceived exertion [Borg CR-10 scale] ant shoulder	Drilling overhead light tool	NE 1.5 (±1.0); E 1.0 (±0.7); MD -31.3%; p=nd [a]
					Perceived exertion [Borg CR-10 scale] arms	Drilling overhead light tool	NE 1.3 (±0.7); E 1.0 (±0.6); MD -22.5%; p=nd [a]
					Perceived exertion [Borg CR-10 scale] back	Drilling overhead light tool	NE 0.8 (±0.6); E 0.3 (±0.6); MD -61.6%; p=nd [a]
Von Glinski	**2019**	**83**	**HAL**	**obj**	Muscle activity [%MVC] TES	Lifting	NE 110.2 (±50.7); E 97.5 (±48.6); MD -11.6%; NS
					Muscle activity [%MVC] LES	Lifting	NE 107.3 (±39.9); E 102.5 (±39.7); MD -4.5%; p<0.05
					Muscle activity [%MVC] RF	Lifting	NE 73.8 (±33.3); E 85.6 (±41.7); MD +16%; NS
Wehner [b]	**2013**	**130**	**active lower extremity exosuit**				
Wei [b]	**2020**	**126**	**MeBot-EXO**				
Weston	**2018**	**84**	**Fawcett Exovest™**	**obj**	Compression force mean [N] L4/L5	Drilling	NE 1167.3 (±280.5); E 1718.1 (±485.5); MD +47.2%; p=nd
					Shear force mean [N] L4/L5 a/p	Drilling	NE 343.6 (±49.2); E 422.8 (±73.7); MD +23.1%; p=nd
Wijeguna-wardana [b]	**2019**	**131**	**ChairX**				
Yin	**2019**	**85**	**WPAD**	**obj**	Heart rate [bpm]	Lifting	NE 57.0 (±11.1); E 53.4 (±9.5); MD -6.3%; p=nd [a]
					Muscle activity [%MVC] TES	Lifting	NE 32.3 (±16.7); E 24.3 (±10.3); MD -24.6%; p=nd [a]
					Muscle activity [%MVC] LES	Lifting	NE 35.2 (±17.6); E 30.0 (±16.9); MD -14.7%; p=nd [a]
Yong	**2019**	**86**	**Waist assist exoskeleton**	**obj**	Muscle activity [mv*s] LES	lifting	NE 1.042 (±0.525); E 0.652 (±0.273); MD -37.4%; p=nd
					Muscle activity [mv*s] TES	lifting	NE 1.035 (±0.498); E 0.648 (±0.259); MD -37.4%; p=nd

				Muscle activity [mv*s] LAT	lifting	NE 0.765 (±0.323); E 0.562 (±0.197); MD -26.6%; p=nd
Zhang [b]	**2016**	**89**	**Passive spine exoskeleton**			

[a] Data was measured from figures

[b] Required data was not provided

[c] The authors indicated muscle activity of the M. vastus intermedius; we assume one of the other knee extensors (M. vastus medialis, lateralis or rectus femoris) was measured instead.

abbreviations

MVC	maximal voluntary contraction	kcal	kilocalories	BB	musculus biceps brachii
MVE	maximal voluntary exertion	kg	kilogram	BF	musculus biceps femoris
RVC	reference voluntary contraction	W	watt	CB	musculus coracobrachialis
RVE	reference voluntary exertion	J	joule	DA	musculus deltoideus anterior
Exo	exoskeleton	N	newton	DM	musculus deltoideus medialis
NE	no exoskeleton	Nm	newton meter	DP	musculus deltoideus posterior
E	with exoskeleton	l	liter	ECR	musculus extensor carpi radialis
MD	mean difference	ml	milliliter	ECU	musculus extensor carpi ulnaris
n/a	not applicable	mmHg	millimeter mercury	EO	musculus external obliquus
nd	not defined	min	minute(s)	FCU	musculus flexor carpi ulnaris
NS	not significant	sec	second(s)	FDS	musculus flexor digitorum superficialis
ant	Anterior	h	hour(s)	GAS	musculus gastrocnemius
post	Posterior	bpm	beats per minute	GLUT	musculus gluteus maximus
a/p	anterior-posterior	HR	heart rate	ILL	musculus Iliocostalis lumborum pars lumborum
L4/L5	lumbar spine position L4/L5	HRR	heart rate range	IO	musculus internus obliquus
lat	Lateral	VO_2	oxygen uptake	LAT	musculus latissimus dorsi
med	Medial	sEA	standardized electromyographic activity	LES	musculus erector spinae lumbalis
subj	subjective measurements	LPD	local perceived discomfort scale	MUL OA	musculus multifidius musculus obliquus abdominis
obj	objective measurements	VAS	visual analog scale	RA RF	musculus rectus abdominis musculus rectus femoris
Ref	Reference			ST	musculus semitendinosus
				TES	musculus erector spinae thoracic
				TR-A	musculus trapezius ascendens
				TR-D	musculus trapezius descendens
				TRI	musculus triceps brachii
				TRI-l	musculus triceps brachii long head
				TM	musculus teres major
				VI	musculus vastus intermedius
				VL	musculus vastus lateralis

Appendix 6 *Quality assessment tool for controlled intervention studies*

Criteria	**Yes**	**No**	**Other (CD, NR, NA)***
1. Was the study described as randomized, a randomized trial, a randomized clinical trial, or an RCT?			
2. Was the method of randomization adequate (i.e., use of randomly generated assignment)?			
3. Was the treatment allocation concealed (so that assignments could not be predicted)?			
4. Were study participants and providers blinded to treatment group assignment?			
5. Were the people assessing the outcomes blinded to the participants' group assignments?			
6. Were the groups similar at baseline on important characteristics that could affect outcomes (e.g., demographics, risk factors, co-morbid conditions)?			
7. Was the overall drop-out rate from the study at endpoint 20% or lower of the number allocated to treatment?			
8. Was the differential drop-out rate (between treatment groups) at endpoint 15 percentage points or lower?			
9. Was there high adherence to the intervention protocols for each treatment group?			
10. Were other interventions avoided or similar in the groups (e.g., similar background treatments)?			
11. Were outcomes assessed using valid and reliable measures, implemented consistently across all study participants?			
12. Did the authors report that the sample size was sufficiently large to be able to detect a difference in the main outcome between groups with at least 80% power?			
13. Were outcomes reported or subgroups analyzed prespecified (i.e., identified before analyses were conducted)?			
14. Were all randomized participants analyzed in the group to which they were originally assigned, i.e., did they use an intention-to-treat analysis?			

Note: CD = cannot determine; NA = not applicable; NR = not reported. For detailed explanation on each single item, see the original source for more information: Risk Assessment Work Group, 2013. Assessing cardiovascular risk: Systematic evidence review from the risk assessment work group. USA.

Explanation of the assessment

Double and single rating of items

The following items have been rated double because of importance and/ or high risk of bias when failing: Items # 1, 2, 7, 11, 12, and 13.

The following items have been rated single because of less importance for the study type and/ or lower risk of bias: Items #3, 4, 5, 6, 8, 9, 10, and 14.

Item #1: randomization

Randomization is judged as “yes” when all factors, i.e. independent variables, of the (statistical) analysis have been randomized. This item is judged as “no” when it appears that only part of the independent variables was randomized.

Item #7: drop out

This item also includes deficits of data, e.g. technical problems were judged as drop out.

Item #11: selective reporting

This item is judged as “yes” (1) when the validity or reliability of the checklist or scale has been reported, (2) when a checklist or scale is cited correctly and whose validity or reliability has been proven in the literature but not cited in the text, and (3) when the objective measurement method, e.g. system with which heart rate is recorded, has been described in detail, i.e. product name, version, and manufacturer.

Item #13: selective reporting

This item is judged as “no” (1) when the description of the data analysis comes first in the Results section, this also applies to any post hoc analyses reported in the Results section that have not been specified in the Methods section, and (2) when there is no distinction between the Methods and Results sections.

Grouping into the seven risk of bias categories

Category 1: Randomization, including items # 1 and 2.

Category 2: Allocation, including items # 3, 6 and 14.

Category 3: Blinding, including items # 4 and 5.

Category 4: Incomplete outcome data, including items # 7 and 8.

Category 5: Selective reporting, including items # 11 and 13.

Category 6: Intervention, including items # 9 and 10.

Category 7: Power, including item # 12.

Risk of bias assessment of the 65 studies (68 references) using the 14-item checklist.

#	Study	2nd Reference	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Abdoli-E 2006	Abdoli-E 2008	2	0	0	NA	NA	1	2	1	1	1	CD	0	0	1
2	Agnew 2008	-	2	0	0	NA	NA	1	2	1	1	1	2	0	2	1
3	Alabdulkarim 2019-I	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
4	Alabdulkarim 2019-II	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
5	Alemi 2019	-	2	0	0	NA	NA	1	2	1	1	1	2	0	0	1
6	Alemi 2020	-	0	0	0	NA	NA	1	2	1	1	1	0	0	2	1
7	Baltrusch 2018	-	2	0	0	NA	NA	1	2	1	1	1	2	0	2	1
8	Baltrusch 2019	-	0	0	0	NA	NA	1	0	1	1	1	2	0	2	1
9	Baltrusch 2020	-	2	0	0	NA	NA	1	0	1	1	1	2	0	2	1
10	Bosch 2016	-	0	0	0	NA	NA	1	2	1	1	1	2	0	0	1
11	Bougrinat 2019	-	0	0	0	NA	NA	1	2	1	1	1	2	0	0	1
12	de Vries 2019	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
13	Dezman 2017	-	2	0	0	NA	NA	1	2	1	1	1	2	0	2	1
14	Ferrigno 2009	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
15	Frost 2009	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
16	Gillette 2019	-	0	0	0	NA	NA	1	2	1	1	1	0	0	2	1
17	Godwin 2009	-	2	0	0	NA	NA	1	2	1	1	1	0	0	2	1
18	Graham 2009	-	2	0	0	NA	NA	1	2	1	1	1	0	0	2	1
19	Groos 2020-I	-	2	0	0	NA	NA	1	2	1	1	1	2	0	0	1
20	Groos 2020-II	-	2	0	0	NA	NA	1	2	1	1	1	0	0	0	1
21	Huysamen 2018-I	-	2	0	0	NA	NA	1	0	1	1	1	2	0	2	1
22	Huysamen 2018-II	-	2	0	0	NA	NA	1	2	1	1	1	2	0	2	1
23	Hyun 2019	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
24	Johansson 2004	-	2	0	0	NA	NA	1	2	1	1	1	2	0	2	1
25	Kim 2018-I	Kim 2018-II	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
26	Kim 2019	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
27	Kim 2020	-	0	0	0	NA	NA	0	2	1	1	1	2	0	0	1
28	Knott 2017	-	0	0	0	NA	NA	1	2	1	1	1	0	0	0	1
29	Koopman 2019	-	2	0	0	NA	NA	1	2	1	1	1	2	0	2	1
30	Lee 2019	-	0	0	0	NA	NA	1	2	1	1	1	2	0	0	1
31	Lee 2020	-	0	0	0	NA	NA	1	0	1	1	1	0	0	0	1
32	Liu 2018	-	2	0	0	NA	NA	1	2	1	1	1	0	0	2	1
33	Lotz 2009	-	2	0	0	NA	NA	1	2	1	1	1	2	0	2	1
34	Luger 2019-I	Luger 2019-II	2	0	0	NA	NA	1	2	1	1	1	2	0	2	1
35	MacLean 2019	-	0	0	0	NA	NA	1	2	1	1	1	2	0	0	1
36	Madinei 2020	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
37	Marino 2019	-	2	0	0	NA	NA	1	0	1	1	1	2	0	2	1
38	Maurice 2020	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
39	Miura 2018-I	Kadone 2017	0	0	0	NA	NA	1	2	1	1	1	0	0	2	1
40	Miura 2018-II	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
41	Moyon 2018	-	0	0	0	NA	NA	1	2	1	1	1	CD	0	0	1
42	Muramatsu 2013	-	0	0	0	NA	NA	1	2	1	1	1	2	0	0	1
43	Nakamura 2017	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
44	Näf 2018	-	2	0	0	NA	NA	1	2	1	1	1	2	0	2	1
45	Naruse 2005	-	0	0	0	NA	NA	1	2	1	1	1	0	0	0	1
46	Pillai 2020	-	2	0	0	NA	NA	1	2	1	1	1	2	0	2	1
47	Rashedi 2014	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
48	Sado 2019	-	0	0	0	NA	NA	1	2	1	1	1	2	0	0	1
49	Schmalz 2019	-	2	0	0	NA	NA	1	2	1	1	1	2	0	2	1
50	Spada 2019	-	0	0	0	NA	NA	1	2	1	1	1	0	0	0	1
51	Sylla 2014	-	0	0	0	NA	NA	1	2	1	1	1	2	0	0	1
52	Thalman 2018	-	0	0	0	NA	NA	1	2	1	1	1	2	0	0	1
53	Theurel 2018	-	2	0	0	NA	NA	1	2	1	1	1	2	0	2	1
54	Ulrey 2013	-	2	0	0	NA	NA	1	2	1	1	1	2	0	2	1
55	Van Engelhoven 2019	-	0	0	0	NA	NA	CD	0	1	1	1	0	0	2	1
56	von Glinski 2019	-	2	0	0	NA	NA	1	2	1	1	1	0	0	2	1
57	Wehner 2013	-	0	0	0	NA	NA	1	2	1	1	1	2	0	0	1
58	Wei 2020	-	2	0	0	NA	NA	1	2	1	1	1	2	0	0	1
59	Weston 2018	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
60	Wijegunawardana 2019	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
61	Yin 2019	-	0	0	0	NA	NA	1	2	1	1	1	2	0	2	1
62	Yong 2019	-	0	0	0	NA	NA	1	2	1	1	1	2	0	0	1
63	Zhang 2016	-	0	0	0	NA	NA	1	0	1	1	1	2	0	0	1

Appendix 7 *Study findings (i.e. SMD and risk of bias) for studies evaluating the effects of using a back supporting exoskeleton on physical stress and strain. [IV = inverse variance; CI= confidence interval; Exo= exoskeleton]*

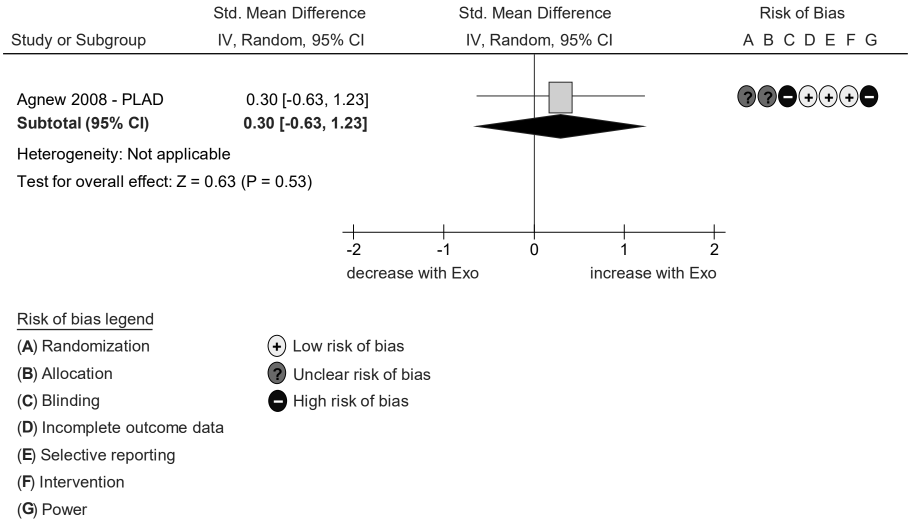


Figure 7 *Back supporting exoskeletons – Shear force*

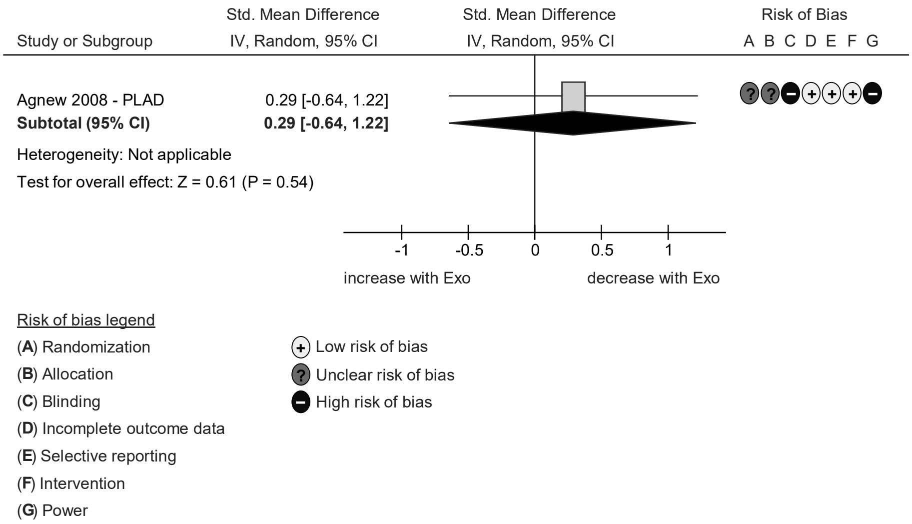


Figure 8 *Back supporting exoskeletons – Compression force*

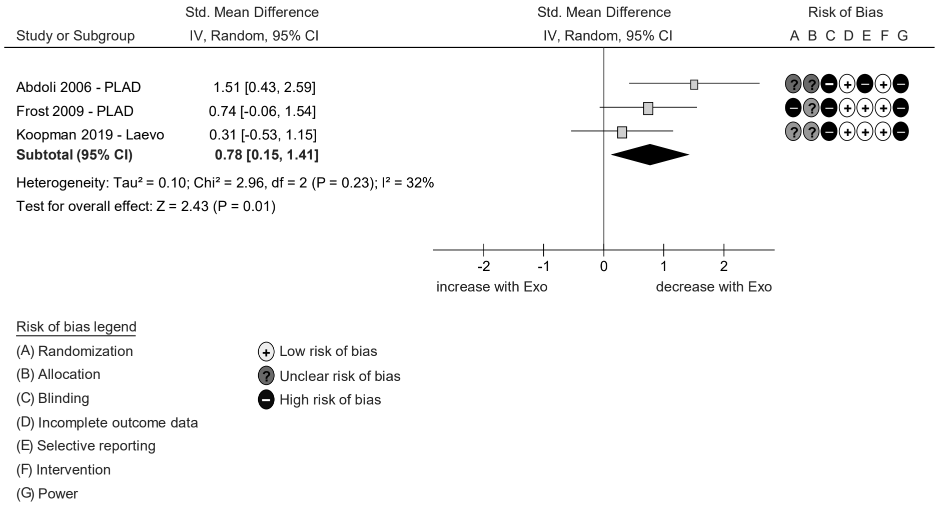


Figure 9 *Back supporting exoskeletons – joint moments*

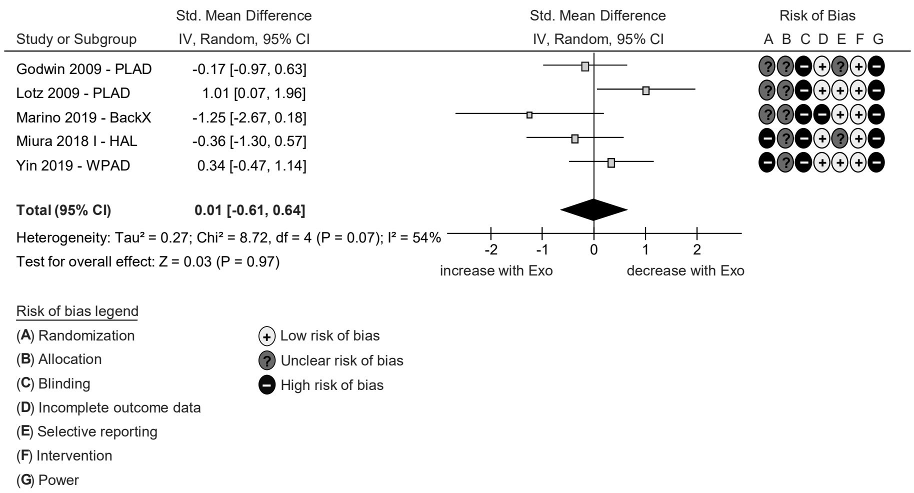


Figure 10 *Back supporting exoskeletons – Heart rate*

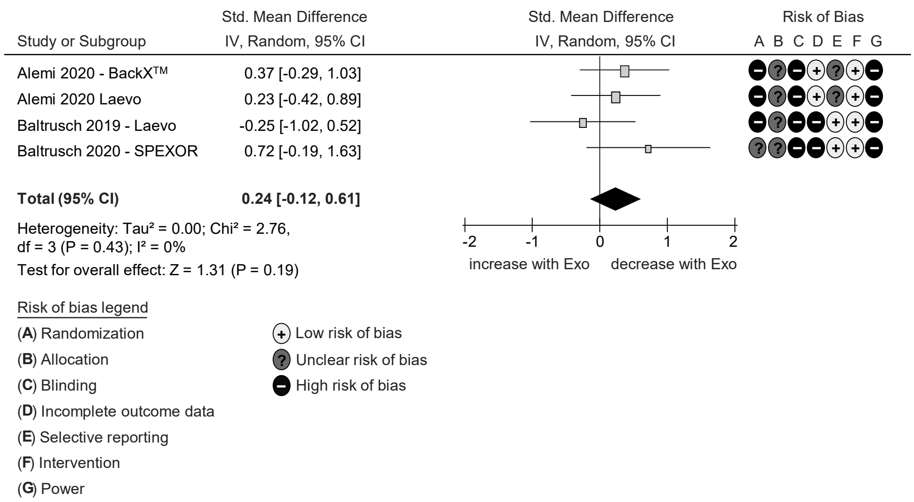


Figure 11 *Back supporting exoskeletons – Energy expenditure*

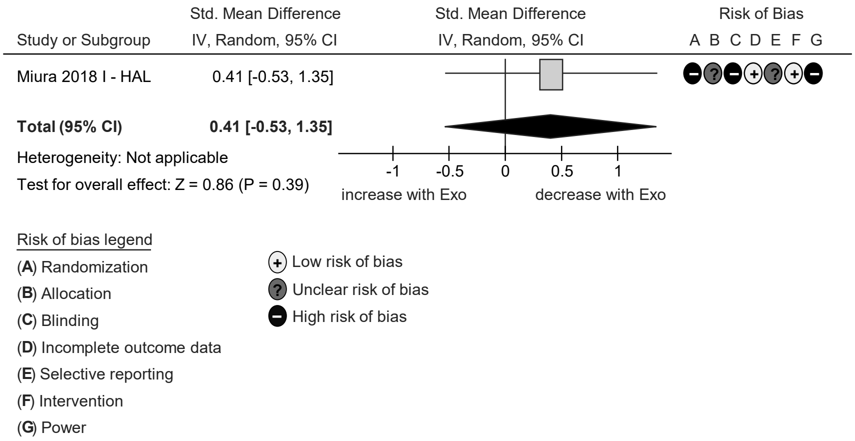


Figure 12 *Back supporting exoskeletons – Blood pressure*

Appendix 8 *Study findings (i.e. SMD and risk of bias) for studies evaluating the effects of using a lower limb supporting exoskeleton on physical stress and strain. [IV = inverse variance; CI= confidence interval; Exo= exoskeleton]*

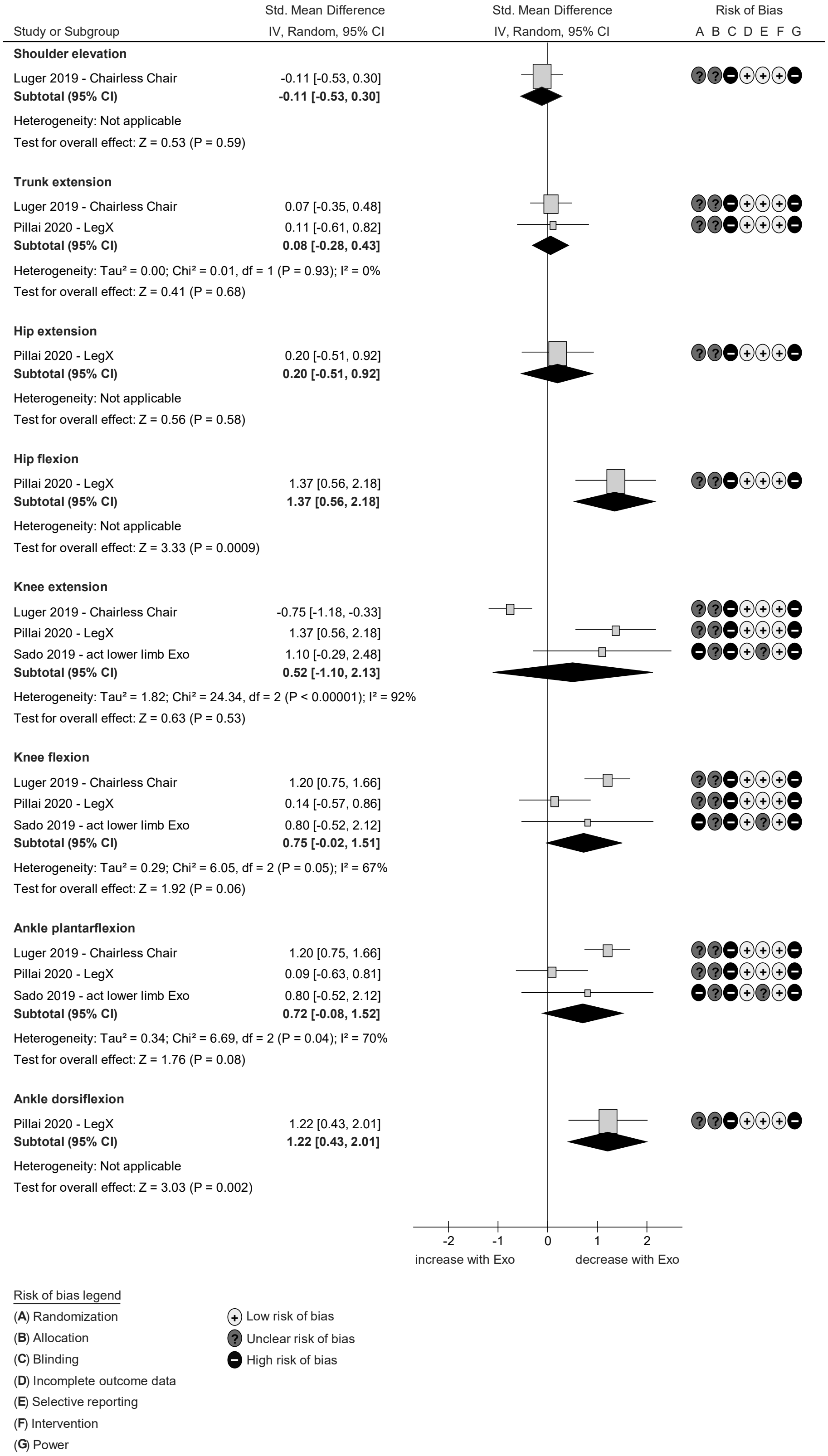


Figure 13 *Lower limb supporting exoskeletons – Muscle activity*

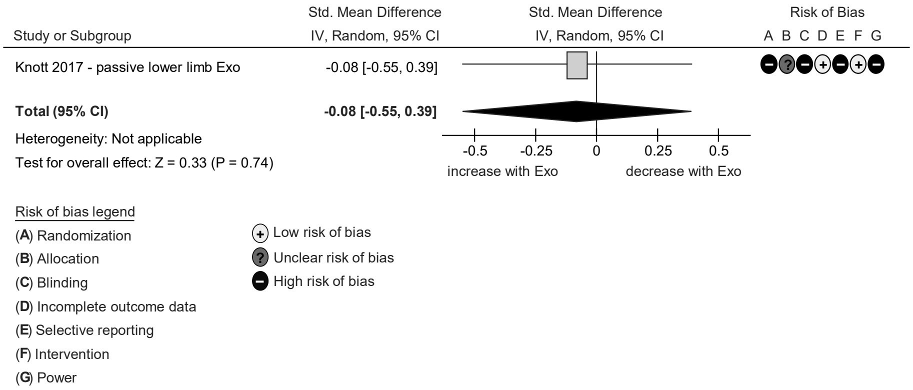


Figure 14 *Lower limb supporting exoskeletons – Heart rate*

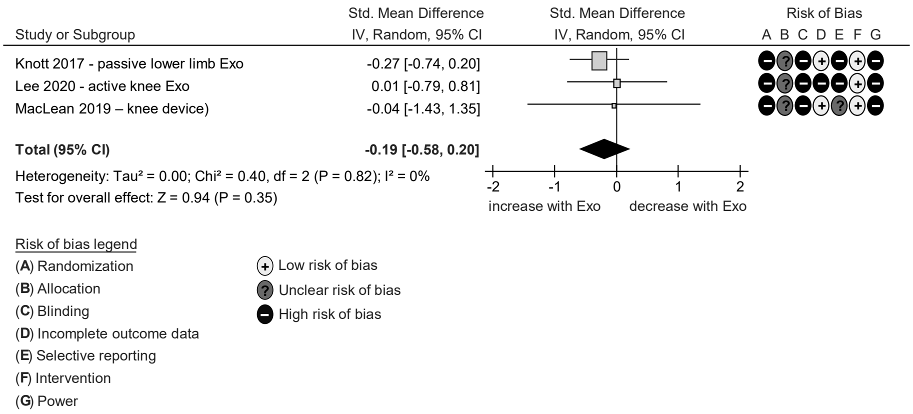


Figure 15 *Lower limb supporting exoskeletons – Energy expenditure*

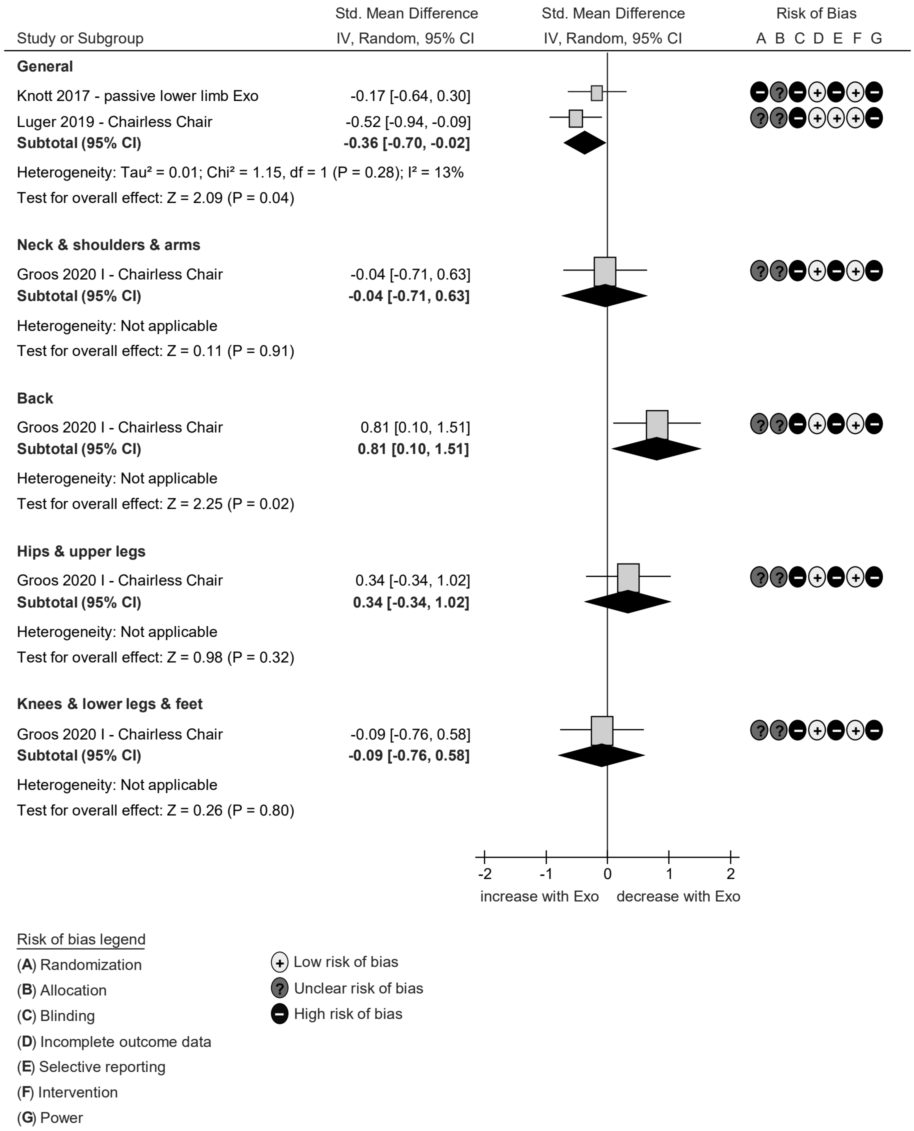
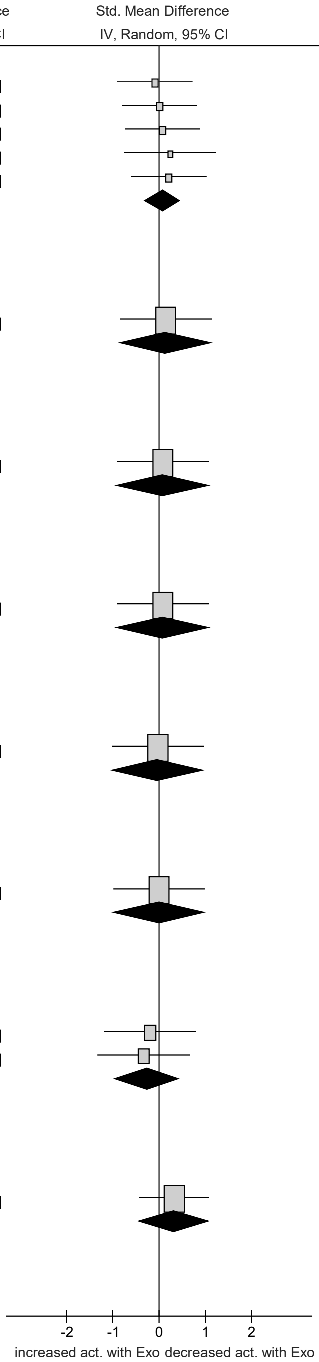


Figure 16 *Lower limb supporting exoskeletons – Perceived strain*

Appendix 9 *Study findings (i.e. SMD and risk of bias) for studies evaluating the effects of using an upper limb supporting exoskeleton on physical stress and strain. [IV = inverse variance; CI= confidence interval; Exo= exoskeleton]*



Study or Subgroup	Std. Mean Difference IV, Random, 95% CI	Risk of Bias A B C D E F G
3.1.7 Trunk flexion		
Alabdulkarim 2019 II - EksoVest[TM]	-0.09 [-0.89, 0.71]	− ? − + + + −
Alabdulkarim 2019 II - Fawcett Exsovest[TM]	0.01 [-0.79, 0.81]	− ? − + + + −
Alabdulkarim 2019 II FORTIS[TM]	0.08 [-0.72, 0.88]	− ? − + + + −
Huysamen 2018 II - passive upper limb Exo	0.24 [-0.74, 1.23]	? ? − + + + −
Kim 2019 - EksoVest[TM]	0.21 [-0.59, 1.01]	− ? − + + + −
Subtotal (95% CI)	**0.08 [-0.29, 0.45]**	
Heterogeneity: Tau² = 0.00; Chi² = 0.40, df = 4 (P = 0.98); I² = 0%		
Test for overall effect: Z = 0.42 (P = 0.67)		
3.1.8 Hip extension		
Huysamen 2018 II - passive upper limb Exo	0.14 [-0.84, 1.13]	? ? − + + + −
Subtotal (95% CI)	**0.14 [-0.84, 1.13]**	
Heterogeneity: Not applicable		
Test for overall effect: Z = 0.29 (P = 0.77)		
3.1.9 Hip flexion		
Huysamen 2018 II - passive upper limb Exo	0.09 [-0.90, 1.07]	? ? − + + + −
Subtotal (95% CI)	**0.09 [-0.90, 1.07]**	
Heterogeneity: Not applicable		
Test for overall effect: Z = 0.17 (P = 0.87)		
3.1.10 Knee extension		
Huysamen 2018 II - passive upper limb Exo	0.09 [-0.90, 1.07]	? ? − + + + −
Subtotal (95% CI)	**0.09 [-0.90, 1.07]**	
Heterogeneity: Not applicable		
Test for overall effect: Z = 0.17 (P = 0.87)		
3.1.11 Knee flexion		
Huysamen 2018 II - passive upper limb Exo	-0.03 [-1.01, 0.95]	? ? − + + + −
Subtotal (95% CI)	**-0.03 [-1.01, 0.95]**	
Heterogeneity: Not applicable		
Test for overall effect: Z = 0.05 (P = 0.96)		
3.1.12 Ankle plantarflexion		
Huysamen 2018 II - passive upper limb Exo	0.00 [-0.98, 0.98]	? ? − + + + −
Subtotal (95% CI)	**0.00 [-0.98, 0.98]**	
Heterogeneity: Not applicable		
Test for overall effect: Z = 0.00 (P = 1.00)		
3.1.13 Ankle dorsiflexion		
Huysamen 2018 II - passive upper limb Exo	-0.20 [-1.18, 0.79]	? ? − + + + −
Theurel 2018- EXHAUSS Stronger	-0.33 [-1.32, 0.65]	? ? − + + + −
Subtotal (95% CI)	**-0.26 [-0.96, 0.43]**	
Heterogeneity: Tau² = 0.00; Chi² = 0.04, df = 1 (P = 0.85); I² = 0%		
Test for overall effect: Z = 0.74 (P = 0.46)		
3.1.14 Wrist flexion		
Van Engelhoven 2018 - ShoulderX	0.32 [-0.42, 1.07]	− − − − ? + −
Subtotal (95% CI)	**0.32 [-0.42, 1.07]**	
Heterogeneity: Not applicable		
Test for overall effect: Z = 0.85 (P = 0.39)		

Risk of bias legend
(**A**) Randomization
(**B**) Allocation
(**C**) Blinding
(**D**) Incomplete outcome data
(**E**) Selective reporting
(**F**) Intervention
(**G**) Power

+ Low risk of bias
? Unclear risk of bias
− High risk of bias

Figure 5 – Part 2 *Upper limb supporting exoskeletons – Muscle activity*

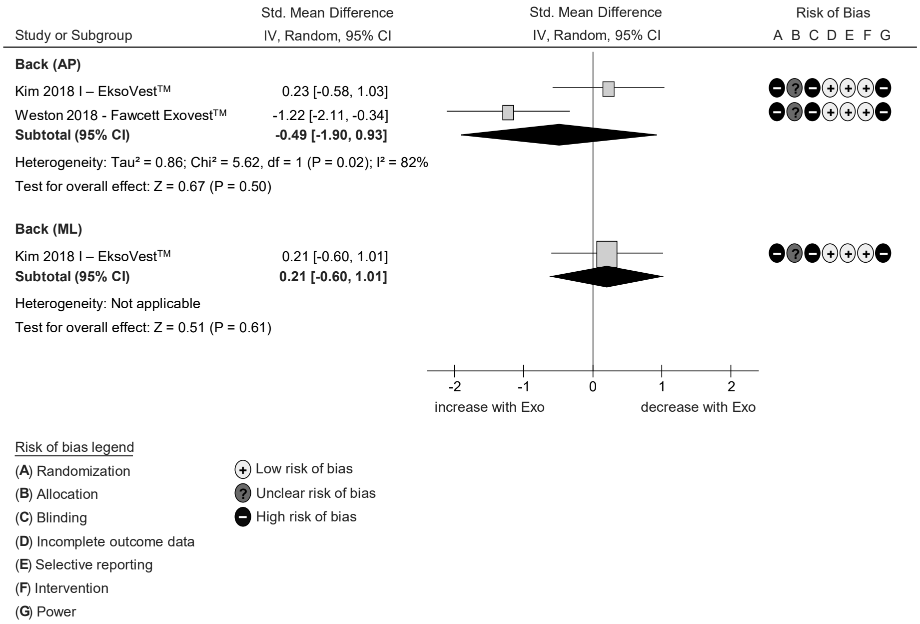


Figure 17 *Upper limb supporting exoskeletons – Shear force*

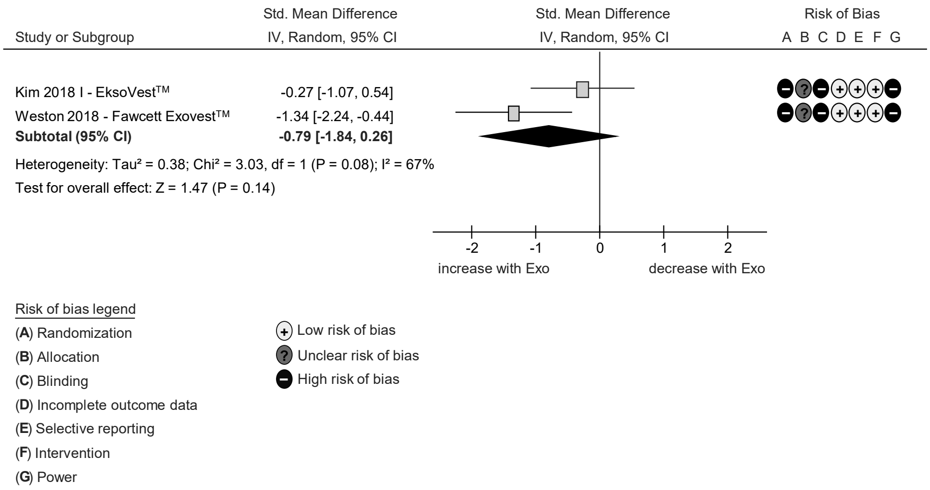


Figure 18 *Upper limb supporting exoskeletons – Compression force*

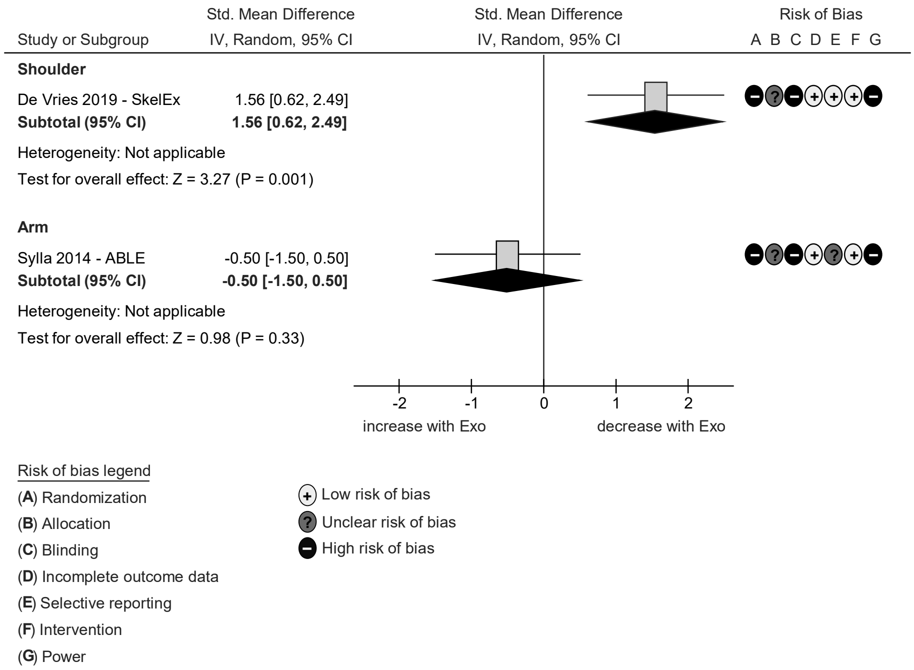


Figure 19 *Upper limb supporting exoskeletons – joint moments*

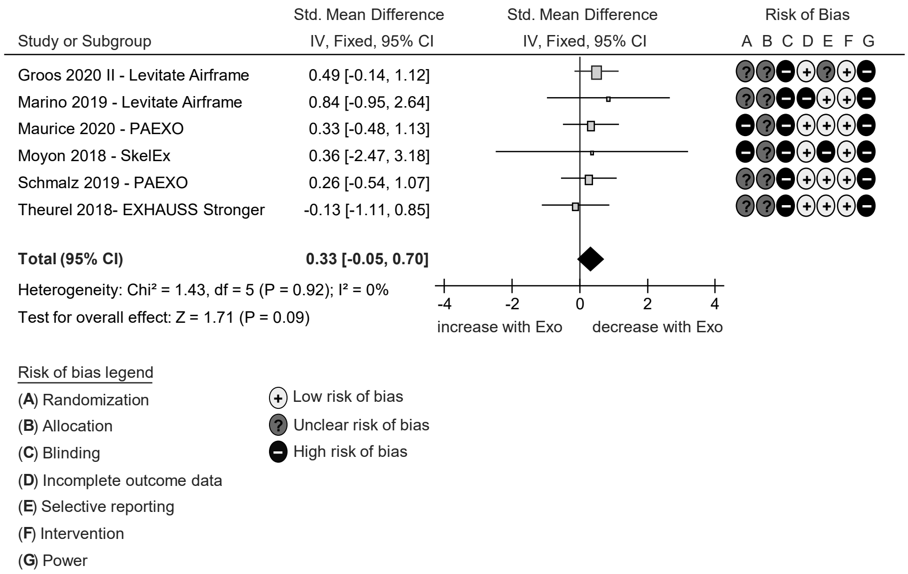


Figure 20 *Upper limb supporting exoskeletons – Heart rate*

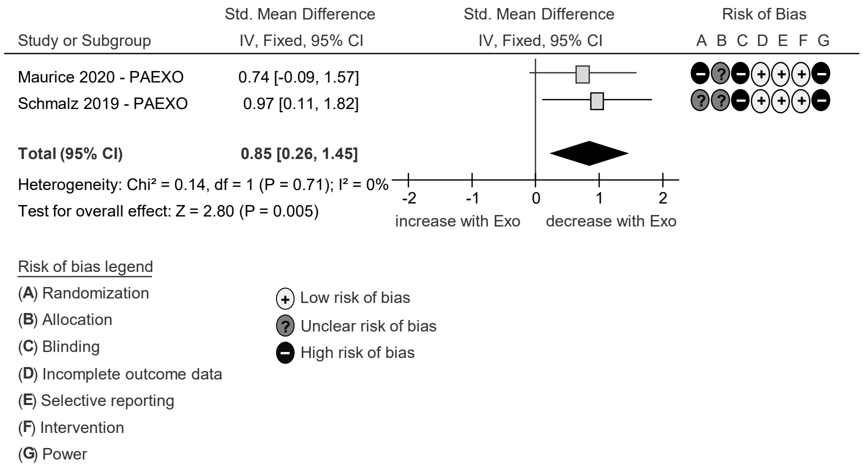


Figure 21 *Upper limb supporting exoskeletons – Energy expenditure*

Appendix 10 *Study findings (i.e. SMD and risk of bias) for studies evaluating the effects of using an ankle supporting exoskeleton on physical stress and strain. [IV = inverse variance; CI= confidence interval; Exo= exoskeleton]*

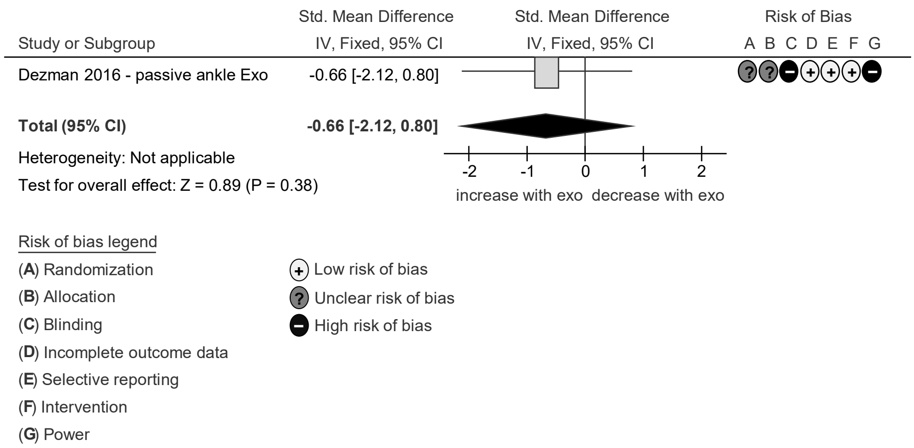


Figure 22 *Ankle supporting exoskeletons – Heart rate*

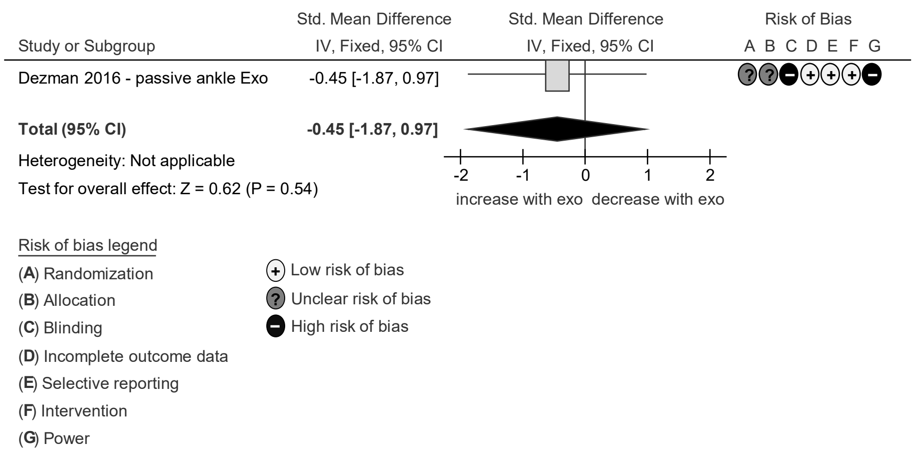


Figure 23 *Ankle supporting exoskeletons – Energy expenditure*

Appendix 11 *Study findings (i.e. SMD and risk of bias) for studies evaluating the effects of using a wrist supporting exoskeleton on physical stress and strain. [IV = inverse variance; CI= confidence interval; Exo= exoskeleton]*

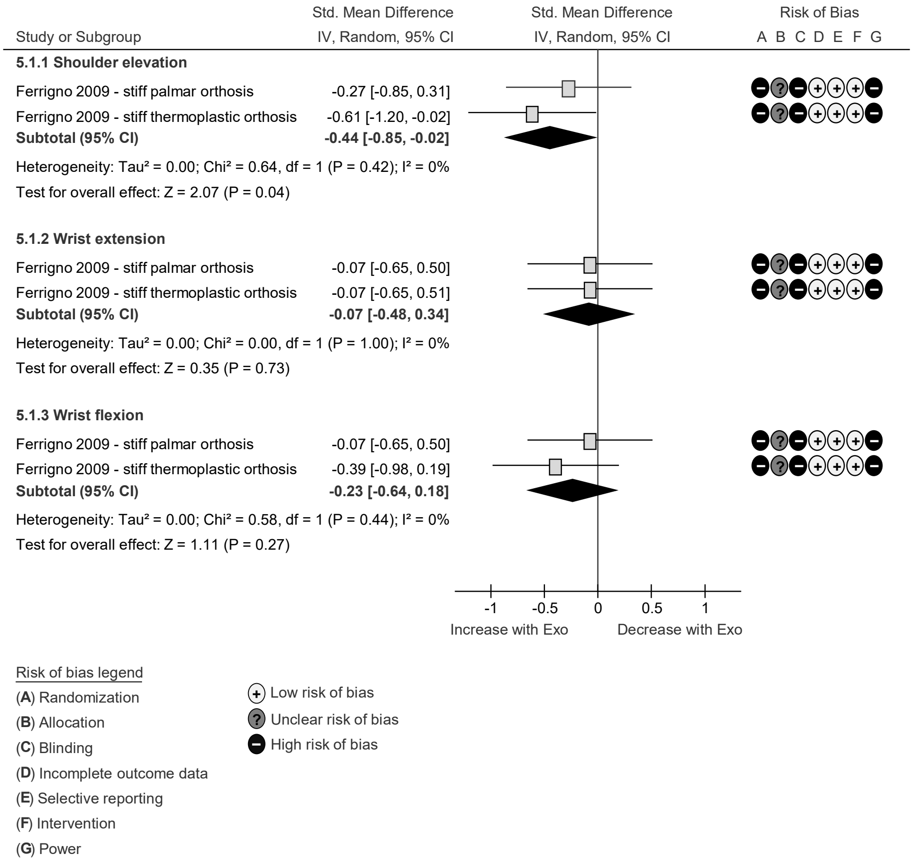


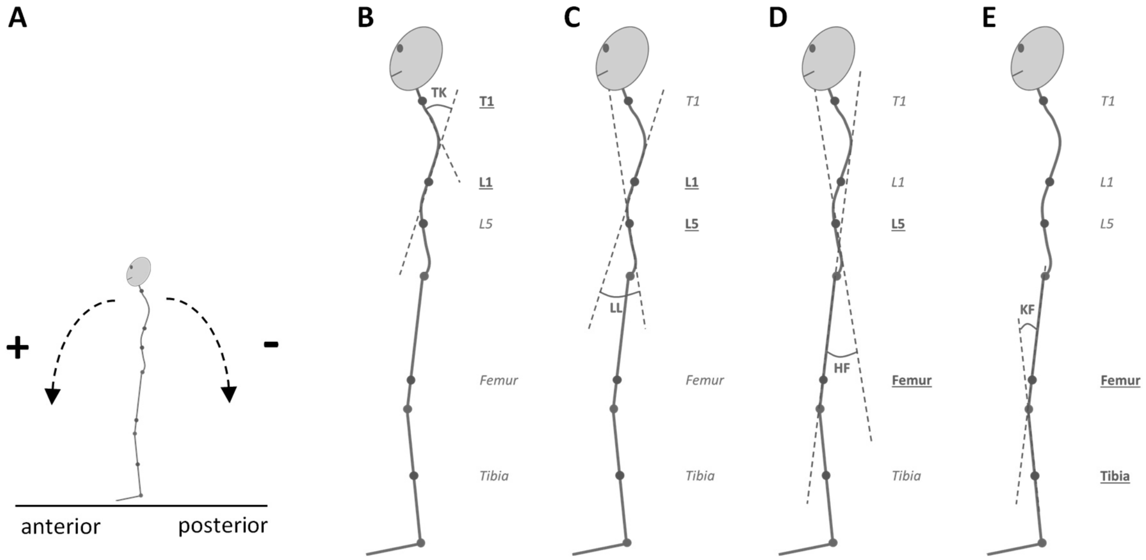
Figure 24 *Wrist supporting exoskeletons – Muscle activity*

Appendix 1

Appendix 1. **A:** Reference contractions for the normalization procedures for the six muscles of which muscle activity was recorded using bipolar surface electromyography. **B:** Reference posture for the position sensors.

A	
Muscle	**Reference contractions**
Erector spinae	Subjects lay prone with the upper body and hips (hip bones) off the bench and the legs fixed with straps, performing *maximal* hip extension against a barrier while keeping the body horizontal and the arms crossed in front of the chest (modified Biering-Sørensen test; Biering-Sørensen, 1984). The signals from the most stable 1-second period out of the 5-seconds lasting period were used.
Biceps femoris	Subjects lay prone with 90° knee flexion, feet flexed, keeping the position while a rope with a 7-kg weight hanging over a pulley and pulling in caudal direction was attached around the ankle. The signals from the most stable 5-seconds out of the 10-seconds lasting period were used.
Rectus abdominis	Subjects lay supine with the upper body and hips off the bench and the legs fixed with straps, performing 45° hip flexion while holding an additional 10-kg weight and keeping the arms crossed in front of the chest (reverse Biering-Sørensen test; Biering-Sørensen, 1984). The signals from the most stable 5-seconds out of the 10-seconds lasting period were used.
Vastus lateralis	Subjects lay prone with 90° knee flexion, feet flexed, keeping the position while a rope with a 10-kg weight hanging over a pulley and pulling in cranial direction was attached around the ankle. The signals from the most stable 5-seconds out of the 10-seconds lasting period were used.
Gastrocnemius medialis	Subject stood upright, performing bilateral, isometric plantar flexion, raising their heels. The signals from the most stable 5-seconds out of the 10-seconds lasting period were used.
Trapezius descendens	Subject stood upright, feet hip-width apart, arms in 90° abduction but slightly in the frontal plane, elbows almost extended but not overstretched, while holding a 2-kg weight in each hand (Mathiassen et al., 1995). The signals from the most stable 5-seconds out of the 10-seconds lasting period were used.
B	**Reference posture**
Posture	Subjects stood comfortably upright, heels, buttocks and upper back touching the wall, arms hanging and head facing straight ahead. The signals from a stable 1-second period of the 5-second posture were used.

Appendix 2



Appendix 2. A: An anterior inclination of the position sensors generates positive values. A posterior inclination of the position sensors generates negative values. **B-E:** The anteroposterior tangent lines of the position sensors placed over the processus spinossi were used for the four predefined angle calculations according to the cobb method (Takács et al., 2018). **B:** Thoracic kyphosis = T1-L1. **C:** Lumbar lordosis = L1-L5. **D:** Hip flexion = L5-Femur. **E:** Knee flexion = |Femur-Tibia|. Prior to the calculations the algebraic signs of the sensors placed on femur and tibia were corrected, means positive values were changed to negative and negative to positive, as the sensors were placed on the anterior body side and therefore mirror-inverted to the sensors placed over the spine.

References

Biering-Sørensen, F. (1984). Physical measurements as risk indicators for low-back trouble over a one-year period. *Spine, 9*(2), 106-119. https://doi.org/10.1097/00007632-198403000-00002

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Takács, M., Orlovits, Z., Jáger, B., & Kiss, R. M. (2018). Comparison of spinal curvature parameters as determined by the ZEBRIS spine examination method and the Cobb method in children with scoliosis. *PloS One, 13*(7), e0200245. https://doi.org/10.1371/journal.pone.0200245

Appendices

Appendix A

Table A.1. Back-tansformed least squares means (standard deviation; SD) of normalized EMG for erector spinae (ES) and biceps femoris (BF) for all experimental conditions.

E	LS	LO	ES_{10} (%MVE)	ES_{50} (%MVE)	ES_{90} (%MVE)	BF_{10} (%RVE)	BF_{50} (%RVE)	BF_{50} (%RVE)
W/O	SQ	IL	4.04 (1.76)	15.79 (1.40)	29.17 (1.40)	6.32 (2.49)	30.35 (2.09)	75.67 (1.80)
		F	3.30 (1.77)	17.39 (1.38)	34.25 (1.35)	6.14 (2.30)	19.49 (2.13)	48.86 (1.86)
		CL	3.72 (1.71)	18.46 (1.35)	34.77 (1.32)	6.03 (2.71)	19.62 (2.26)	45.98 (1.98)
	ST	IL	4.72 (1.55)	15.59 (1.38)	25.21 (1.39)	7.42 (2.40)	42.69 (1.72)	91.58 (1.61)
		F	3.76 (1.71)	18.44 (1.36)	33.86 (1.32)	5.84 (2.44)	34.62 (1.75)	75.09 (1.60)
		CL	3.85 (1.59)	18.90 (1.34)	34.32 (1.32)	7.19 (2.62)	31.97 (2.02)	58.03 (1.79)
W	SQ	IL	4.39 (1.82)	15.44 (1.42)	26.70 (1.41)	5.21 (2.39)	26.12 (1.96)	69.45 (1.64)
		F	3.74 (1.78)	16.91 (1.39)	32.53 (1.37)	5.13 (2.36)	16.34 (2.12)	45.26 (1.74)
		CL	3.58 (1.79)	17.64 (1.36)	32.54 (1.36)	4.51 (2.78)	16.17 (2.08)	43.36 (1.84)
	ST	IL	5.37 (1.59)	15.88 (1.41)	25.54 (1.39)	5.96 (1.99)	36.70 (1.74)	85.15 (1.61)
		F	4.32 (1.80)	18.04 (1.38)	32.78 (1.35)	5.05 (2.00)	28.90 (1.71)	69.26 (1.58)
		CL	4.11 (1.68)	18.20((1.34)	33.26 (1.33)	5.84 (2.50)	24.38 (2.02)	50.94 (1.82)

Factors include exoskeleton (E), lifting style (LS) and lifting orientation (LO). Abbreviations: W/O, without; W, with; SQ, squat; ST, stoop; IL, ipsilateral; F, frontal; CL, contralateral; ES/BF_{10}, 10^{th} percentile or static EMG activity; ES/BF_{50}, 50^{th} percentile or median EMG activity; ES/BF_{90}, 90^{th} percentile or peak EMG activity; %MVE, EMG normalization to maximal reference contraction; %RVE, EMG normalization to submaximal reference contraction.

Table A.2. Results of RM-ANOVA for the main and interaction effects on log-transformed normalized EMG of the erector spinae (ES) and biceps femoris (BF).

Effect	ES_{10}	ES_{50}	ES_{90}	BF_{10}	BF_{50}	BF_{90}
E	**6.646 (0.014, 0.164†)**	**6.377 (0.016, 0.158†)**	**22.836 (0.000, 0.402‡)**	**20.003 (0.000, 0.364‡)**	**21.858 (0.000, 0.384‡)**	**11.470 (0.002, 0.247†)**
LS	**9.864 (0.004, 0.225†)**	**6.487 (0.016, 0.160†)**	**4.201 (0.048, 0.110)**	1.541 (0.223, 0.042)	**41.463 (0.000, 0.542‡)**	**40.075 (0.000, 0.534‡)**
LO	**19.864 (0.000, 0.369‡)**	**74.553 (0.000, 0.687‡)**	**112.499 (0.000, 0.768‡)**	1.060 (0.352, 0.029)	**31.697 (0.000, 0.475‡)**	**61.537 (0.000, 0.638‡)**
E × LS	1.647 (0.208, 0.046)	1.404 (0.244, 0.040)	**12.657 (0.001, 0.271‡)**	0.178 (0.676, 0.005)	0.485 (0.491, 0.014)	0.461 (0.502, 0.013)
E × LO	**5.312 (0.007, 0.135†)**	**7.287 (0.001, 0.176†)**	0.643 (0.529, 0.019)	0.589 (0.558, 0.017)	1.462 (0.239, 0.040)	0.292 (0.747, 0.008)
LS × LO	2.278 (0.110, 0.063)	**9.508 (0.000, 0.219†)**	**28.515 (0.000, 0.456‡)**	**5.324 (0.007, 0.132†)**	**5.368 (0.007, 0.133†)**	**15.267 (0.000, 0.295‡)**
E × LS × LO	0.858 (0.429, 0.025)	1.708 (0.189, 0.048)	**8.461 (0.001, 0.199†)**	0.353 (0.704, 0.010)	0.588 (0.558, 0.017)	1.627 (0.204, 0.044)

Note: values display F (with p, η_p^2 in parentheses), and significant effects are displayed bold.

Main and interaction effects include exoskeleton (E), lifting style (LS) and lifting orientation (LO). Abbreviations: ES/BF_{10}, 10^{th} percentile or static EMG activity; ES/BF_{50}, 50^{th} percentile or median EMG activity; ES/BF_{90}, 90^{th} percentile or peak EMG activity; F, test value; p, significance level; η_p^2, partial eta-squared effect size; †, median effect size ($\eta_p^2 \geq 0.13$); ‡, large effect size ($\eta_p^2 \geq 0.26$).

Appendix B

Table B.1. Back-transformed least squares means (standard deviation; SD) of normalized EMG for rectus abdominis (RA), vastus lateralis (VL), gastrocnemius medialis (GM) and trapezius descendens (TD) for all experimental conditions.

E	LS	LO	RA_{10} (%RVE)	RA_{50} (%RVE)	RA_{90} (%RVE)	VL_{10} (%RVE)	VL_{50} (%RVE)	VL_{90} (%RVE)	GM_{10} (%RVE)	GM_{50} (%RVE)	GM_{90} (%RVE)	TD_{10} (%RVE)	TD_{50} (%RVE)	TD_{90} (%RVE)
W/O	SQ	IL	1.26 (2.11)	3.45 (2.05)	7.18 (2.06)	27.60 (1.92)	80.84 (1.80)	149.66 (1.79)	8.56 (2.16)	30.47 (2.21)	78.85 (1.99)	3.90 (2.10)	32.34 (1.73)	82.86 (1.49)
		F	1.24 (2.16)	3.57 (2.05)	7.25 (2.06)	31.05 (1.81)	85.13 (1.77)	141.38 (1.72)	7.49 (2.02)	24.78 (1.88)	66.44 (1.96)	3.71 (2.60)	30.36 (1.86)	87.21 (1.53)
		CL	1.24 (2.15)	3.37 (2.04)	7.13 (2.08)	17.61 (2.46)	55.23 (2.00)	100.54 (1.98)	5.29 (2.00)	17.19 (2.03)	55.82 (1.85)	2.87 (2.68)	27.38 (1.93)	76.41 (1.50)
	ST	IL	1.21 (2.10)	3.25 (2.09)	7.33 (2.08)	14.54 (2.62)	32.51 (2.03)	59.27 (1.87)	10.12 (2.36)	82.69 (1.91)	186.11 (1.81)	3.30 (1.94)	19.57 (2.23)	67.73 (1.55)
		F	1.21 (2.13)	3.37 (1.99)	7.50 (2.05)	10.40 (3.09)	24.61 (2.35)	49.82 (2.15)	9.63 (2.24)	84.70 (1.81)	163.72 (1.71)	3.11 (2.06)	20.96 (2.13)	71.86 (1.67)
		CL	1.21 (2.10)	3.14 (2.08)	7.23 (2.11)	6.03 (2.73)	14.94 (2.55)	31.57 (2.54)	7.88 (2.46)	36.33 (1.76)	71.42 (1.66)	2.30 (1.92)	15.71 (2.24)	63.09 (1.59)
W	SQ	IL	1.19 (2.21)	3.22 (2.11)	6.96 (2.08)	25.61 (1.85)	72.66 (1.78)	134.46 (1.73)	9.69 (2.24)	34.67 (2.16)	88.16 (1.97)	4.53 (2.12)	34.95 (1.70)	81.91 (1.46)
		F	1.20 (2.21)	3.46 (2.09)	7.13 (2.09)	30.60 (1.84)	73.88 (1.86)	123.60 (1.82)	8.61 (2.14)	30.04 (2.01)	76.97 (1.97)	4.14 (2.51)	31.96 (1.89)	83.76 (1.57)
		CL	1.16 (2.17)	3.19 (2.10)	6.85 (2.12)	12.83 (2.94)	41.66 (2.18)	81.62 (2.04)	6.87 (2.15)	24.20 (2.14)	63.87 (2.00)	3.33 (2.53)	27.15 (1.94)	73.22 (1.60)
	ST	IL	1.20 (2.14)	3.05 (2.08)	7.08 (2.09)	14.13 (2.66)	32.38 (2.18)	58.86 (2.02)	14.52 (2.26)	90.99 (1.85)	190.64 (1.76)	3.66 (1.96)	24.54 (1.96)	71.99 (1.51)
		F	1.16 (2.07)	3.20 (2.05)	7.23 (2.09)	10.11 (2.96)	23.67 (2.32)	47.14 (2.23)	12.24 (2.45)	92.95 (1.76)	167.98 (1.70)	3.39 (2.16)	20.25 (2.16)	73.80 (1.60)
		CL	1.21 (2.15)	3.10 (2.08)	7.14 (2.13)	6.54 (2.63)	16.87 (2.58)	39.11 (2.44)	10.75 (2.40)	48.86 (1.70)	87.47 (1.61)	2.54 (2.05)	17.67 (2.06)	62.71 (1.72)

Factors include exoskeleton (E), lifting style (LS) and lifting orientation (LO). Abbreviations: W/O, without; W, with; SQ, squat; ST, stoop; IL, ipsilateral; F, frontal; CL, contralateral; RA/VL/GM/TD_{10}, 10th percentile or static EMG activity; RA/VL/GM/TD_{50}, 50th percentile or median EMG activity; RA/VL/GM/TD_{90}, 90th percentile or peak EMG activity; %RVE, EMG normalization to submaximal reference contraction.

Table B.2. Results of RM-ANOVA for the main and interaction effects on log-transformed, normalized EMG of the rectus abdominis (RA), vastus lateralis (VL), gastrocnemius medialis (GM) and trapezius descendens (TD).

Effect	RA_{10}	RA_{50}	RA_{90}	VL_{10}	VL_{50}	VL_{90}	GM_{10}	GM_{50}	GM_{90}	TD_{10}	TD_{50}	TD_{90}
E	**5.542 (0.025, 0.140†)**	**18.812 (0.000, 0.356‡)**	**6.671 (0.014, 0.164†)**	1.175 (0.286, 0.035)	3.266 (0.080, 0.088)	1.809 (0.188, 0.050)	**54.910 (0.000, 0.611‡)**	**35.868 (0.000, 0.506‡)**	**37.328 (0.000, 0.516‡)**	**13.031 (0.001, 0.271‡)**	**4.905 (0.033, 0.123)**	0.013 (0.909, 0.000)
LS	0.817 (0.373, 0.023)	**14.513 (0.001, 0.299‡)**	**4.607 (0.039, 0.119)**	**46.580 (0.000, 0.577‡)**	**85.266 (0.000, 0.716‡)**	**71.432 (0.000, 0.679‡)**	**16.724 (0.000, 0.323‡)**	**149.120 (0.000, 0.810‡)**	**179.860 (0.000, 0.837‡)**	**10.670 (0.002, 0.234†)**	**54.063 (0.000, 0.607‡)**	**24.956 (0.000, 0.416‡)**
LO	0.296 (0.745, 0.009)	**13.901 (0.000, 0.290‡)**	**3.861 (0.026, 0.102)**	**37.481 (0.000, 0.524‡)**	**53.564 (0.000, 0.611‡)**	**60.671 (0.000, 0.639‡)**	**13.162 (0.000, 0.273‡)**	**83.256 (0.000, 0.704‡)**	**125.544 (0.000, 0.782‡)**	**29.991 (0.000, 0.461‡)**	**14.137 (0.000, 0.288‡)**	**15.411 (0.000, 0.306‡)**
E × LS	**5.209 (0.029, 0.133†)**	0.264 (0.611, 0.008)	0.014 (0.906, 0.000)	1.946 (0.173, 0.056)	**4.612 (0.039, 0.124)**	**4.683 (0.038, 0.124)**	2.775 (0.105, 0.073)	1.023 (0.319, 0.028)	1.833 (0.185, 0.050)	0.526 0.473, 0.015)	1.232 90.275, 0.034)	**5.454 (0.025, 0.135†)**
E × LO	0.180 (0.836, 0.005)	2.441 (0.095, 0.067)	0.327 (0.723, 0.010)	0.626 (0.538, 0.018)	0.148 (0.862, 0.004)	1.104 (0.338, 0.032)	1.174 (0.315, 0.032)	**9.306 (0.000, 0.210†)**	**5.362 (0.007, 0.133†)**	0.228 (0.797, 0.006)	**5.617 (0.006, 0.138†)**	1.939 (0.152, 0.052)
LS × LO	**3.803 (0.027, 0.101)**	0.485 (0.618, 0.014)	0.491 (0.614, 0.014)	**6.395 (0.003, 0.157†)**	**5.553 (0.006, 0.140†)**	1.294 (0.281, 0.037)	2.385 (0.100, 0.064)	**24.321 (0.000, 0.410‡)**	**81.465 (0.000, 0.699‡)**	0.538 (0.586, 0.015)	0.854 (0.430, 0.024)	0.085 (0.918, 0.002)
E × LS × LO	**4.879 (0.011, 0.125)**	1.708 (0.189, 0.048)	1.928 (0.153, 0.054)	**4.142 (0.020, 0.110)**	**3.531 (0.035, 0.096)**	**4.825 (0.011, 0.126)**	1.781 (0.176, 0.048)	0.365 (0.696, 0.010)	**6.228 (0.003, 0.151†)**	0.059 (0.943, 0.002)	**3.717 (0.029, 0.096)**	0.501 (0.608, 0.014)

Note: values display F (with p, η_p^2 in parentheses), and significant effects are displayed bold.

Main and interaction effects include exoskeleton (E), lifting style (LS) and lifting orientation (LO). Abbreviations: RA/VL/GM/TD_{10}, 10th percentile or static EMG activity; RA/VL/GM/TD_{50}, 50th percentile or median EMG activity; RA/VL/GM/TD_{90}, 90th percentile or peak EMG activity; F, test value; p, significance; η_p^2, partial eta-squared effect size; †, median effect size (η_p^2≥0.13); ‡, large effect size (η_p^2≥0.26).

Appendix C

Table C.1. Mean (SD) of joint angles knee flexion (KF), hip flexion (HF), lumbar lordosis (LL) and thoracic kyphosis (TK) and of heart rate (HR) for all experimental conditions.

E	LS	LO	KF_{MIN} (°)	KF_{50} (°)	KF_{MAX} (°)	HF_{MIN} (°)	HF_{50} (°)	HF_{MAX} (°)	LL_{MIN} (°)	L_{50} (°)	LL_{MAX} (°)	TK_{MIN} (°)	TK_{50} (°)	TK_{MAX} (°)	HR (bpm)
W/O	SQ	IL / L	-1.24 (4.99)	29.42 (9.62)	65.99 (15.67)	-2.96 (4.54)	36.53 (7.83)	85.71 (10.30)	-3.03 (4.52)	8.35 (5.51)	18.69 (7.63)	-6.60 (6.94)	4.58 (7.37)	14.12 (7.76)	95.05 (11.22)
		F	0.51 (4.38)	35.04 (8.61)	74.38 (14.58)	-0.93 (4.61)	41.25 (7.10)	89.84 (9.86)	-3.34 (4.50)	8.20 (5.63)	16.53 (7.04)	-9.50 (7.13)	1.68 (7.48)	11.03 (7.75)	94.99 (11.10)
		CL	1.33 (5.02)	32.57 (8.72)	72.88 (14.15)	-0.19 (5.00)	34.74 (7.36)	81.10 (9.01)	-	-	-	-	-	-	-
	ST	IL / L	-1.20 (6.48)	11.92 (8.05)	27.13 (10.44)	-2.56 (5.71)	24.70 (7.61)	62.11 (11.15)	-2.48 (3.84)	9.93 (4.62)	23.75 (7.17)	-5.65 (7.27)	7.19 (7.27)	17.75 (7.81)	92.03 (10.62)
		F	-0.89 (5.94)	10.57 (8.73)	23.56 (12.54)	-1.79 (5.62)	27.68 (8.38)	65.47 (12.79)	-3.14 (4.16)	11.38 (5.31)	24.47 (7.61)	-9.52 (7.38)	2.58 (7.80)	12.37 (7.84)	92.52 (10.88)
		CL	-1.00 (5.64)	9.88 (7.58)	22.68 (12.14)	-0.90 (5.71)	21.45 (8.21)	55.77 (12.51)	-	-	-	-	-	-	-
W	SQ	IL / L	1.22 (5.68)	32.78 (9.43)	62.88 (13.96)	0.66 (5.78)	41.19 (8.09)	84.30 (8.48)	-2.48 (4.30)	8.87 (5.77)	20.03 (7.38)	-5.32 (6.73)	4.47 (7.27)	13.07 (7.63)	93.67 (11.50)
		F	3.45 (5.16)	39.19 (9.41)	73.73 (14.43)	2.02 (5.50)	45.75 (7.61)	88.63 (8.00)	-3.31 (4.56)	8.52 (6.38)	17.29 (7.65)	-8.37 (6.64)	1.92 (6.91)	10.81 (6.84)	93.70 (11.45)
		CL	4.39 (6.53)	35.36 (9.23)	70.27 (13.64)	2.83 (6.21)	38.69 (7.79)	80.66 (7.64)	-	-	-	-	-	-	-
	ST	IL / L	1.32 (6.95)	17.53 (9.62)	31.75 (10.64)	1.00 (5.83)	33.09 (9.41)	69.49 (10.88)	-1.69 (3.81)	10.83 (5.04)	26.06 (7.56)	-5.80 (6.75)	5.44 (7.42)	14.91 (8.12)	90.72 (10.05)
		F	1.81 (5.82)	16.67 (9.47)	29.61 (12.32)	1.64 (6.45)	35.90 (9.66)	71.25 (13.21)	-2.40 (4.23)	11.84 (5.77)	26.24 (7.94)	-9.54 (7.00)	1.59 (7.45)	10.60 (7.17)	90.15 (11.06)
		CL	5.68 (7.17)	17.69 (10.30)	28.95 (13.40)	5.59 (5.89)	30.12 (9.38)	59.69 (13.59)	-	-	-	-	-	-	-

Factors include exoskeleton (E), lifting style (LS) and lifting orientation (LO). Abbreviations: W/O, without; W, with; SQ, squat; ST, stoop; IL, ipsilateral; L, lateral; F, frontal; CL, contralateral; KF/HF/LL/TK_{MIN}, minimum angle; KF/HF/LL/TK_{50}, 50th percentile or median angle; KF/HF/LL/TK_{MAX}, maximum angle; bpm, beats per minute.

Table C.2. Results of RM-ANOVA for the main and interaction effects on joint angles knee flexion (KF), hip flexion (HF), lumbar lordosis (LL) and thoracic kyphosis (TK) and on heart rate (HR).

Effect	KF_{MIN}	KF_{50}	KF_{MAX}	HF_{MIN}	HF_{50}	HF_{MAX}	LL_{MIN}	LL_{50}	LL_{MAX}	TK_{MIN}	TK_{50}	TK_{MAX}	HR
E	**51.121 (0.000, 0.594‡)**	**55.409 (0.000, 0.613‡)**	**7.783 (0.009, 0.182†)**	**95.520 (0.000, 0.732‡)**	**78.151 (0.000, 0.691‡)**	**11.509 (0.002, 0.247†)**	2.765 (0.105, 0.073)	3.805 (0.105, 0.073)	**12.921 (0.001, 0.270‡)**	3.245 (0.080, 0.085)	**5.027 (0.031, 0.126)**	**20.856 (0.000, 0.373‡)**	**23.416 (0.000, 0.401‡)**
LS	3.246 (0.080, 0.085)	**219.195 (0.000, 0.862‡)**	**298.671 (0.000, 0.895‡)**	0.385 (0.539, 0.011)	**145.410 (0.000, 0.806‡)**	**236.505 (0.000, 0.871‡)**	**5.118 (0.030, 0.128)**	**33.530 (0.000, 0.489‡)**	**88.341 (0.000, 0.716‡)**	0.153 (0.698, 0.004)	**5.034 (0.031, 0.126)**	**8.976 (0.005, 0.204†)**	**48.053 (0.000, 0.579‡)**
LO	**14.081 (0.000, 0.287‡)**	**13.008 (0.000, 0.271‡)**	**9.910 (0.000, 0.221†)**	**13.626 (0.000, 0.280‡)**	**99.888 (0.000, 0.741‡)**	**117.035 (0.000, 0.770‡)**	**13.042 (0.001, 0.271‡)**	**4.278 (0.046, 0.109)**	**9.979 (0.003, 0.222†)**	**123.507 (0.000, 0.779‡)**	**112.604 (0.000, 0.763‡)**	**126.158 (0.000, 0.783‡)**	0.010 (0.920, 0.000)
E × LS	0.383 (0.540, 0.011)	**12.378 (0.001, 0.261‡)**	**43.900 (0.000, 0.556‡)**	0.254 (0.618, 0.007)	**28.341 (0.000, 0.447‡)**	**37.253 (0.000, 0.516‡)**	1.169 (0.287, 0.032)	0.397 (0.533, 0.011)	3.038 (0.090, 0.080)	**5.398 (0.026, 0.134†)**	**11.286 (0.002, 0.244†)**	**15.823 (0.000, 0.311‡)**	0.568 (0.456, 0.016)
E × LO	**3.401 (0.039, 0.089)**	0.968 (0.385, 0.027)	**3.822 (0.027, 0.098)**	0.549 (0.580, 0.015)	0.359 (0.700, 0.010)	0.944 (0.394, 0.026)	2.402 (0.130, 0.064)	3.491 (0.070, 0.091)	**5.392 (0.026, 0.133†)**	0.003 (0.957, 0.000)	3.813 (0.059, 0.098)	**7.398 (0.010, 0.174†)**	2.456 (0.126, 0.066)
LS × LO	**7.148 (0.002, 0.170†)**	**40.874 (0.000, 0.539‡)**	**48.526 (0.000, 0.581‡)**	2.630 (0.079, 0.070)	3.071 (0.053, 0.081)	3.112 (0.051, 0.082)	0.305 (0.584, 0.009)	**26.290 (0.000, 0.429‡)**	**56.033 (0.000, 0.616‡)**	**4.724 (0.037, 0.119)**	**19.005 (0.000, 0.352‡)**	**24.212 (0.000, 0.409‡)**	0.004 (0.949, 0.000)
E × LS × LO	2.147 (0.124, 0.058)	**4.703 (0.012, 0.118)**	**3.524 (0.035, 0.091)**	0.378 (0.686, 0.011)	0.216 (0.807, 0.006)	0.720 (0.490, 0.020)	1.080 (0.306, 0.030)	0.390 (0.537, 0.011)	0.003 (0.959, 0.000)	0.185 (0.670, 0.005)	0.802 (0.377, 0.022)	0.273 (0.605, 0.008)	2.939 (0.095, 0.077)

Note: values display F (with p, η_p^2 in parentheses), and significant effects are displayed bold.

Main and interaction effects include exoskeleton (E), lifting style (LS) and lifting orientation (LO). Abbreviations: KF/HF/LL/TK_{MIN}, minimum angle; KF/HF/LL/TK_{50}, 50th percentile or median angle; KF/HF/LL/TK_{MAX}, maximum angle; F, test value; p, significance; η_p^2, partial eta-squared effect size; †, median effect size (η_p^2>0.13); ‡, large effect size (η_p^2>0.26).

Erklärung zum Eigenanteil der Dissertation

Die Arbeit wurde am Institut für Arbeitsmedizin, Sozialmedizin und Versorgungsforschung unter Betreuung von PD Dr. Benjamin Steinhilber durchgeführt.

Systematisches Review mit Meta-Analysen (Bär et al. 2021):

Die Konzeption des Reviews erfolgte in Zusammenarbeit mit PD Dr. Benjamin Steinhilber (Leitung des Forschungsschwerpunktes Arbeitsbedingte Belastungen – Arbeitsgestaltung), Dr. Tessy Luger (Akademische Mitarbeiterin) und mit Unterstützung durch Prof. Dr. Monika A. Rieger (Ärztliche Direktion des Instituts).

Die Literatursuche wurde von Dr. T. Luger durchgeführt. Die Screenings, Analysen und kritische Bewertung der Literatur wurden von mir in Zusammenarbeit mit Dr. T. Luger durchgeführt.

Die Extrahierung, Präparierung der Daten und die Durchführung der Meta-Analysen wurde von mir und mit Unterstützung von Dr. T. Luger durchgeführt.

Die Interpretation der Ergebnisse wurde in Zusammenarbeit mit PD Dr. B. Steinhilber und Dr. T. Luger und mit Unterstützung durch Prof. Dr. Monika A. Rieger durchgeführt.

Ich versichere, das Manuskript selbstständig (unter Supervision durch Dr. T. Luger und PD Dr. B. Steinhilber) verfasst zu haben und keine weiteren als die von mir verwendeten Quellen verwendet zu haben.

Experimentelle Laborstudie ADVANCE (Luger et al., 2021; Bär et al., 2022a und 2022b):

Die Konzeption der Studie erfolgte durch PD Dr. Benjamin Steinhilber (Leitung des Forschungsschwerpunktes Arbeitsbedingte Belastungen – Arbeitsgestaltung), Dr. Tessy Luger (Akademische Mitarbeiterin), Robert Seibt (Akademischer Mitarbeiter) und mit Unterstützung durch Prof. Dr. Monika A. Rieger (Ärztliche Direktion des Instituts).

Die Entwicklung der Forschungsfragen erfolgte in Zusammenarbeit mit PD Dr. B. Steinhilber, Dr. T. Luger, R. Seibt und Prof. Dr. M. A. Rieger.

Der Aufbau der Studie erfolgte in Zusammenarbeit mit PD Dr. Benjamin Steinhilber, Dr. Tessy Luger und Robert Seibt.

Sämtliche Versuche wurden (nach Einarbeitung durch Labormitglieder PD Dr. B. Steinhilber, Dr. T. Luger, R. Seibt) entweder von mir und in Zusammenarbeit mit oder unter meiner Supervision von Pia Rimmele, Stefanie Lorenz, Gianluca Caputo und Silvia Weymeyer durchgeführt.

Die Datenauswertung für Bär et al. (2022a) wurde von mir und für Bär et al. (2022b) in Zusammenarbeit mit Julia Gabriel (unter Supervision von PD Dr. B. Steinhilber, Dr. T. Luger, R. Seibt) durchgeführt. Die Datenauswertung von Luger et al. (2021) wurde von Dr. T. Luger durchgeführt.

Die statistische Auswertung erfolgte, nach vorheriger Beratung durch das Institut für Biometrie und nach Anleitung durch Dr. T. Luger und PD Dr. B. Steinhilber durch mich (für Bär et al. 2022a und 2022b) und durch Dr. T. Luger (für Luger et al. 2021).

Ich versichere, die Manuskripte (Bär et al. 2022a und 2022b) selbstständig (unter Supervision von PD Dr. B. Steinhilber und Dr. T. Luger) verfasst zu haben und keine weiteren als die von mir verwendeten Quellen verwendet zu haben.

Dissertationsschrift:

Ich versichere, die Dissertationsschrift selbstständig (unter der Betreuung von PD Dr. B. Steinhilber) verfasst und keine weiteren als die von mir verwendeten Quellen verwendet zu haben.

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