

Short-term effects of the Auxivo LiftSuit during lifting and static leaning

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ABSTRACT

Back support exosuits can support workers in physically demanding jobs by reducing muscle load, which could reduce risk of work-related musculoskeletal disorders. This paper presents a two-session evaluation of a commercial exosuit, the Auxivo LiftSuit 1.1. In session 1, 17 participants performed single repetitions of lifting and static leaning tasks with and without the LiftSuit. In session 2, 10 participants performed 50 box lifting repetitions with and without the LiftSuit. In session 1, the exosuit was considered mildly to moderately helpful, and reduced erector spinae and middle trapezius electromyograms. In session 2, the exosuit was not considered helpful, but reduced the middle trapezius electromyogram and trunk and thigh ranges of motion. These effects are likely due to placement of elastic elements and excessive stiffness at the hips. Overall, the LiftSuit appears suboptimal for long-term use, though elastic elements on the upper back may reduce muscle activation in future exosuit designs.

1. Introduction

Back support exoskeletons and exosuits are becoming an increasingly popular tool for workers in physically demanding occupations such as warehouse work, baggage handling, and agriculture (Kermavnar et al., 2021; Bär et al., 2021). Worn on the trunk and optionally the limbs, such devices can incorporate both active components (i.e., motors (Babič et al., 2021; Koopman et al., 2020; Poliero et al., 2021; Park et al., 2022)) and passive components such as carbon fiber beams (Alemi et al., 2019), springs (Huysamen et al., 2018a) and elastic bands (Lamers et al., 2018) that store and release energy, with the overall goal of reducing muscle load, joint moments, and shear and compression forces at lower spine (Kermavnar et al., 2021; Bär et al., 2021). Since work-related musculoskeletal disorders represent a major global health problem (Swain et al., 2020; James et al., 2018), these technologies may in the long term benefit human health and wellbeing.

Short-term studies have repeatedly shown that exoskeletons can effectively reduce muscle activation (Kermavnar et al., 2021; Bär et al., 2021), and some studies have suggested that active devices may provide more support than passive ones (Babič et al., 2021; Koopman et al., 2019; Park et al., 2022; Huysamen et al., 2018b). However, as active exoskeletons tend to be expensive and heavy, there is also great interest in devices that may provide less assistance but can do so at a fraction of the cost and weight of active devices. Particularly exosuits, which are

loosely defined as wearable assistive devices built only using soft materials, have attracted significant interest since they tend to be relatively lightweight, cheap and resistant to damage. Despite their low cost, exosuits can nonetheless reduce muscle activation and fatigue (Alemi et al., 2019; Lamers et al., 2018; Goršič et al., 2021; Schmidt et al., 2017), and have shown promising pilot results in field trials (Yandell et al., 2020). However, despite emerging research on evaluation tools (Zelik et al., 2022), there is still relatively little information about the short-term effects of soft exosuits.

In this paper, we focus on the LiftSuit 1.1, first released for purchase in 2021 by Auxivo AG (Schwerzenbach, Switzerland) (Auxivo, 2021). As it is one of the first occupational exosuits available to the public (the other being the Apex from HeroWear, USA), it could achieve broad adoption in diverse fields. However, unlike the Apex, which has been evaluated both by its developers (Lamers et al., 2018; Lamers et al., 2020; Yandell et al., 2020) and our own team (Goršič et al., 2021), the LiftSuit has not been scientifically evaluated. It does share several design elements with the Apex: for example, both consist of upper-body sections, thigh sleeves, and elastic bands that store and release energy. Thus, the LiftSuit might have similar effects to the Apex. However, they do differ in several ways and may thus have different effects. Even if effects are similar, the first scientific evaluation of the LiftSuit is likely to encourage broader adoption of both the LiftSuit and other exosuits. Our study thus presents a two-session evaluation of the LiftSuit, focusing on

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lifting and leaning tasks. Based on our experience from a previous Apex study (Goršič et al., 2021), we hypothesized that the LiftSuit would reduce mean and peak electromyograms (EMG) of the erector spinae (ES), with no significant effects on body kinematics or EMG of other muscles.

2. Materials and methods

The study consisted of two LiftSuit evaluation sessions, with participants allowed to take part in either both sessions or only session 1. Participants are described in section 2.1 and the LiftSuit is presented in section 2.2. The protocol for both sessions is given in section 2.3. Sections 2.4 and 2.5 describe measurements and signal processing while section 2.6 describes statistical analysis.

2.1. Participants

Seventeen individuals (9 women, 8 men) with no history of chronic back pain or back injury took part in session 1. They were 27.4 ± 5.4 (mean $\pm$ standard deviation) years old (range 20–36), with heights of 170.3 ± 7.1 cm (range 158–189) and mass of 69.4 ± 14.7 kg (range 49–96). All 17 were right-handed.

Of these 17 participants, 10 (5 women, 5 men) also took part in session 2. These 10 were 28.4 ± 6.4 years old (range 20–36), with heights of 170.0 ± 5.2 cm (range 161–179) and mass of 71.2 ± 14.5 kg (range 49–96).

Four participants who took part in both sessions had participated in our previous Apex study (Goršič et al., 2021) approximately nine months before this study. Other participants reported no experience

with exoskeletons/exosuits.

2.2. Auxivo LiftSuit

A participant wearing the LiftSuit 1.1 is shown in Fig. 1. The device weighs 0.9 kg and comprises an upper-body section (similar to a backpack with shoulder straps and a chest strap), a support strap around the waist, thigh sleeves, and two elastic bands in an X-shape on the back that connect the upper-body section to the thigh sleeves. Two clips, one on each shoulder strap, allow assistance to be activated/deactivated (by opening/closing the clips) and manually adjusted (by tightening the straps). If activated, the straps on the back are tightened close to the body, and the two textile spring parts stretch whenever the wearer leans forward or crouches, assisting the movement of the spine. If deactivated, the device is slack and does not apply any assistive forces, though it may still affect the wearer via, e.g., weight or constriction.

2.3. Study protocol

The study was approved by the University of Wyoming Institutional Review Board, protocol #20200129DN02643. Due to the COVID-19 pandemic, participants and researchers wore face masks, and social distancing was maintained whenever possible. The study consisted of two sessions.

2.3.1. Session 1: Brief lifting and leaning tasks

This session took ~ 1.5 h and involved a modified version of a protocol previously used to evaluate the HeroWear Apex (Goršič et al., 2021). Upon participant arrival, the LiftSuit was demonstrated, the



Fig. 1. A participant wearing the Auxivo LiftSuit (Auxivo AG, Switzerland): front, back and side views. The participant is also wearing the sensors used in the study (e.g., wireless electromyography sensors under shirt, optical tracking markers on shoulders, hips and knees).

study purpose and procedure were explained, and the participant gave informed consent. Body measurements were recorded and EMG electrodes (section 2.4) were applied. Participants completed maximum voluntary contraction (MVC) tests for all evaluated muscles, and Vicon reflective markers were then applied.

Data collection was done in three blocks: in block 1, multiple tasks were done without the exosuit; in block 2, the same tasks were done with the activated exosuit; in block 3, the tasks were done without the exosuit again. This is a variant of withdrawal study design (Graham et al., 2012) that was also used in the previous Apex study (Goršič et al., 2021) and other exosuit studies (Lamers et al., 2020). Between blocks 1 and 2, there was an exosuit fitting and familiarization period. With the help of a researcher, participants donned the exosuit, adjusted the straps for optimal support, tightened the thigh sleeves, and activated the exosuit. They then walked around and lifted/carried objects in an unstructured manner for a few minutes. Any reported comfort issues were addressed as much as possible by readjusting the exosuit straps before the start of block 2. All sensors were checked before each block and adjusted as needed. After block 3, all sensors were removed and participants were paid \$20.

The tasks in each block were:

- lifting a plastic box with handles and a 15-lb (6.8-kg) weight in it from the floor in front of the participant to waist level (the height of the participant's waist) in the sagittal plane using both arms,
- lowering the same box and weight from waist level to the floor in the sagittal plane,
- lifting the same box with a 30-lb (13.6-kg) weight from the floor to waist level in the sagittal plane using both arms,
- lowering the same box and weight from waist level to the floor in the sagittal plane,
- lifting a 17.5-lb dumbbell from the floor beneath the participant's dominant hand to a standing position using the dominant hand,
- walking across the room while carrying the same box with a 15-lb weight in front of the participant at waist level using both arms,
- holding a static forward leaning pose with straight legs and a 30-degree hip angle for 30 s,
- holding a static forward leaning pose with straight legs and a 60-degree hip angle for 30 s.

Since the exosuit was designed for lifting and forward leaning tasks, these were also the focus of our study. We limited ourselves to lighter loads following Institutional Review Board recommendations regarding physically intensive research during the COVID-19 pandemic.

No specific strategy was prescribed for the tasks; participants could, for example, lift the box from the floor by either stooping or squatting. The task order within each block was varied randomly between participants (with no two participants having the same order) but was the same for all three blocks of a participant. Within each block, each task was performed twice and measured signals were visually monitored; if signal quality was poor (due to occluded optical markers, noticeable electrode movement, or an EMG amplitude clearly over 2 times the MVC value, indicating an artefact), that trial was discarded, corrections were made as needed (e.g., EMG electrodes retaped), and the trial was repeated until two good trials were recorded. About 5% of trials were discarded and redone. A photo of a participant performing a lifting task is shown in Fig. 2.

2.3.2. Session 2: Repetitive lifting

This session took ~1 h and was similar to a study by Baltrusch et al. (2020). Like session 1, body measurements were recorded, EMG electrodes were applied, MVC tests were completed, and reflective markers were applied. The protocol then consisted of two 5-min lifting blocks with a 20-min break between blocks. One block was performed with the activated exosuit and the other without the exosuit; the order was counterbalanced so that half the participants performed the exosuit



Fig. 2. A participant lifting a box from the floor while wearing the exosuit and sensors. Optical tracking markers are visible on the body and box. Electromyography sensors are not visible from this angle.

block first. The exosuit fitting and familiarization were done prior to the exosuit block with the same procedure as in session 1 to address comfort issues. In each block, participants continuously lifted a box (that weighed 10% of the participant's body weight) at a speed of 10 lifts per minute, for a total of 50 lifts per block. A metronome was used to ensure consistent lifting speed (Madinei et al., 2021). It was set to 40 beats per minute, with 4 beats within each lift to indicate 4 lift components: lowering body and grabbing box, lifting box to an upright position, lowering body and releasing box, and returning to an upright position without box. No lifting technique was prescribed.

Between the two blocks, participants sat down and rested. Before block 2, all sensors were reexamined and reapplied if necessary. After both blocks were completed, all sensors were removed, and participants were paid \$15.

2.4. Measurements

Three measurement types were taken: kinematics, EMG, and self-report ratings. Participants' body kinematics were measured using eight Vicon Bonita optical cameras (Vicon Motion Systems, UK) and retroreflective markers at 160 Hz. In both sessions, markers were placed at the left and right acromioclavicular joints, greater trochanters, and lateral knees. In session 1 only, markers were also placed at the lateral malleoli, toes, and heels. They were also placed on each side of the box

and each end of the dumbbell.

EMG was measured from the left and right ES, rectus abdominis (RA), and middle trapezius (MT) using the Trigno Avanti wireless system (Delsys Inc, Boston, MA) at 2148 Hz. The Avanti system consists of reusable bipolar electrodes with a 10-mm interelectrode distance and 99.9% silver contact material. The skin was shaved and cleaned, and electrodes were placed following SENIAM recommendations (Hermens et al., 1999): for ES, at L3 height, approximately 4 cm left and right from the midline of the spine; for RA, 3 cm from the midline of the abdomen and 2 cm above the umbilicus; for MT, at 50% between the medial border of the scapula and spine, at the level of T3, in the direction of the line between T5 and the acromion. The same EMG application procedure was followed in both sessions.

All self-report scales were described orally by the experimenter just before beginning data collection, and all participant answers were given orally on discrete numeric scales. Reminders about scale definitions were given as needed. During session 1, self-report ratings were collected during block 2 (with exosuit) and after blocks 2 and 3. In block 2, after each task, participants rated how much effort it took to perform that task with the exosuit compared to without the exosuit. The scale ranged from +5 (much easier with) to -5 (much easier without), with 0 representing no difference and ± 1 and ± 3 representing mildly and moderately easier. After block 2, participants answered the same question over all tasks; after block 3, they answered it again. This is an ad-hoc scale previously used in our Apex study (Goršič et al., 2021). After block 2, participants completed the Body Part Discomfort Scale (BPD) (Corlett and Bishop, 1976). They were shown a chart of numbered body regions and pointed at regions where any discomfort was present; they then rated discomfort in each region between 1 (mild) to 5 (severe).

During session 2, participants self-reported perceived effort to perform the task with vs. without the exosuit using the same -5 to +5 ad-hoc scale as above after completing both blocks. Additionally, after the first, third, and fifth minute of lifting in each block, participants self-reported perceived exertion on the Rate of Perceived Exertion (RPE) scale (Day et al., 2004) between 0 (nothing at all) and 10 (very, very heavy activity), with 1 representing very light, 3 moderate, 5 heavy and 7 very heavy. Finally, after the exosuit block, participants completed the BPD (Corlett and Bishop, 1976) as above.

2.5. Signal processing for EMG and kinematics

EMG and kinematic signals were first segmented into individual tasks. The start and end times for each task were determined similarly for each session. For session 1:

- Walking while carrying box: one gait cycle midway across the room.
- Lifting a box/dumbbell: from the maximal to the minimal height of the greater trochanters.
- Lowering the box: from maximal to minimal height of greater trochanters.
- Leaning tasks: all 30 s of static lean.

For session 2, the last three lifts with good-quality data (no artifacts in EMG, no obstructed markers) in the first, third and fifth minute were segmented into the lifting and lowering part as described for lifting and lowering tasks in session 1. Only the last three "good" lifts in those minutes were analyzed to avoid possible transient effects associated with starting lifting and answering self-report questions.

For kinematic analysis, the three-dimensional trunk reference frame was defined following recommendations of Wu and Cavanagh (1995). The center of the two acromioclavicular joints and the center of the two greater trochanters were used to define the vertical axis. The cross product of the vertical axis and the vector connecting the acromioclavicular joints was used to define the anterior-posterior axis. The cross product of the vertical and anterior axes was used to define the medial-lateral axis. Cardan angles with a rotation order of

flexion-extension (medial-lateral axis), lateral flexion (anterior-posterior axis), and left-right rotation (vertical axis) were calculated between the trunk reference frame and global reference frame to determine three-dimensional trunk angles. The two-dimensional thigh vector was defined by the greater trochanter and lateral knee. Two-dimensional thigh flexion-extension angles were calculated as the angle between the thigh vector and the vertical axis in the sagittal plane. In session 1, trunk ranges of motion (ROM) in flexion-extension, lateral flexion, and left-right rotation as well as the thigh ROM in flexion-extension were used as outcome variables and measured in degrees. In session 2, only trunk and thigh ROM in flexion-extension were used since all movements were done in the sagittal plane. Thigh ROM was calculated as the mean of the left and right thigh ranges.

Segmented EMG signals were inspected to find cases where EMG amplitudes exceeded 2 times the MVC value. Those signal segments were discarded since they were likely artifacts. This was done on a signal-by-signal basis: for example, if only left RA EMG had excessive amplitudes, EMG segments of other muscles from the same trial were retained. This occurred in approximately 1% of signal segments.

Signals were first filtered using a fourth-order Butterworth bandpass filter (20–450 Hz). Filtered signals were rectified and filtered using a fourth-order Butterworth lowpass filter with a cutoff at 10 Hz to obtain linear envelopes. Each envelope was divided by the maximum value obtained during the MVC test. Finally, two outcome variables were calculated: peak EMG (peak envelope value, expressed as % MVC) and mean EMG (mean envelope value, expressed as % MVC). Both are common outcome measures in studies of back support exoskeletons (Aleml et al., 2019; Lamers et al., 2018).

For session 1, for each task, all outcome variables (ROM, peak EMG, mean EMG) were calculated separately for the two trials and then averaged across both trials. If an EMG outcome variable from one trial had to be discarded, only the other trial's value was used without averaging. For session 2, outcomes were calculated for lifting and lowering the box separately, for the last 3 lifts in the first, third and fifth minutes. The values were then averaged across the three lifts for each minute.

2.6. Statistical analysis

All statistical tests were done using SPSS Statistics 28 (IBM Corporation, Armonk, NY).

2.6.1. Session 1

Kinematic and EMG outcome variables were analyzed as follows. For each outcome variable and task separately, one-way repeated-measures analyses of variance (RMANOVA) with Greenhouse-Geisser corrections were used to calculate linear contrasts comparing block 2 (exosuit) to the mean of blocks 1 and 3 (no exosuit). A one-sample *t*-test was then used to compare the contrast to a mean of zero. For each contrast, the significance (two-tailed *p*-value) and effect size (Cohen's *d*) are reported. As there were multiple tasks for each outcome variable, the Benjamini-Hochberg procedure (Benjamini and Hochberg, 1995) with a base alpha level of .05 was used to reduce false discovery rate within each outcome variable.

For self-report ratings, one-sample *t*-tests were used to compare ratings to a mean of zero. This was done for each task within block 2 and for the two overall ratings. When normality requirements were violated, one-sample Wilcoxon signed-rank tests were used instead. BPD ratings were reported descriptively.

2.6.2. Session 2

For kinematics, EMG, and RPE ratings, two-way RMANOVA with the Greenhouse-Geisser correction were conducted for each outcome variable. Each RMANOVA had two within-subject factors: the presence of the exosuit (two levels: with/without) and the time (3 levels: after 1, 3, or 5 min). For each RMANOVA, significance and effect size (partial eta

squared) are reported for both main effects and the interaction effect.

For self-report ratings of perceived exosuit assistance, one-sample t-tests were used to compare ratings to a mean of zero, similarly to session 1. Discomfort ratings were reported descriptively.

3. Results

All participants completed the protocol. In session 1, one participant's EMG was discarded due to poor quality, resulting in valid EMG from 16 participants in session 1. All other data are reported for the full sample.

On all boxplots (Figs. 3–6), the middle bar represents the median, top and bottom box edges represent 25th and 75th percentiles, whiskers extend to the most extreme observation within 1.5 times interquartile range from the nearest quartile, and circles represent individual outliers.

3.1. Session 1

Table 1 shows results of self-report ratings: reported values and results of one-sample t-tests. Medians range from 0 to 2, with 1 indicating “mildly easier” and 3 indicating “moderately easier.” Tables 2–5 then show p-values and effect sizes of linear contrasts for kinematics (Table 2), RA EMG (Table 3), ES EMG (Table 4), and MT EMG (Table 5). Kinematics and peak EMG were not used as outcome variables for static leaning tasks.

As seen in Tables 2–5, the contrasts were primarily significant for the MT, with some significant results observed in ES and kinematics as well. Negative Cohen's d values for the significant contrasts indicate that MT and ES EMG were reduced by the exosuit. Figs. 3 and 4 show example right MT results when lifting and lowering a 15-lb box (Fig. 3) and during static leaning (Fig. 4). Fig. 5 shows left ES peak EMG when lifting and lowering a 30-lb box.

On the BPD, three participants reported no discomfort. Seven

reported discomfort in regions 9 and 10 (left and right thighs), with one rating it 1, three rating it 3, two rating it 4, and one rating it 5. Six reported it in region 8 (buttocks), with three rating it 2, two rating it 3, and one rating it 1. Two reported it in region 2 (shoulders), rating it 2 and 3. Two reported it in region 6 (mid back), rating it 1 and 3. Two reported it in region 7 (lower back), rating it 1 and 3. Finally, one reported it in region 1 (neck), rating it 2.

3.2. Session 2

In session 2, one-sample t-tests on ratings of perceived exosuit assistance found no significant differences from a mean of zero, indicating that the exosuit was not perceived as helpful. Median RPE ratings were identical for exosuit and no-exosuit blocks: 1.5 after the first minute, 2 after the third minute, and 3 after the fifth minute.

Effect sizes and p-values from two-way RMANOVA are reported in Table 6. The three outcome variables with the largest exosuit effects in both box lifting and lowering (peak right MT EMG, trunk FE ROM, thigh FE ROM) are shown in Fig. 6.

On the Body Part Discomfort Scale, three participants reported no discomfort. Two reported discomfort in region 7 (lower back), rating it 1 and 4. Two reported it in region 8 (buttocks), both rating it 2. Two reported it in regions 9 and 10 (left and right thighs), both rating it 1. Finally, one reported it in region 6 (mid back), rating it 1.

4. Discussion

4.1. Session 1

Results of session 1 are most easily compared to our previous study with the HeroWear Apex (Goršič et al., 2021), which used a modified version of the current protocol with additional sit-to-stand tasks but no leaning tasks. That study had a slightly larger sample ($N = 18$ for EMG)

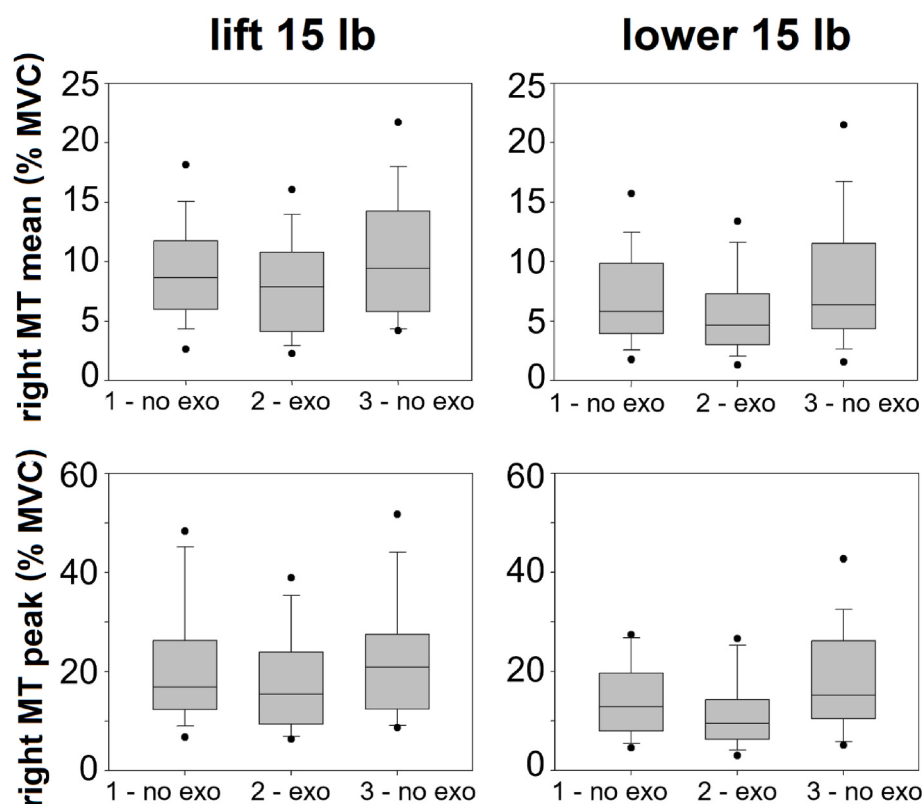


Fig. 3. Session 1: Mean (top) and peak (bottom) electromyogram values for the right middle trapezius (MT) when lifting (left) and lowering (right) a 15-lb box. The three boxes in each plot correspond to the three session blocks. MVC = maximum voluntary contraction.

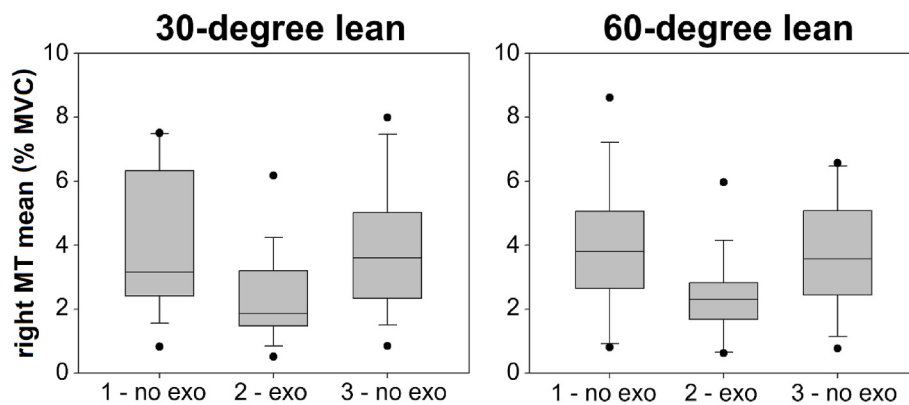


Fig. 4. Session 1: Mean electromyogram values for the right middle trapezius (MT) while maintaining a 30-degree (left) or 60-degree (right) static leaning pose. The three boxes in each plot correspond to the three session blocks. MVC = maximum voluntary contraction.

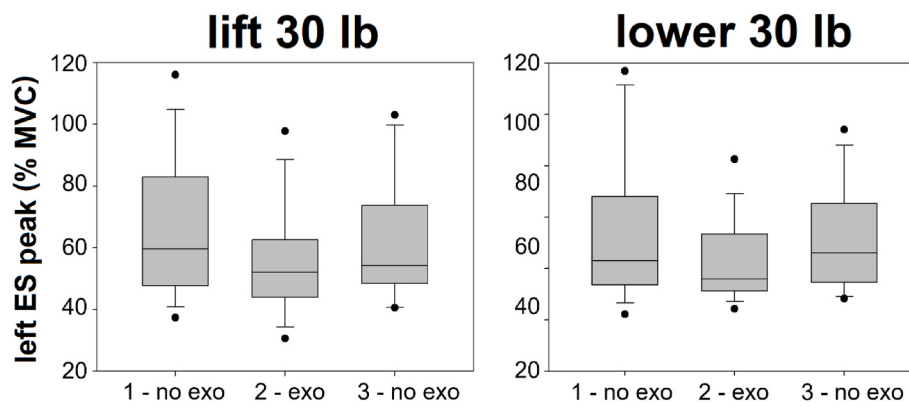


Fig. 5. Session 1: Peak electromyogram values for the left erector spinae (ES) when lifting (left) and lowering (right) a 30-lb box. The three boxes in each plot correspond to the three session blocks. MVC = maximum voluntary contraction.

and found consistent decreases in ES EMG across lifting and lowering tasks, with no change in RA EMG and changes in MT EMG only during one sit-to-stand task. Conversely, our study found some decreases in peak ES EMG when lifting the 30-lb box (Table 4), but also found much more consistent decreases in MT EMG (Table 5). Other exoskeleton studies have previously found larger EMG reductions with heavier loads (Park et al., 2022), so the ES result is not entirely unexpected. However, the MT result is unexpected, as the MT is not commonly investigated in studies of back support exoskeletons and exosuits: two 2021 review papers (Kermavnar et al., 2021; Bär et al., 2021) found only one MT result, which was an increase rather than a decrease due to the exoskeleton (Amandels et al., 2018). While one decrease in MT EMG was reported by our Apex study (Goršič et al., 2021), the more consistent decreases in this study cannot be coincidental.

The larger MT EMG decreases and smaller ES EMG decreases may be because the elastic part of the LiftSuit is on the upper back, almost exactly at MT height. On the other hand, the elastic part of the Apex runs from the mid-back to the mid-thigh, closer to the ES, and the Apex developers have stated that their device was specifically designed to generate forces roughly parallel to lumbar extensor muscles and ligaments (Lamers et al., 2018). Other trunk exoskeletons also commonly provide assistance around the hips (Baltrusch et al., 2020; Madinei et al., 2021), which generally may explain why other devices achieve more consistent ES EMG decreases but have no documented MT results.

Aside from EMG results, participants found the tasks mildly to moderately easier to perform with the exosuit than without it; results of the ad-hoc scale were similar to those in the Apex study (Goršič et al., 2021). With regard to kinematics, changes in trunk lateral flexion ROM and thigh flexion/extension ROM were also observed (Table 2). Our

previous Apex study found reduced trunk flexion/extension ROM when lifting a dumbbell (Goršič et al., 2021), but did not find changes in trunk lateral flexion or thigh flexion/extension. In that previous study, we posited that kinematic changes were more prominent during asymmetric lifts since the exosuit's elastic bands do not provide as much assistance when the load is placed to the side; we feel that this is still the case with the LiftSuit. The increases in lateral flexion ROM and decreases in thigh flexion/extension ROM when lifting objects (Table 2) indicate that participants changed their lifting strategy, which is likely due to the exosuit's stiffness limiting the motions that can be performed.

4.2. Session 2

In session 2, participants did not consider the task easier with the exosuit even though decreases in peak MT EMG were observed. The study of Baltrusch et al. (2020), which inspired the protocol for session 2, found decreases in back muscle EMG and no kinematic changes. Thus, we believe that the lack of perceived helpfulness in our study is due to lack of reductions in back muscle (ES) activity. Instead, the kinematic changes (reduced trunk and thigh flexion/extension ROM – Fig. 6) indicate that participants changed their lifting strategy as a result of wearing the exosuit. Similar reductions in ROM during lifting were observed in a different Baltrusch study (Baltrusch et al., 2019).

As a follow-up, we checked trunk angles when participants grabbed the box (i.e., when they switched from lowering to straightening their body) and at the beginning of a new lift (i.e., when they switched from straightening to lowering their body with no box in hand). With the exosuit, participants bent their trunk farther to grab the box (e.g., in first minute: median 85.2° from vertical with exosuit, 79.8° without),

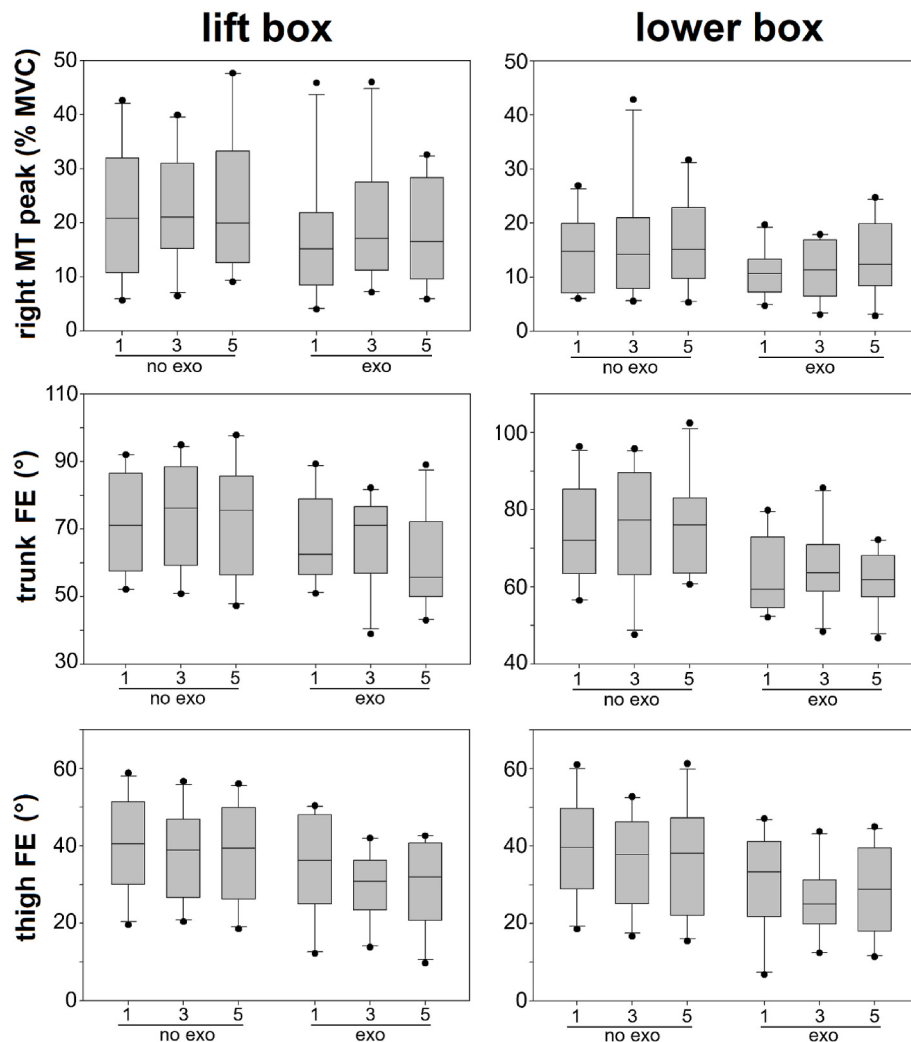


Fig. 6. Session 2: Peak right middle trapezius (MT) electromyogram (top), trunk flexion/extension (FE) range of motion (middle), and thigh FE range of motion (bottom) when lifting (left) and lowering (right) a box. The six boxes in each plot indicate the value after the first, third and fifth minute without the exosuit as well as after the first, third and fifth minute with the exosuit. MVC = maximum voluntary contraction.

Table 1

Session 1: Self-reported ratings of how much effort it took to perform different tasks with the exosuit compared to doing them without the exosuit, presented as median (interquartile range). P-values indicate results of one-sample t-tests or one-sample signed rank tests comparing the ratings to zero.

Task	Rating	P-value
Lift dumbbell	1 (0–1)	.059
Lift 15-lb box	2 (1–3)	.003
Lift 30-lb box	2 (1–3)	<.001
Lower 15-lb box	1 (1–2)	.013
Lower 30-lb box	1 (0.5–2)	.002
Walk with 15-lb box	0 (–1–0)	.114
Lean 30°	1 (0–2)	<.001
Lean 60°	1.5 (1–3)	<.001
Overall after block 2	1.5 (1–2.5)	<.001
Overall after block 3	1 (1–2.5)	<.001

indicating that the exosuit encouraged lifting with the back rather than with the legs (i.e., stoop rather than squat). They also straightened less when beginning a new lift (e.g., in first minute: median 16.5° from vertical with exosuit, 11.5° without), which may be an energy conservation strategy.

Our subjective opinion for the lack of positive results is that the

LiftSuit does not appear to be flexible enough: as it is very stiff around the low back and hips, squatting motions are uncomfortable for wearers. Thus, wearers are more likely to lift with their back, leaning their hips back into the exosuit. Similar changes in lifting strategy were observed in our previous work (Goršič et al., 2020) and others' work (Koopman et al., 2020), and were emphasized as a possible confound in a recent review (Bär et al., 2021). Leaning into the exosuit provides some support and feels helpful for a single lift, leading to positive results in session 1. However, repetitive lifting in this way is taxing for the ES (leading to no EMG decrease) and uncomfortable. This is also supported by BPD results, where discomfort commonly occurs in regions 8–10 (thighs and buttocks); participants who reported discomfort elsewhere were probably able to adjust the exosuit to be comfortable around the hips at the cost of tightness elsewhere. Since the exosuit is already very adjustable to individual body dimensions, this issue would likely need to be addressed by providing more flexible (rather than stiff) support components.

4.3. Study limitations

As perhaps the main weakness of the study, our protocol did not strictly prescribe task completion strategies. For example, when lifting a box, participants could choose to lift with their back or with their legs, and could hold the box anywhere relative to the body. This was

Table 2

Session 1: Effect size (Cohen's *d*) and significance (p-values) for contrasts on kinematic outcome variables in different tasks. Each contrast compares the exosuit block to the mean of both no-exosuit blocks. Bolded values indicate significant contrasts after the Benjamini-Hochberg procedure. FE = flexion/extension, LF = lateral flexion, LR = left-right rotation.

Task	Trunk FE		Trunk LF		Trunk LR		Thigh FE	
	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>
Lift dumbbell	-.145	.367	.619	.004	-.067	.717	-.378	.030
Lift 15-lb box	-.062	.669	.443	.123	.317	.266	-.204	.108
Lift 30-lb box	.020	.853	.226	.386	-.095	.704	-.213	.009
Lower 15-lb box	.043	.687	.628	.075	0.017	.644	-.140	.176
Lower 30-lb box	.032	.780	.247	.405	-.079	.762	-.245	<.001
Walk with box	.213	.272	.451	.056	-.061	.687	.478	.010

Table 3

Session 1: Effect size (Cohen's *d*) and significance (p-values) for linear contrasts on different rectus abdominis electromyography outcome variables in different tasks. Each contrast compares the exosuit block to the mean of both no-exosuit blocks. There were no significant contrasts.

Task	Left mean		Left peak		Right mean		Right peak	
	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>
Lift dumbbell	.078	.565	.446	.104	.308	.145	.492	.132
Lift 15-lb box	-.031	.671	.169	.267	.131	.335	.216	.403
Lift 30-lb box	.017	.867	.116	.375	.267	.138	.602	.099
Lower 15-lb box	.131	.132	.444	.183	.252	.072	.222	.395
Lower 30-lb box	-.062	.573	.111	.425	.048	.723	.237	.390
Walk with box	.030	.655	.060	.531	.007	.943	-.088	.548
Lean 30°	.026	.695	–	–	-.093	.486	–	–
Lean 60°	-.042	.788	–	–	.009	.944	–	–

originally permitted so that we could observe possible spontaneous changes in movement strategy due to the exosuit, which have been observed in prior work (Goršič et al., 2020; Koopman et al., 2020). However, we acknowledge that this introduces uncontrolled variability and is likely suboptimal. In the future, we will explore study protocols where different strategies are explicitly prescribed. For example, we

may follow the protocol of Luger et al. (2021), who asked participants to perform lifts with both stooping and squatting postures. Alternatively, we may follow the protocol of Kozinc et al. (2020), who proposed a “standard” test battery for trunk exoskeletons.

Additionally, our EMG results do indicate effects that may become significant with a larger sample – for example, the multiple cases with *d* = −0.2 for ES in Table 4 and the multiple cases with *d* > 0.4 for RA in Table 3. Thus, some actual effects of the exosuit may have been missed due to confounding factors such as sweat and fatigue. At the same time, our sample is comparable to other studies in the field: two 2021 reviews found 6–18 participants in most back exoskeleton studies (Kermavannar et al., 2021; Bär et al., 2021). Therefore, any missed effects of the exosuit are likely relatively small and can still be estimated from effect size results. Specifically, the exosuit may have small beneficial effects on ES EMG in session 1 (Table 4), but may actually increase RA EMG, as indicated by Cohen's *d* of up to .602 in Table 3. However, this RA EMG increase may not be practically very important – nearly all RA EMG results were below 10% MVC.

Finally, the −5 to +5 scale of perceived exosuit assistance is an ad-hoc scale that was used in our previous Apex work but not validated (Goršič et al., 2021) and thus has some weaknesses. For example, some participants had difficulty separating perceived exosuit assistance and comfort – in other words, they rated the exosuit as not providing assistance if it was uncomfortable, regardless of whether they felt assistive

Table 4

Session 1: Effect size (Cohen's *d*) and significance (p-values) for contrasts on erector spinae electromyography outcome variables in different tasks. Each contrast compares the exosuit block to the mean of both no-exosuit blocks. Bolded values indicate significant contrasts after the Benjamini-Hochberg procedure.

Task	Left mean		Left peak		Right mean		Right peak	
	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>
Lift dumbbell	.029	.850	-.146	.371	-.095	.315	.015	.947
Lift 15-lb box	-.091	.663	-.213	.256	.068	.657	.058	.760
Lift 30-lb box	-.216	.128	-.434	.007	-.100	.444	-.445	.002
Lower 15-lb box	-.248	.420	-.005	.983	-.166	.035	-.008	.958
Lower 30-lb box	-.152	.091	-.431	.014	-.077	.260	-.213	.157
Walk with box	-.005	.981	-.228	.282	.098	.389	.002	.991
Lean 30°	-.214	.096	–	–	-.215	.110	–	–
Lean 60°	-.288	.100	–	–	-.206	.114	–	–

Table 5

Session 1: Effect size (Cohen's *d*) and significance (p-values) for contrasts on middle trapezius electromyography outcome variables in different tasks. Each contrast compares the exosuit block to the mean of both no-exosuit blocks. Bolded values indicate significant contrasts after the Benjamini-Hochberg procedure.

Task	Left mean		Left peak		Right mean		Right peak	
	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>	<i>d</i>	<i>p</i>
Lift dumbbell	-.262	.195	-.331	.151	-.012	.924	-.189	.332
Lift 15-lb box	-.537	.001	-.424	.001	-.412	.011	-.337	.022
Lift 30-lb box	-.287	.037	-.352	.060	-.294	.053	-.178	.334
Lower 15-lb box	-.462	.001	-.653	<.001	-.422	.009	-.547	.002
Lower 30-lb box	-.227	.077	-.543	.002	-.424	.003	-.509	.002
Walk with box	.306	.360	.081	.665	-.137	.349	-.199	.353
Lean 30°	-.677	.006	–	–	-.807	<.001	–	–
Lean 60°	-.587	.001	–	–	-.817	.002	–	–

Table 6

Session 2: Effect size (partial eta squared - η^2) and significance (p-values) for repeated-measures analyses of variance on different kinematic and electromyographic (EMG) outcome variables when lifting and when lowering the box. There are two main effects (exosuit, time) and one interaction effect (exosuit x time). RA = rectus abdominis, ES = erector spinae, MT = middle trapezius, FE ROM = flexion/extension range of motion. Bolded values indicate $p < 0.1$.

Outcome variable	Lift box						Lower box					
	Exosuit		Time		Interaction		Exosuit		Time		Interaction	
	η^2	p	η^2	p	η^2	p	η^2	p	η^2	p	η^2	p
RA: left mean	.106	.327	.121	.309	.002	.927	.069	.462	.169	.235	.021	.730
RA: left peak	.085	.385	.043	.626	.091	.416	.019	.706	.121	.342	.056	.573
RA: right mean	.091	.367	.175	.198	.060	.503	.101	.341	.102	.360	.044	.600
RA: right peak	.002	.898	.131	.278	.035	.646	.021	.673	.026	.693	.136	.270
ES: left mean	.071	.429	.321	.049	.025	.744	.004	.854	.076	.460	.102	.355
ES: left peak	.033	.594	.207	.127	.017	.743	.109	.321	.183	.175	.073	.461
ES: right mean	.143	.223	.226	.113	.116	.319	.028	.622	.014	.841	.221	.117
ES: right peak	.117	.303	.187	.163	.021	.768	.056	.485	.055	.522	.178	.181
MT: left mean	.116	.305	.337	.038	.069	.522	.018	.698	.024	.727	.004	.931
MT: left peak	.138	.260	.262	.069	.140	.258	.005	.837	.035	.693	.067	.520
MT: right mean	.238	.128	.390	.015	.056	.579	.175	.201	.030	.688	.016	.848
MT: right peak	.299	.082	.061	.504	.040	.658	.296	.084	.186	.166	.061	.557
Trunk FE ROM	.366	.049	.069	.495	.266	.068	.609	.005	.074	.482	.113	.333
Thigh FE ROM	.436	.027	.225	.121	.049	.600	.584	.006	.158	.219	.035	.701

forces generated by the exosuit. We do believe that the scale is still comparable between the two sessions of this study (since it was used by the same participants) and with the previous Apex study (since it was used by participants drawn from the same general pool and in similar circumstances). However, in the future, we may either validate the scale or use a different, more established scale.

5. Conclusion

In session 1, where each task was only done twice, the exosuit reduced MT EMG when lifting and lowering a 15-lb box and during both leans. It also reduced ES peak EMG when lifting and lowering a 30-lb box and during the 60-degree lean. We originally expected more consistent ES EMG reductions and no MT EMG reductions. We believe that the MT effect is due to the exosuit's elastic components being placed on the upper back, which is an uncommon choice in back support exoskeleton/exosuit design. Nonetheless, the exosuit was perceived as mildly to moderately helpful in session 1. Reductions in MT EMG were also observed in session 2, but there were no ES EMG reductions, and the exosuit was not considered helpful. Instead, it appeared to encourage wearers to lift with their back, which may be detrimental in the long term. Thus, while the LiftSuit does have some short-term benefits, its design does not appear optimal for long-term use.

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

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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References

- Alemi, M.M., Geissinger, J., Simon, A.A., Chang, S.E., Asbeck, A.T., 2019. A passive exoskeleton reduces peak and mean EMG during symmetric and asymmetric lifting. *J. Electromyogr. Kinesiol.* 47, 25–34.
- Amandels, S., het Eyndt, H.O., Daenen, L., Hermans, V., 2018. Introduction and testing of a passive exoskeleton in an industrial working environment. In: *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018)*, pp. 387–392.
- Auxivo, A.G., 2021. The LiftSuit [Online]. Available: <https://www.auxivo.com/liftsuit>. (Accessed 8 November 2021).
- Babić, J., et al., 2021. Challenges and solutions for application and wider adoption of wearable robots. *Wearable Technol.* 2, e14.
- Baltrusch, S.J., van Dieën, J.H., Bruijn, S.M., Koopman, A.S., van Bennekom, C.A.M., Houdijk, H., 2019. The effect of a passive trunk exoskeleton on metabolic costs during lifting and walking. *Ergonomics* 62 (7), 903–916.
- Baltrusch, S.J., et al., 2020. SPEXOR passive spinal exoskeleton decreases metabolic cost during symmetric repetitive lifting. *Eur. J. Appl. Physiol.* 120, 401–412.
- Bär, M., Steinhilber, B., Rieger, M.A., Luger, T., 2021. The influence of using exoskeletons during occupational tasks on acute physical stress and strain compared to no exoskeleton – a systematic review and meta-analysis. *Appl. Ergon.* 94, 103385.
- Benjamini, Y., Hochberg, Y., 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *J. R. Stat. Soc. Ser. B* 57 (1), 289–300.
- Corlett, E.N., Bishop, R.P., 1976. A technique for measuring postural discomfort. *Ergonomics* 9, 175–182.
- Day, M.L., McGuigan, M.R., Brice, G., Foster, C., 2004. Monitoring exercise intensity during resistance training using the session RPE scale. *J. Strength Condit. Res.* 18 (2), 353–358.
- Goršič, M., Regmi, Y., Johnson, A.P., Dai, B., Novak, D., 2020. A pilot study of varying thoracic and abdominal compression in a reconfigurable trunk exoskeleton during different activities. *IEEE Trans. Biomed. Eng.* 67 (6), 1585–1594.
- Goršič, M., Song, Y., Dai, B., Novak, D., 2021. Evaluation of the HeroWear Apex back-assist exosuit during multiple brief tasks. *J. Biomech.* 126, 110620.
- Graham, J.E., Karmarkar, A.M., Ottenbacher, K.J., 2012. Small sample research designs for evidence-based rehabilitation: issues and methods. *Arch. Phys. Med. Rehabil.* 9 (8 Suppl), S111–S116.
- Hermens, H.J., et al., 1999. European Recommendations for Surface Electromyography: Results of the SENIAM Project. Roessingh Research and Development, Enschede, Netherlands.
- Huysamen, K., Bosch, T., de Looze, M., Stadler, K.S., Graf, E., O'Sullivan, L.W., 2018a. Evaluation of a passive exoskeleton for static upper limb activities. *Appl. Ergon.* 70, 148–155.
- Huysamen, K., de Looze, M., Bosch, T., Ortiz, J., Toxiri, S., O'Sullivan, L.W., 2018b. Assessment of an active industrial exoskeleton to aid dynamic lifting and lowering manual handling tasks. *Appl. Ergon.* 68, 125–131.
- James, S.L., et al., 2018. Global, regional, and national incidence, prevalence, and years lived with disability for 354 diseases and injuries for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *Lancet* 392, 1789–1858.
- Kermavnar, T., de Vries, A.W., de Looze, M.P., O'Sullivan, L.W., 2021. Effects of industrial back-support exoskeletons on body loading and user experience: an updated systematic review. *Ergonomics* 64 (6), 685–711.
- Koopman, A.S., Kingma, I., de Looze, M.P., van Dieën, J.H., 2020. Effects of a passive back exoskeleton on the mechanical loading of the low-back during symmetric lifting. *J. Biomech.* 102, 109486.

- Koopman, A.S., et al., 2019. The effect of control strategies for an active back-support exoskeleton on spine loading and kinematics during lifting. *J. Biomech.* 91, 14–22.
- Koopman, A.S., et al., 2020. Biomechanical evaluation of a new passive back support exoskeleton. *J. Biomech.* 105, 109795.
- Kozinc, Ž., Baltrusch, S., Houdijk, H., Šarabon, N., 2020. Reliability of a battery of tests for functional evaluation of trunk exoskeletons. *Appl. Ergon.* 86, 103117.
- Lamers, E.P., Yang, A.J., Zelik, K.E., 2018. Feasibility of a biomechanically-assistive garment to reduce low back loading during leaning and lifting. *IEEE Trans. Biomed. Eng.* 65 (8), 1674–1680.
- Lamers, E.P., Soltys, J.C., Scherpereel, K.L., Yang, A.J., Zelik, K.E., 2020. Low-profile elastic exosuit reduces back muscle fatigue. *Sci. Rep.* 10, 15958.
- Luger, T., Bär, M., Seibt, R., Rimmele, P., Rieger, M.A., Steinhilber, B., 2021. 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. *Appl. Ergon.* 97, 103530.
- Madinei, S., Kim, S., Srinivasan, D., Nussbaum, M.A., 2021. Effects of back-support exoskeleton use on trunk neuromuscular control during repetitive lifting: a dynamical systems analysis. *J. Biomech.* 123, 110501.
- Park, H., Kim, S., Nussbaum, M.A., Srinivasan, D., 2022. Effects of using a whole-body powered exoskeleton during simulated occupational load-handling tasks: a pilot study. *Appl. Ergon.* 98, 103589.
- Poliero, T., et al., 2021. Versatile and non-versatile occupational back-support exoskeletons: a comparison in laboratory and field studies. *Wearable Technol.* 2, e12.
- Schmidt, K., et al., 2017. The Myosuit: Bi-articular anti-gravity exosuit that reduces hip extensor activity in sitting transfers. *Front. Neurobot.* 11, 57.
- Swain, C.T.V., Pan, F., Owen, P.J., Schmidt, H., Belavy, D.L., 2020. No consensus on causality of spine postures or physical exposure and low back pain: a systematic review of systematic reviews. *J. Biomech.* 102, 109312.
- Wu, G., Cavanagh, P.R., 1995. ISB recommendations for standardization in the reporting of kinematic data. *J. Biomech.* 28 (10), 1257–1261.
- Yandell, M.B., Wolfe, A.E., Marino, M.C., Harris, M.P., Zelik, K.E., 2020. Effect of a back-assist exosuit on logistics worker perceptions, acceptance and muscle activity. In: *International Symposium on Wearable Robotics (WeRob)*.
- Zelik, K.E., Nurse, C.A., Schall Jr., M.C., Seseke, R.F., Marino, M.C., Gallagher, S., 2022. An ergonomic assessment tool for evaluating the effect of back exoskeletons on injury risk. *Appl. Ergon.* 99, 103619.

Abbreviations

- BPD:** Body Part Discomfort Scale
EMG: electromyography
ES: erector spinae
MT: middle trapezius
MVC: maximum voluntary contraction
RA: rectus abdominis
RMANOVA: repeated-measures analysis of variance
ROM: range of motion
RPE: Rate of Perceived Exertion