Applied Ergonomics 127 (2025) 104514

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/jerg

Evaluation of the support provided by a soft passive exoskeleton in individuals with back pain

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ARTICLE INFO

Keywords:
Work ergonomics
Electromyography
Repetitive lifting

ABSTRACT

Physically straining occupations involving repetitive lifting and forward leaning increase risk of back pain. In response, back exoskeletons have been developed to alleviate strain on back muscles and potentially prevent such pain. In people experiencing back pain, these may also help decrease the pain-related activity limitations during work or leisure.

This experimental study evaluated the effects of a soft passive back exoskeleton on muscle activity, acute pain, kinesiophobia, and movement kinematics. Individuals experiencing mild to moderate back pain ($n = 35$) performed forward leaning and lifting tasks, both with and without the support of the back exoskeleton. Electromyography data were collected for trunk and hip muscles, alongside hip and spine kinematics, reported pain levels and concerns regarding daily activities.

Back exoskeleton support reduced back muscle activity during forward leaning by up to 35% ($p_{Exo} < 0.001$) and during lifting tasks by up to 24% ($p_{Exo} < 0.001$). Participants reported reduced lumbar pain ($p < 0.01$) and decreased kinesiophobia ($p < 0.001$) across all tasks when supported by the exoskeleton. Minimal influence on movement kinematics was observed and there were no observable changes in abdominal co-activation compared to tasks performed without exoskeleton support. These results indicate that the LiftSuit, a passive back exoskeleton, can effectively reduce back muscle activity, acute pain, and kinesiophobia among individuals with back pain during forward leaning and repetitive lifting tasks. These findings suggest that passive back exoskeletons may be beneficial during physically demanding tasks in workers experiencing mild to moderate back pain.

1. Introduction

Manual handling of heavy loads and repetitive lifting at work are major causes of back pain (Sauter et al., 2021). In Switzerland alone, the annual costs of back pain due to heavy lifting and painful postures are estimated to be over 400 Mio USD, with operational expenses such as reduced productivity or sick days accounting for an additional 400 Mio USD (Läubli, 2014). Despite back pain being the leading cause of global disability (Hoy et al., 2014), understanding back pain's underlying origins remains challenging, making its treatment difficult. In clinical practice 90% of cases are categorized as non-specific back pain, which means no clear cause for the pain can be identified (Dankaerts et al., 2007). However, mechanical factors as well as psychological factors seem to play a key role in the development of back pain (Van Dillen et al., 2007; Clays et al., 2007).

The fear-avoidance model explains how misinterpreting pain as a sign of harm, coupled with negative emotional states and a tendency to catastrophize pain, leads to an avoidance of movement known as kinesiophobia (Leeuw et al., 2007a). This behavior could exacerbate pain, disability, and depression (Knezevic et al., 2021). An ongoing debate persists regarding the role of mechanical factors in their exact contribution to back pain (Papi et al., 2017). However, there is evidence suggesting that repetitive and high spinal loading, combined with poor movement control, may contribute to the problem. Kingma et al. (2010) showed that repetitive heavy lifting can result in high compression forces on the lower back, increasing injury risk. Likewise, poor movement control has been observed in individuals with chronic back pain (O'Sullivan et al., 2003; Radebold et al., 2001; Van Dieën et al., 2003b,a; Willigenburg et al., 2013), hindering the spine's ability to adapt to biomechanical stresses and increasing risks of injury (Panjabi, 1992; Reeves et al., 2007). Recent studies have shown a connection between fear of pain and impaired motor function in both individuals with and without lower back pain, highlighting a link between these

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https://doi.org/10.1016/j.apergo.2025.104514
Received 2 October 2024; Received in revised form 5 March 2025; Accepted 27 March 2025
Available online 12 April 2025

factors (Schmid et al., 2021; Wernli et al., 2020). These interactions can have clinically relevant consequences, such as reduced range of motion, increased co-contraction of para-spinal muscles, and increased loading on spinal tissues (Schmid et al., 2021). On the other hand, improvements in terms of perceived pain are often accompanied by increased spinal movement range and velocity, suggesting a recovery from protective movement patterns, though the causal relationship is yet unclear (Wernli et al., 2020).

Passive back support exoskeletons have been developed to support the back muscles during physically demanding tasks. Being sleek, lightweight and affordable, low maintenance, they find good use in manual material handling. Various recent studies with healthy participants demonstrated support in back muscles during leaning and lifting when using passive back exoskeletons, therefore having the potential to prevent cases of work-related back pain (Cardoso et al., 2024; Baltrusch et al., 2018; Banks et al., 2024; Goršič et al., 2020, 2021; Graham et al., 2009; Kermavnar et al., 2021; Koopman et al., 2020; Van Sluijs et al., 2023b). However, despite these recent advances in the development and evaluation of passive back exoskeletons, gaps remain in our understanding of their influence on individuals already presenting with back pain.

To our knowledge only three studies assessed pain or discomfort in individuals with back pain while using exoskeleton assistance (Baltrusch et al., 2019; Kozinc et al., 2021; Quirk et al., 2023). Quirk and colleagues were the first to measure muscle activity in subjects with low back pain and reported a reduction of back muscle activity when using an active back-support exoskeleton (Quirk et al., 2023). No significant differences in back pain were observed in their study with an active exoskeleton, assessing 15 subjects performing squat and stoop lifts. Kozinc et al. (2021) did a pilot study including 12 subjects with low back pain and measured significant differences in pain in a leaning task, but not in squat or stoop lifting. A third study assessing a passive exoskeleton on 13 subjects with low back pain observed significant reductions in lower back discomfort when lifting, forward bending and three-point kneeling (Baltrusch et al., 2019). While no study measured increased pain when working with a back exoskeleton, these partly contradicting results underline the need to study the effects of exoskeleton support in those suffering from back pain. Especially, since this condition is common in the device target audience. Furthermore, since pain is often paired with fear of pain, or kinesiophobia, and pain avoiding movement patterns, it is relevant to see how exoskeleton use influences kinesiophobia, movement range of motion and velocity. Quirk and colleagues (Quirk et al., 2023) report less movement concern and minimal movement restriction when using an exoskeleton. Another under-explored area is the impact of exoskeletons on acute versus chronic back pain as none of the previous studies differentiated on pain duration.

This experimental study aims to determine whether a passive back exoskeleton can reduce muscle activity in back muscles as well as kinesiophobia in individuals with mild to moderate acute and chronic back pain during leaning and lifting tasks. We further aim to confirm previous findings that passive exoskeletons could help reduce acute pain and to explore its effects on range of motion and velocity of the hip and spine in the selected dynamic tasks. We hypothesized that performing tasks with the support of a passive back exoskeleton would (i) reduce back muscle activity, (ii) reduce perceived back pain, (iii) reduce kinesiophobia, (iv) increase sagittal hip and back range of motion and velocity, and (v) have similar effects on participants with either acute or chronic pain. This work is relevant, as the resulting findings could inform on the use of passive back exoskeletons, and on their suitability for people suffering from back pain.

2. Methods

2.1. Participants

The inclusion criteria for this study were as follows: $\geq$ 18 and $\leq$ 65 years of age; mild to moderate back pain severity (1-4/10 on a Numeric Rating Scale (NRS)). Exclusion criteria were: history of pelvic or spinal surgery; specific lumbar pathology (fracture, infection or tumor); anxiolytic medication; pregnancy. The recruitment strategy was targeted towards those employed in physically demanding professions, and involved word-of-mouth and distribution of flyers in physiotherapy clinics, hospitals, nursing homes, logistics centers and various construction businesses.

Since levels of pain vary over time, participants were contacted the day prior to the scheduled measurements and asked to rate their back pain. If the pain was either non-existent or exceeded the intensity of 4/10 on the NRS, the meeting was canceled or rescheduled.

All participants were fully briefed on the experimental protocol and potential risks, and they provided written informed consent. Measurements were conducted in line with the Declaration of Helsinki and the study protocol was approved by the institutional ethics commission of ETH Zurich (EK-2023-N-225).

2.2. Soft passive exoskeleton

In this study, the LiftSuit2 (*Auxivo AG, Switzerland*) was used. The intended use of the LiftSuit is providing support to healthy individuals. It is a soft, lightweight (~1 kg) passive back exoskeleton worn like a backpack with additional cuffs around the thighs (Fig. 1 (a)). Two elastic springs linked to non-elastic bands run from the shoulders alongside the back muscles to the back of the legs, therefore connecting the upper and lower body. After donning the exoskeleton the support is “activated” by pre-tensioning the elastic springs using two handles at collarbone-level. In leaning and lifting, these springs support the back muscles by storing and releasing energy. The assistive force depends on the amount of spring pre-tension (can be adjusted continuously) and the change in length, which depends on the task and user anatomy. According to the manufacturer average provided support is 280 N). The LiftSuit2 comes in two sizes (S/M & L/XL) and can be further adjusted to the leg and chest circumference, as well as the torso length. To facilitate sensor placement, the hip belt and parts of the webbing were removed for the measurement. The performance of the LiftSuit2 was previously evaluated in studies with healthy subjects (Van Sluijs et al., 2023b,a).

2.3. Study protocol

After signing informed consent, participants completed a set of initial questionnaires. Participants were then instructed on exoskeleton donning and adjustment, and performed shortened versions of the occupational tasks to get familiar with the exoskeleton and the experimental protocol. After familiarization, sensors for surface electromyography (EMG) and kinematics measurements were placed and reference voluntary contractions were performed for normalization purpose. Measurements of muscle activity and kinematics were then performed of the pending experimental occupational tasks, which were performed in two conditions: wearing the exoskeleton with the support of the textile springs (Support) and wearing the exoskeleton without textile springs (No Support). Participants were not informed about the conditions, and were instructed to “activate” the exoskeleton by pulling on the handles on the chest, independent of the condition. The tasks remained in a specific order, but the condition was pseudo-randomized using latin squares. Following each task, participants rated acute pain, kinesiophobia, exertion, and comfort they experienced. Upon completing all tasks, the participants were asked to fill out questionnaires regarding the usability of the exoskeleton (Fig. 1 (b)).

The study aimed to evaluate the effect of wearing the exoskeleton by performing tasks that mimic its real-world applications in physical labor. This approach was also intended to align with previous studies on exoskeletons and back pain, facilitating benchmark comparisons, as suggested in Torricelli et al. (2020). In accordance with guidelines provided by De Bock et al. (2022) a combination of static and dynamic tasks were performed:

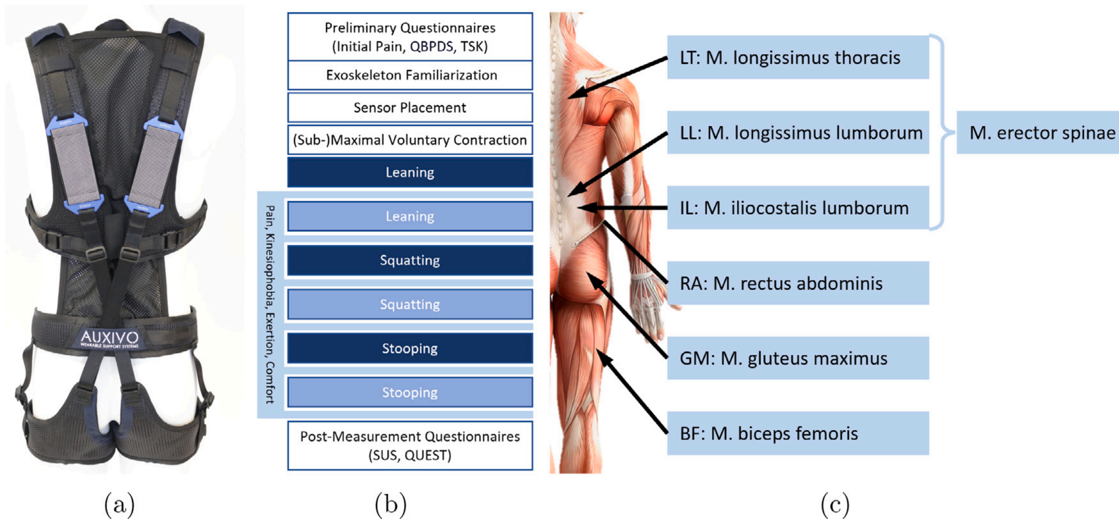


Fig. 1. (a) Soft passive exoskeleton used in this study (LiftSuit2 by Auxivo AG). (b) Study protocol (QBPDS: Quebec Back Pain Disability Scale; TSK: Tampa Scale of Kinesiophobia; SUS: System Usability Scale; QUEST: Quebec User Evaluation of Satisfaction with Assistive Technology). Dark blue and light blue correspond the two conditions presented in randomized order. (c) Sensors were placed according to McGill et al. (McGill (1991)) or SENIAM guidelines (Stegeman and Hermens (2007)).

2.3.1. Static leaning task

Participants were instructed to consecutively hold two forward leaning postures (30° and 60°) for 10 s. For repeatability, the positions were determined beforehand using a digital inclinometer on the pelvis, whereby the finger-floor distance was measured and set on height-adjustable crossbars. The test participants then found their position by touching the respective crossbars, and were instructed to keep the legs and the back as straight as possible and to look at two marks on the floor, located 3 m and 1 m away from their standpoint.

2.3.2. Dynamic squat and stoop lifting tasks

Participants performed two sets of 10 lifts: squat lifting and stoop lifting (Fig. 2 (a&b)). On two seconds intervals, the participants were asked to: (1) lower to a 6 kg kettlebell weight, (2) lift the weight to a neutral standing position, (3) lower the weight to the ground, and (4) stand back up to the starting position without the weight. These timed intervals resulted in a lift cycle of 8 s. The first 50% of the lift cycle were defined as 'lifting' the weight, whereas the second 50% were defined as 'lowering' the weight (Fig. 2 (c)). Participants were instructed to 'keep the back as straight as possible while bending the hips and knees' for squat lifts and to 'keep the legs as straight as is still comfortable while bending the hips and spine' for stoop lifts. The weight was set as 6 kg to allow for comparison with other studies (Van Sluijs et al., 2023b; Quirk et al., 2023).

2.4. Outcome measures and data processing

2.4.1. Subjective measures

Questions about the background, history, location and severity of back pain were asked by a licensed physiotherapist. Subsequently, the Quebec Back Pain Disability Scale (QBPDS) (Kopec et al., 1995) and the Tampa Scale of Kinesiophobia (TSK-17) (Miller et al., 1991) were used to determine onset pain management, disability and kinesiophobia. Participants were categorized based on self-reported history of pain: acute (< 4 weeks), sub-acute (4–12 weeks), and chronic (> 12 weeks). The TSK ranges from 17 to 68 points with a score higher than 37 being defined as 'high kinesiophobia' (Miller et al., 1991). Task-specific kinesiophobia was measured using ten relevant images from the Photograph Series of Daily Activities (PHODA) (Leeuw et al., 2007b), which can capture fear of movement by asking about the concern from 0 to 10 when imagining doing the tasks depicted on the photographs.

Following each task, participants rated acute pain intensity, task-specific kinesiophobia, exertion and constraint. Pain was assessed using an 11 point Numeric Rating Scale (NRS) for six regions on the spine: (A) cervical spine; (B) cervicothoracic junction; (C) thoracic spine; (D) thoracolumbar junction; (E) lumbar spine; (F) lumbosacral junction. Exertion and constraint were both rated on a CR-10 Borg scale (Borg, 1990). For all questions, 0 referred to no pain/concern/exertion/constraint, and 10 referred to worst imaginable pain/concern/exertion/constraint.

At the end of the experiment, the System Usability Scale (SUS) (Brooke, 1995) and the Quebec User Evaluation of Satisfaction (QUEST) (Demers et al., 1996) were used to determine device usability.

2.4.2. Muscle activity

Muscle activity was measured on the dominant hand side at six locations: M. erector spinae at the medial thoracic (M. longissimus thoracis, LT) and lumbar level (M. longissimus lumborum, LL), as well as the lateral lumbar level (M. iliocostalis lumborum, IL), the M. gluteus maximus (GM), the M. biceps femoris (BF), and the M. rectus abdominis (RA) (Fig. 1 (c)). These particular muscles were chosen due to their role in generating force around the spine and hip (LT, LL, IL, GM, BF) during forward leaning and lifting movements, or in order to account for potential compensatory muscle activity (RA). Surface EMG was recorded using Trigno sensors (*Delsys Ltd, Natick, United States*). Sensors on LL and RA were placed according to McGill et al. (McGill, 1991) and on LT, IL, GM and BF according to SENIAM guidelines (Stegeman and Hermens, 2007).

Considering the tested population and the potential risk of amplifying back pain, a combination of submaximal (SMVC) and maximal (MVC) voluntary contractions were chosen as reference for EMG normalization (SMVC LT & LL: isometric back extension against gravity on a bench with the torso overhanging; MVC IL: isometric side planks against maximal resistance; MVC RA: isometric abdominal crunching against maximal resistance; MVC GM: isometric hip extension with a 90° knee bend in prone position against maximal resistance; MVC BF: isometric knee flexion in a 45° knee flexion angle in prone position against maximal resistance). The maximum root mean square (RMS) value of two 10 s attempts performed at least 1 min apart was used to normalize the data.

Raw EMG data was filtered (zero-lag 4th order butterworth filter; 10–500 Hz). Data was then visually inspected in the time and frequency domain, and excluded if poor quality was observed. For the static leaning task, the RMS over a 5 s window was calculated and used as outcome measure. For the dynamic tasks, a linear envelope was created by a low-pass filter of the rectified data (butterworth; 3 Hz). Muscular effort was then calculated as the average area under the curve (AUC)

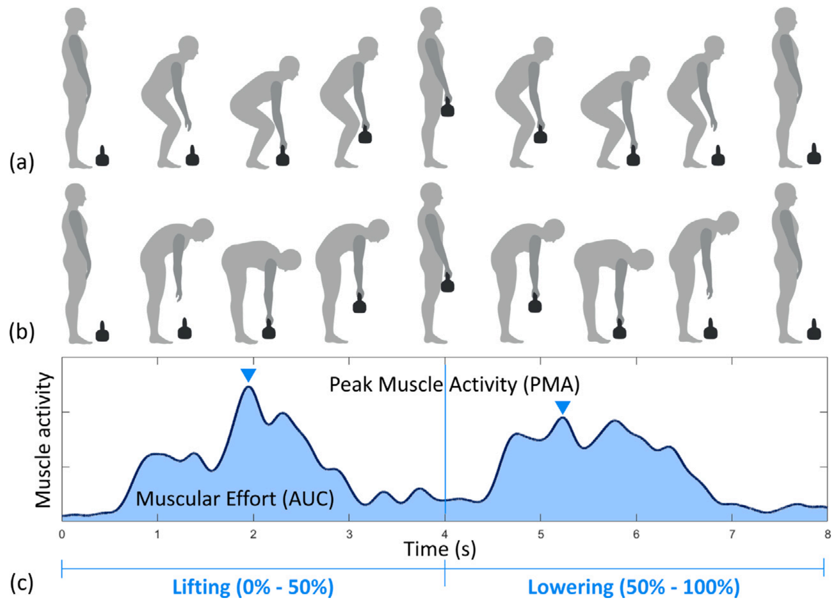


Fig. 2. (a) Squat and (b) stoop lifting task. (c) Exemplary plot of muscle activity with the assessment of peak muscle activity (PMA) indicated as triangles in the lifting and lowering phase, and muscular effort calculated as area under the curve (AUC) during the whole lift cycle.

of lifts 2–9, which was used as outcome measure. Additionally, peak muscle activity (PMA) of lifting (0%–50%) and lowering (50%–100%) was assessed using a peakfinder (Fig. 2 (c)). The median of the 8 respective peaks was computed, resulting in one median value per lift set for each participant.

2.4.3. Kinematics

Peak hip and spine angle, as well as angular velocity can be found in Fig. 3(c). Following methods adapted from Shahvarpour et al. (2018), angular sagittal plane kinematics of the hip and the spine were measured using inertial motion units (*Delsys Ltd, Natick, United States*). Three sensors were attached on (1) the lateral side of the thigh pointing towards the trochanter major (Thigh_IMU), (2) the midpoint between the posterior superior spinae iliaca (Pelvis_IMU) pointing cranially, and (3) the processus spinosus of the T1 vertebra (T1_IMU) pointing cranially.

The angles of the hip (Hip = Thigh_IMU - Pelvis_IMU), and the spine (Spine = Pelvis_IMU - T1_IMU) were derived. At the start of every task, participants stood upright for 10 s, which allowed the calculation of the zero angles. Angular kinematic data was filtered using a zero-lag 4th order low-pass butterworth filter (3 Hz). The filtered data was then visually inspected in the time domain to identify anomalies. Instances of unnatural movement spikes (velocity > 148°/s) were removed to increase accuracy. For the dynamic tasks, peak angles and peak velocities in each lift cycles were determined using a peakfinder and the average is reported.

2.5. Statistical analysis

Data processing and statistical analyses were performed using MATLAB 2023a (*MathWorks, Natick, United States*).

For the discrete data (pain, kinesiophobia, exertion, constraint) hypotheses were tested using Wilcoxon signed-rank tests, and the median and interquartile range (IQR) are reported. For the continuous physiological data (muscle activity and kinematic) hypothesis testing was done using two-way repeated measures ANOVAs, and results were reported as mean and standard deviation (SD). For the forward leaning task, the factors "Angle" (30° vs. 60°) and "Exo" (No Support vs. Support) were defined, including the interaction effect. For the lifting task, the factors "Lift" (Squat vs. Stoop) and "Exo" (No Support vs. Support) were defined, as well as the interaction effect.

For the ANOVA analysis of muscle activity, effects are considered significant if $p < 0.008$ (Bonferroni correction for six muscles). For the ANOVA analysis of the kinematics, effects are considered significant if $p < 0.025$ (Bonferroni correction for two joints). For statistical analyses performed on subjective data the significance level was set at p-value of 0.05.

3. Results

3.1. Sample

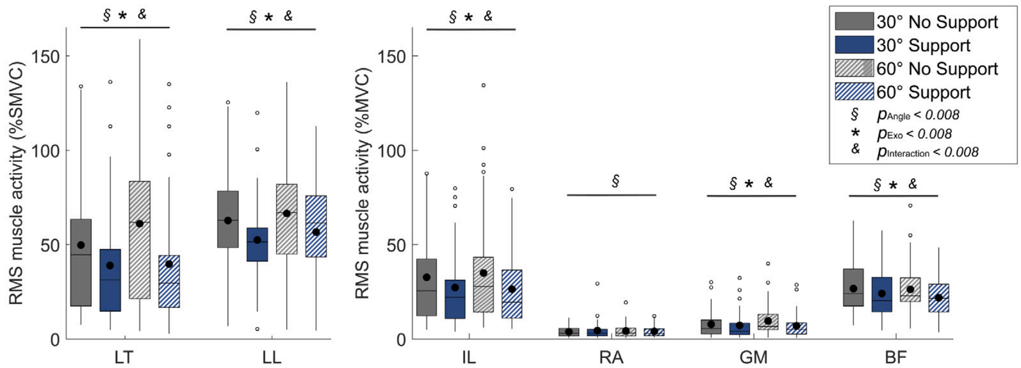
Of the 35 participants, 80% worked in an occupational field representative for the use of the LiftSuit2 (Logistics & Transport: 34.3%; Healthcare: 31.4%; Construction: 8.6%; Agriculture: 5.7%, Table A.2) with an average of 5.0 hours (SD: 2.7 h) of moderate to heavy physical workload per day. Three participants had prior experience with the LiftSuit.

The participants (n = 35; 12 female) were between 19 y and 65 y old (Mean: 35.9 y; SD: 12.2 y), with body heights spanning from 1.57 m to 2.00 m (Mean: 1.76 m; SD: 0.10 m) and body weights ranging from 55 kg to 104 kg (Mean: 75.6 kg; SD: 13.2 kg).

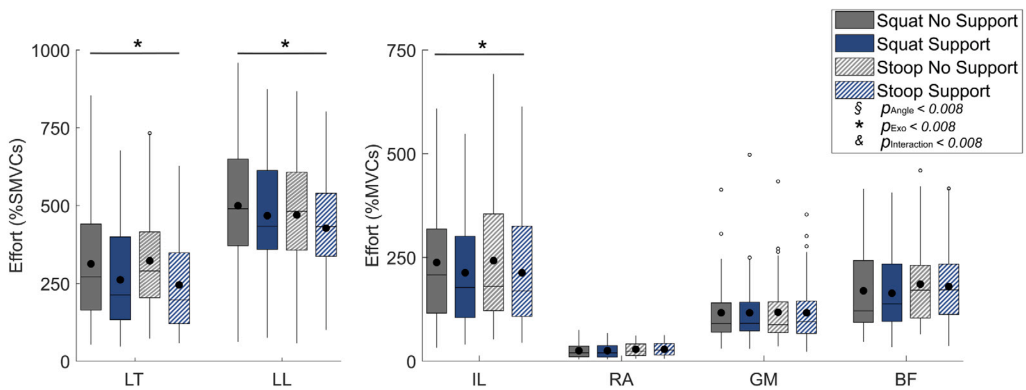
Initial pain was predominantly reported in the lower back region with a mean rating of 1.5/10 (SD: 1.6). 49% ($n = 17$) of the participants were classified as acute, 9% ($n = 3$) as sub-acute, and 43% ($n = 15$) as chronic pain. Onset kinesiophobia ranged from 18 - 49/68 (Median: 32; IQR: 8), with 12 participants (34%) exceeding the high kinesiophobia cut-off of 37 points. Onset back pain disability ranged from 1 - 47/100 (Median: 10; IQR: 11.5), indicating minimal to moderate disability in activities of daily living (Kopec et al., 1995).

3.2. Muscle activity

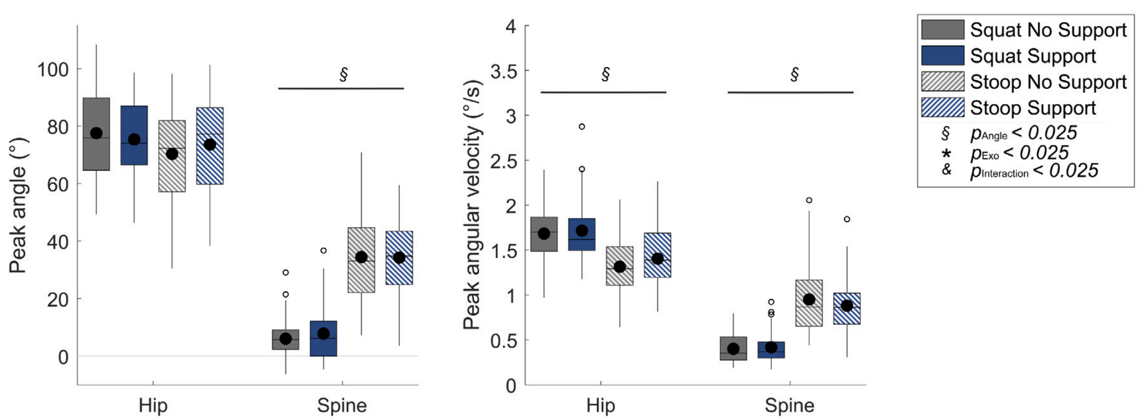
The support of the exoskeleton reduced back muscle activity (RMS amplitudes) of all measured back muscles (LT, LL, IL) with statistical significance when leaning forward to 30° and 60° (Fig. 3(a) & Table 1). There were statistically significant effects of leaning angle (30° vs. 60°) in all six muscles, and an interaction effects between 'Angle' and 'Exo' for all muscles except for the RA. LT activity was reduced by 22% in 30° and 35% in 60° ($p_{\text{Exo}} < 0.001$ & $p_{\text{Int}} < 0.001$). Lumbar muscles showed similar results. LL activity was reduced by 16% in 30° and 15% in 60° ($p_{\text{Exo}} = 0.001$ & $p_{\text{Int}} = 0.002$) and the IL showed a decrease



(a)



(b)



(c)

Fig. 3. (a) Effect of exoskeleton support on muscle activity RMS amplitude as a percent of submaximal voluntary contraction (%SMVC) or maximal voluntary contraction (%MVC) between the No Support condition in gray and Support condition in blue during forward leaning to 30° and 60°. (b) Effect of exoskeleton support and lifting strategy on muscular effort as a percent of submaximal voluntary contraction (%SMVC*s) or maximal voluntary contraction (%MVC*s). (c) Effect of exoskeleton support on hip and spine kinematics. The data are displayed as boxplots, with a dot representing the mean value.

of 17% in 30° and 25% in 60° ($p_{Exo} < 0.001$ & $p_{Int} < 0.001$). The RA was not affected by the exoskeleton (n.s.) and showed minimal activity throughout the task (Mean RMS < 5% MVC). The hip extensors GM and BF showed statistically significant effects, but levels of activity in these muscles during the forward leaning task were small (Fig. 3(a)).

During both squat lifting and stoop lifting, the support of the exoskeleton reduced muscular effort (AUC) in all measured back muscles (Fig. 3(b) and Table 1). The lifting style (squat vs. stoop) did not have a statistically significant effect on muscle activation, nor were any interaction effects between exoskeleton support and lift style observed. The largest effect of the exoskeleton support on muscular effort was observed in the LT with a reduction of 16% in squat lifting, and 24% in stoop lifting ($p_{Exo} < 0.001$). No effect of exoskeleton support was observed in the abdomen and hip extensor muscles. Similar results were observed for peak muscle activity (PMA) during squat and stoop lifting, see supplementary Table A.3.

3.3. Subjective measures

During all three tasks, pain was most often reported in the lumbar spine region (E, n = 25) and lumbo-sacral regions (F, n = 16). Lumbar

Table 1
Effect of exoskeleton support in the forward leaning and lifting tasks. For the forward leaning task RMS activity (in %MVC), and a repeated measures 2-way ANOVA with factors Angle (30° vs. 60°), Exo (No Support vs. Support) and the interaction effect are reported. For the lifting task the total effort calculated as area under the curve (AUC in %MVCs), and a repeated measures 2-way ANOVA with factors Liftstyle (Squat vs. Stoop), Exo (No Support vs. Support) and the interaction effect are reported. EMG of the M. longissimus thoracis (LT), the M. longissimus lumborum (LL), the M. iliocostalis lumborum (IL) the M. rectus abdominis (RA), the M. gluteus maximus (GM), and the M. biceps femoris (BF). M: Mean, SD: Standard Deviation, Δ: Change from Support to No Support condition, RMS: Root Mean Square, AUC: Area Under Curve, NS: No Support condition, S: Support condition, $Delta$(%NS): Change in percent calculated as $(M_{NS} - M_S)/M_{NS} \times 100$, p-values of the ANOVA analysis.

	Forward Leaning 30°					***Forward Leaning 60°***							
	RMS_{NS}		RMS_S			RMS_{NS}		RMS_S					
	M	SD	M	SD	Δ	M	SD	M	SD	Δ	p_{Angle}	p_{Exo}	p_{Int}
LT	49.8	34.7	38.7	31.8	22.0	61.1	42.5	39.7	34.2	35.0	<0.001	<0.001	<0.001
LL	62.8	25.0	52.5	21.4	16.4	66.6	32.2	56.7	26.4	14.8	<0.001	0.001	0.002
IL	32.7	24.6	27.3	20.7	16.6	35.0	29.5	26.4	19.0	24.6	<0.001	<0.001	<0.001
RA	3.9	2.8	4.5	5.2	−15.8	4.3	3.8	4.1	2.9	5.3	<0.001	0.423	0.397
GM	7.8	7.0	7.2	7.4	7.6	9.6	8.1	6.9	6.5	27.5	<0.001	0.005	0.002
BF	26.7	13.2	24.2	13.2	9.6	26.3	13.4	21.8	10.1	17.1	<0.001	0.006	0.002
	Squat Lifting					***Stoop Lifting***							
	AUC_{NS}		AUC_S			AUC_{NS}		AUC_S					
	M	SD	M	SD	Δ	M	SD	M	SD	Δ	$p_{Liftstyle}$	p_{Exo}	p_{Int}
LT	313.1	204.7	261.4	160.2	16.5	322.9	170.7	245.4	144.7	24.0	0.711	<0.001	0.135
LL	499.2	217.4	467.4	191.7	6.4	469.6	191.0	427.3	172.1	9.0	0.589	<0.001	0.938
IL	238.1	151.7	213.5	140.8	10.4	242.6	172.3	213.4	149.5	12.0	0.48	<0.001	0.116
RA	25.4	17.6	25.5	17.2	−0.3	28.7	17.8	28.6	16.3	0.4	0.946	0.653	0.498
GM	116.8	76.8	116.8	81.8	0.0	118.0	77.8	117.0	75.1	0.9	0.462	0.924	0.413
BF	169.9	103.6	163.9	92.7	3.5	185.6	89.5	180.2	81.5	2.9	0.687	0.238	0.740

pain ranged between NRS 0 and 5. Exoskeleton support reduced pain on a group level in forward leaning (ΔMedian = 1.0, $p < 0.01$), squat lifting (ΔMedian = 1.0, $p < 0.001$), and stoop lifting (ΔMedian = 2.0, $p < 0.01$), see Fig. 4 (a). During forward leaning 11 participants reported a reduction of pain, eight participants did not perceive a change in pain, one participant reported an increase of pain, and 12 participants reported no pain in either condition. During squat lifting 17 participants reported a reduction in pain (ranging between 1 and 4 levels), four participants reported no change in pain, one participant reported an increase in pain, and 10 participants reported no pain in either condition. During stoop lifting 16 participants reported a reduction in pain with exoskeleton support, eight participants reported no change in pain severity, one person reported an increase in pain and seven participants experienced no pain in either condition in the lumbar region. Furthermore, a decrease of pain with exoskeleton use was visible in the lumbo-sacral region (F) in squat lifting (ΔMedian = 1.0, $p < 0.05$) and stoop lifting (ΔMedian = 1.0, $p < 0.05$). Over all three tasks, pain was mentioned less than 10 times in the regions A-D (cervical spine - thoracolumbar junction), which is why no statistical tests were carried out for these regions.

The ratings of task-related kinesiophobia (PHODA) ranged from 0 ('no concerns') to 10 ('extreme concerns'). The support of the exoskeleton caused a statistically significant decrease in kinesiophobia in all three tasks (Fig. 4 (b)). The difference in median between the two conditions was 0.4 in forward leaning ($p < 0.001$), 1.6 in squat lifting ($p < 0.001$), and 1.0 in stoop lifting ($p < 0.001$).

Participants reported little exertion over all the tasks with medians ranging from 1 ('extremely easy') to 3 ('easy'). An effect of the exoskeleton could be measured in the squat lifting task, reducing the median of experienced exertion from 3 ('easy') to 2 ('very easy') ($p < 0.05$). No statistically significant change could be seen in leaning ($p = 0.059$) and stoop lifting ($p = 0.082$). Perceived constraint in the No Support condition was rated with a median of 1 ('minor constraint') and differed to the Support condition with a rating of 3 ('mild constraint') in all three tasks ($p_{leaning} < 0.001$, $p_{squat} < 0.01$, $p_{stoop} < 0.01$).

Participants indicated a mean SUS of 83/100 (SD: 11.99). Scores between 80 and 90 are considered excellent and indicate that the exoskeleton's acceptance was very high (Bangor et al., 2008). On the QUEST device subscale score, the usability of the device was rated a median of 4/5 (IQ1: 4; IQ3: 5).

3.4. Kinematics

No statistically significant main effects of exoskeleton on maximum hip or spine flexion, or peak angular velocity were observed (see Table A.4). A trend towards an interaction between lift style and exoskeleton support on maximal hip flexion angle was observed ($p_{Style*Exo} = 0.032$). The mean maximal hip flexion angle was similar between conditions, with 77.5° in the No Support condition and 75.4° in the Support condition. Likewise, during stoop lifting, maximal hip flexion angle was 70.3° in the No Support condition and 73.6° in the Support condition (Fig. 3(c)).

4. Discussion

The present study investigated the impact of the support of a soft passive back exoskeleton on muscle activity, pain, kinesiophobia, and movement kinematics in tasks involving forward leaning, squat and stoop lifting in individuals suffering from back pain. The exoskeleton support caused reductions in back muscle activity, pain and task-specific kinesiophobia in all three tasks, whereas kinematics were not influenced. Time since onset of pain had no influence on muscle activity outcomes.

The data confirms our hypothesis that the support of the exoskeleton reduces back muscle activity in forward leaning, and lifting. Additionally, reductions in activity of the hip extensor muscles could be observed when leaning forward. An earlier study assessed the use of the LiftSuit2 in healthy individuals performing comparable tasks (Van Sluijs et al., 2023b). They showed similar effects in forward leaning with a decrease of back muscle activity of 12%–26% compared to 16%–34% in this study. Furthermore, muscular effort was very similar in both studies with back muscle effort changes of 6%–16% reported by Van Sluijs et al. and changes of 7%–16% in our measurements. These findings hint, that the LiftSuit2 has a similar effect on muscle activity in healthy individuals and individuals with mild to moderate back pain. A study assessing the effects of an active back exoskeleton on muscle activity in individuals with back pain reported reductions in peak muscle activity when lifting a 6 kg weight of 11.1% using squat style and 14.2% using stoop style lifting (Quirk et al., 2023). This confirms that, independent of actuation mechanism, back support exoskeletons can support individuals with back pain by reducing workload for relevant muscles.

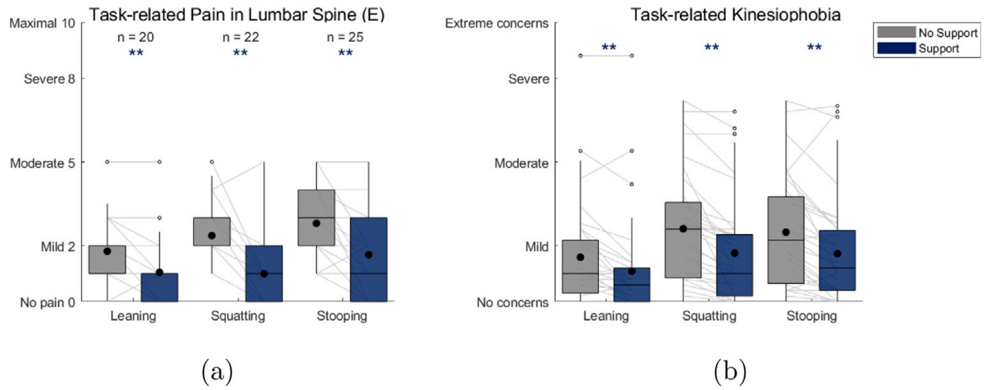


Fig. 4. Change in (a) task-related lumbar back pain severity and (b) kinesiophobia between the no support in gray and support condition in blue during forward leaning, squat lifting, and stoop lifting. The data are displayed as boxplots, with a dot representing the mean. The gray lines indicate individual data. Wilcoxon signed rank p-values are reported, *: $p<0.05$, **: $p<0.01$.

Muscle activity of the abdominal muscle was generally low and did not show changes in conditions throughout all tasks. This implies that no co-contraction or activity redistribution between the measured muscles happened as a consequence of exoskeleton support, and suggests that the presence of the exoskeleton did not fundamentally change how participants performed the tasks. This is also supported by the only minor changes observed in terms of movement kinematics. Also, despite generating torque around the hip, there were no statistically significant reductions in hip extensor muscles during dynamic lifting. These results are consistent with findings in healthy participants (Van Sluijs et al., 2023b) and individuals with back pain (Quirk et al., 2023).

The pattern of back muscle activity, as well as the effect of exoskeleton support on back muscle activity, were similar for both lift styles. Even though there is a bias towards squat lifting being more healthy than stoop lifting, there are individual benefits in both lifting styles (Von Arx et al., 2021). The fact that the LiftSuit provides meaningful support in both lifting styles promises to encourage versatile lift strategies during physically demanding tasks. Lastly, the effect of exoskeleton support on muscle activity was not influenced by kinesiophobia, pain or disability (see supplementary materials), suggesting that the effect of the exoskeleton on muscle activity is consistent across different levels of these factors. Interestingly, an effect of QBPDS suggests that higher levels of reported disability are associated with increased levels of muscle activity independent of exoskeleton use. This could be due to the increased effort required to perform tasks or compensatory mechanisms that individuals with higher disability might use.

The use of the exoskeleton reduced pain severity in the lumbar region during leaning and lifting tasks with statistical significance, supporting our hypothesis. From the 25 participants reporting pain during the stoop lifting task 16 reported a reduction in pain severity between 1 and 4 levels with exoskeleton support, while one person indicated an increase of one pain level with exoskeleton support. This suggests not all participants benefit from exoskeleton support in the same way, however a majority of participants reported positive effects. These findings align with the reductions in pain and lumbar discomfort reported in leaning tasks in recent studies by Kozinc et al. (2021) and in both leaning and lifting tasks by Baltrusch et al. (2019). However, previous studies failed to show consistent results, potentially due to their relatively small sample sizes (between 12 and 15 participants) which might have limited statistical power. Despite this, the trends suggest that occupational back exoskeletons have the potential to reduce low back pain. Two studies assessed the minimal clinically important change (MCIC) in sub-acute or chronic non-specific low back pain as being 1.5 points (Van der Roer et al., 2006; Kovacs et al., 2007). Thus, the changes of pain in stoop lifting (ΔMedian = 2.0) could be considered a clinically relevant improvement, though MCIC should be seen as a context-specific value rather than a fixed number (Beaton et al., 2002). A decrease in pain could likely result from the consistent reduction in muscle activity observed, which could decrease spinal loading and strain on surrounding tissues.

Interestingly, exoskeleton support reduced levels of kinesiophobia in leaning as well as lifting tasks, aligning with a previous study assessing the effect of back support in individuals with back pain (Quirk et al., 2023). This underscores the potential benefits of using exoskeletons to support individuals whose work capacity is limited by fear-avoidance behaviors. A potential concern is that familiarization with an exoskeleton could lead to increased kinesiophobia when it is not worn. This heightened kinesiophobia might result in a reduced quality of life in daily activities. Volders and colleagues (Volders et al., 2015) suggested that the context in which exposure-based therapies, like wearing an exoskeleton to reduce fear, are conducted can impact the long-term reduction of fear of pain. These findings indicate that aiming for achievement is more effective than aiming to avoid pain. When a worker is informed that the purpose of wearing an exoskeleton is pain relief, discontinuing its use may result in increased kinesiophobia. Conversely, if the worker understands that the exoskeleton is designed to facilitate a gradual return to work, the reduction in fear is likely to persist even after the exoskeleton is no longer worn. Therefore, the focus of exoskeleton usage should be on motivating the worker to return to or sustain work, rather than solely aiming to alleviate pain.

Usability of the exoskeleton was generally rated high with least satisfaction in comfort and constraint. As the force of the exoskeleton is not perpendicular to the legs, discomfort is likely to happen at the leg cuffs. As the activation of the exoskeleton is done by pulling on the activation straps, the support can be adapted individually. It is noteworthy that the participants, even though most of them had no training, found the right activation level to limit the discomfort to a minimum, and cause negligible difference in kinematics while still supporting the muscles. This indicates an intuitive and easy to use device.

As for limitations, we should acknowledge that high expectations from the participants might have influenced subjective measurements like pain and kinesiophobia. To minimize this bias, we changed the support without informing the participants about the condition. However, complete blinding was not possible. Additionally, a selection bias may exist due to participants' positive attitudes towards new technology and its potential to alleviate potential long-term pain. It should also be noted that the study was conducted in a lab environment with short working tasks, involving only 20 lifts with an activated exoskeleton.

This limited exposure is likely not enough for familiarization, leaving uncertain how biomechanics might adapt over time. The brief application period may also affect the trade-off between support and discomfort, possibly leading participants to tolerate more discomfort for increased support. Finally, the tasks were symmetrically structured and constrained in time and movement. While this design reduces confounding factors, it does not capture the full range of potential applications for the device. Future studies should include more asymmetric tasks and investigate the effects of training and familiarization on occupational exoskeleton performance.

5. Conclusion

Our findings indicate, that passive soft back exoskeletons reduce back muscle activity in individuals with mild to moderate back pain in forward leaning and lifting with minimal effect on movement kinematics. Furthermore, the support of the back exoskeleton seems to reduce pain and kinesiophobia. While previous research indicated the potential of passive back exoskeletons to prevent back pain in healthy individuals working in physically demanding jobs, these findings suggest that passive back exoskeletons have the potential to support workers with existing back pain. Collecting clinical data assessing the potential of back support exoskeletons to ameliorate working conditions for those working in physically straining occupations through their impact on pain is an important next step in the field of ergonomics.

CRediT authorship contribution statement

Tobias Luder: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michael Meier:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Rea Neuweiler:** Writing – review & editing, Formal analysis. **Olivier Lambercy:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Ethical standards

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the institutional Ethics Committee of ETH Zurich (13 September 2023/EK-2023-N-225).

Funding statement

The Rehabilitation Engineering Laboratory is supported by the ETH Zurich Foundation in collaboration with Hocoma AG.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Olivier Lambercy is an academic advisor to Auxivo AG. Tobias Luder, Rea Neuweiler and Michael Meier have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank Johanna Sornig for her contribution to data collection, and Dane Donegan for guidance during the analysis of the IMU data. We are grateful to Julia van Sluijs for contributing to the illustrations and to all volunteers who participated in the study.

Table A.2
Occupational fields of the participants.

Occupational Field	Subfield	*n*
Logistics & Transport	Logistics	6
	Moving Services	4
	Postal Services	1
	Commercial Kitchen	1
Healthcare	Nursing	8
	Physiotherapy	2
	Chiropractic Care	2
Construction	Landscaping	1
	Masonry	1
	Carpentry	1
Agriculture	Forestry	1
	Farming	1
Others	Student	3
	Office Administration	2
	Education	1

Appendix A. Supplementary file 1

A.1. General linear model analysis

Since back pain is a complex phenomenon we hypothesized that factors such as pain duration, kinesiophobia, level of pain or disability resulting from pain could influence the effect of exoskeleton support on muscle activity patterns.

A.1.1. Methods

To explored whether the effect of the exoskeleton on muscle activity is influenced by duration (acute, sub-acute vs. chronic), kinesiophobia, pain or disability we did a general linear model (GLM) analysis. For this, a mixed model (dependent variable: muscular effort LL) with fixed factors “exo”, “lift”, “pain duration category”, random factor “subject” and covariates TSK score, pain, QBPDS score and task-specific kinesiophobia was performed.

A.1.2. Results

The mixed model analysis yielded a main effect of “Exo” ($F = 7.570$, $p = 0.007$), confirming exoskeleton support reduced LL muscular effort (AUC) during lifting. However, no interaction effects between “Exo” and the TSK score, pain, task-specific Kinesiophobia or pain duration (p’s > 0.478) on muscle activity (AUC LL) were observed, indicating the effect of the exoskeleton on LL muscular effort was independent of these factors. A statistically significant main effect of the QBPDS score was observed ($F = 5.467$, $p = 0.026$), indicating a positive correlation between muscular effort independent of exoskeleton condition and the QBPDS score. No main effects of task, TSK score, pain, task-specific kinesiophobia or pain duration were observed (p’s > 0.180).

A.1.3. Conclusion

The effect of exoskeleton support on muscle activity did not seem to be influenced by kinesiophobia, pain or disability, suggesting that the effect of the exoskeleton on muscle activity is consistent across different levels of these factors. Interestingly, an effect of QBPDS suggests that higher levels of reported disability are associated with increased levels of muscle activity independent of exoskeleton use. This could be due to the increased effort required to perform tasks or compensatory mechanisms that individuals with higher disability might use.

Table A.3
For comparison of this study to Quirk et al. (2023) and Van Sluijs et al. (2023b) the Peak Muscle Activity (PMA) in squat and stoop lifting of the M. longissimus thoracis (LT), the M. longissimus lumborum (LL), the M. iliocostalis lumborum (IL) the M. rectus abdominis (RA), the M. gluteus maximus (GM), and the M. biceps femoris (BF) are reported. The peak muscle activity during the lifting phase (0–50%lift cycle) and during the lowering phase (50–100%lift cycle) were detected using a peak finder. A two-way repeated measures ANOVA with main effects Liftstyle (squat vs. stoop), Exo (Support vs. No Support) and the interaction between Liftstyle and Exo. P-values are considered significant if $p < 0.0083$ (Bonferroni correction for six muscles). M: Mean, SD: Standard Deviation, Δ: Change from Support to No Support condition, RMS: Root Mean Square, PMA: Peak Muscle Activity, NS: No Support condition, S: Support condition, %NS: Change in percent calculated as $(M_{NS} - M_S)/M_{NS} \times 100$.

	Squat - Lifting Phase					*Stoop - Lifting Phase*							
	PMA_{NS}		PMA_S			PMA_{NS}		PMA_S					
	M	SD	M	SD	Δ(%NS)	M	SD	M	SD	Δ(%NS)	$p_{Liftstyle}$	p_{Exo}	p_{Int}
LT	122.7	109.9	101.2	82.0	17.5	128.7	71.7	100.4	71.9	22.0	0.017	< 0.001	0.222
LL	152.7	66.7	145.1	63.4	5.0	166.7	68.1	144.5	56.8	13.4	0.027	0.008	0.046
IL	72.1	49.3	60.9	42.8	15.5	78.8	53.3	69.7	47.3	11.5	0.012	0.001	0.855
RA	6.3	4.3	6.3	4.3	−0.4	7.5	4.8	8.4	5.5	−13.0	0.136	0.501	0.529
GM	47.6	25.5	50.1	28.9	−5.3	43.2	25.2	45.5	30.8	−5.2	0.013	0.125	0.526
BM	53.7	28.0	53.9	29.5	−0.3	63.2	25.3	63.7	27.5	−0.8	0.207	0.689	0.726
	Squat - Lowering Phase					*Stoop - Lowering Phase*							
	PMA_{NS}		PMA_S			PMA_{NS}		PMA_S					
	M	SD	M	SD	Δ(%NS)	M	SD	M	SD	Δ(%NS)	$p_{Liftstyle}$	p_{Exo}	p_{Int}
LT	93.5	77.1	66.3	43.3	29.1	101.8	65.6	69.8	52.5	31.5	0.028	< 0.001	0.223
LL	124.2	51.5	113.1	47.5	8.9	137.2	60.6	117.9	44.8	14.1	0.011	0.003	0.273
IL	63.3	41.8	52.3	39.5	17.4	62.5	40.5	58.7	39.3	6.1	0.275	0.007	0.128
RA	6.3	4.6	6.2	4.5	0.2	7.4	4.7	7.8	5.3	−5.2	0.278	0.694	0.767
GM	40.6	22.5	42.4	25.4	−4.4	35.9	22.4	38.1	22.2	−6.3	0.002	0.108	0.791
BF	48.0	29.9	45.7	28.4	4.9	54.7	23.5	55.6	24.8	−1.8	0.300	0.766	0.114

Table A.4
Effect of exoskeleton support hip and spine kinematics in lifting tasks. The peak angle (in °) and peak angular velocity (in °/s) of the hip and knee joint, and repeated measures 2-way ANOVA's with factors Liftstyle (Squat vs. Stoop), Exo (No Support vs. Support) and the interaction effect are reported. M: Mean, SD: Standard Deviation, NS: No Support condition, S: Support condition, *p*-values of the ANOVA analysis.

	Peak Angle (°)										
	$Squat_{NS}$		$Squat_S$		$Stoop_{NS}$		$Stoop_S$				
	M	SD	M	SD	M	SD	M	SD	$p_{Liftstyle}$	p_{Exo}	p_{Int}
Hip	77.5	16.5	75.4	14.1	70.3	16.7	73.6	15.6	0.162	0.655	0.032
Spine	6.1	7.4	7.8	9.5	34.5	15.5	34.2	15.1	< 0.001	0.481	0.110
	Peak Angular Velocity (°/s)										
	$Squat_{NS}$		$Squat_S$		$Stoop_{NS}$		$Stoop_S$				
	M	SD	M	SD	M	SD	M	SD	$p_{Liftstyle}$	p_{Exo}	p_{Int}
Hip	1.7	0.3	1.7	0.3	1.3	0.3	1.4	0.3	< 0.001	0.056	0.153
Spine	0.4	0.2	0.4	0.2	1.0	0.4	0.9	0.3	< 0.001	0.529	0.059

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