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Effects of a Passive Back Support Exoskeleton when Lifting and Carrying Lumber Boards

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***Abstract*— Passive back support exoskeletons, which support the human trunk using elements like springs and elastic bands, have demonstrated positive results in laboratory-based studies, but have seen significantly less field testing. As an intermediate step between generic lab evaluations and field tests, we conducted a single-session lab evaluation of the HeroWear Apex exoskeleton with mockup construction tasks: 20 adult men (without extensive construction experience) lifted, carried and raised lumber boards (265 cm length, up to 18 kg total load). The exoskeleton significantly reduced mean erector spinae electromyograms, with effect sizes (Cohen's d) ranging from -0.2 to -0.55 – corresponding to reductions of 5-25% relative to no-exoskeleton electromyogram values. In asymmetric carrying tasks, the exoskeleton provided more assistance to the more heavily loaded erector spinae muscle. Additionally, in lifting tasks, the exoskeleton decreased trunk/hip flexion/extension range of motion and increased knee range of motion, indicating changes in lifting strategy. These results indicate potential exoskeleton benefits for lumber board carrying and will serve as the basis for further evaluations with workers in the field.**

***Clinical Relevance*— This study establishes that a passive back exoskeleton reduces erector spinae electromyograms by 5-25% when lifting and carrying lumber boards used in construction work.**

I. Introduction

In the past five years, passive back support exoskeletons have become a popular technology to support workers in jobs that involve repetitive manual material handling [1]–[3]. By physically supporting the human trunk using passive mechanical elements such as springs and elastic bands, such exoskeletons can reduce biomechanical loads on the lower back [4]–[9]. In the long term, such biomechanical load reduction may reduce risk of back injury and chronic low back pain commonly seen in jobs such as construction, agriculture and logistics [10], [11].

To date, most evaluation studies have examined passive back exoskeletons in generic laboratory-based tasks such as lifting a box and lifting dumbbells [5]–[9]. One study has even proposed a battery of generic tasks that could be used to evaluate all back exoskeletons [12]. However, there are significantly fewer evaluation studies involving tasks directly relevant for jobs such as construction, where workers typically carry more bulky, nonstandard items and lift to a variety of different heights. A study by Yandell et al. [13] evaluated logistics workers performing mockup work tasks in a laboratory using a back exoskeleton and found both reductions in back muscle electromyograms (EMG) and positive worker perceptions. Two other studies evaluated farmers [14] and automotive industry workers [15] using passive back exoskeletons at their workplaces and similarly found reductions in EMG as well as positive exoskeleton perceptions. Another study conducted in a hospital environment found positive exoskeleton perceptions but did not obtain objective measures [16]. However, a study by Amandels et al. [17] evaluating a back exoskeleton in a multi-workstation shop floor environment found increased EMG and discomfort with the exoskeleton, indicating negative results. A study by Motmans et al. [18] analyzed cheese order picking with a back exoskeleton and did find reductions in EMG, but the reductions were small and posture was not changed. Thus, the effects of passive back exoskeletons in work environments remain underexplored, with mixed results that likely depend on the specific work environment.

Our group is interested in the effects of back exoskeletons on construction workers. As an intermediate step between lab studies with generic tasks and field tests on construction sites, this paper presents an evaluation of a passive back exoskeleton in mockup construction tasks (lifting and carrying long lumber boards) in a lab environment, similarly to previous back exoskeleton work by Yandell et al. [13] and other studies with non-back exoskeletons [9]. While we plan to involve both novices (without extensive construction experience) and actual construction workers in the long term, the current paper presents only results with novices.

II. Materials and Methods

A. Exoskeleton and Sensors

The exoskeleton used for the study was the Apex (HeroWear, Nashville, TN), a passive back exoskeleton that weighs 1.5 kg and comprises an upper-body section (similar to a backpack with shoulder and chest straps), thigh sleeves, and two elastic bands along the back that connect the upper-body section to the thigh sleeves. A switch on the shoulder is used to engage or disengage exoskeleton assistance. If engaged, the elastic bands stretch whenever the wearer leans forward or crouches, generating assistive torques about the lumbar spine. The Apex was originally presented by Lamers et al. [6] and has been used in several studies [7], [13], [19].

EMG was measured from the left and right erector spinae (ES) and rectus abdominis (RA) using the Trigno Avanti wireless system (Delsys Inc., Boston, MA) at 1926 Hz. Electrode placements and maximum voluntary contraction

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(MVC) procedures were the same as in our previous Apex study [7].

Kinematics were measured using eight Vicon Bonita cameras (Vicon Motion Systems, UK) and reflective markers at 160 Hz. Markers were placed at the participant's left and right acromioclavicular joints, elbows, wrists, greater trochanters, lateral knees, lateral malleoli, toes, and heels. Markers were also placed on the lumber boards manipulated by the participant (see Study Protocol section).

B. Participants

Twenty adult men with no history of chronic back pain or back injury participated in the study. Thirteen had no experience in construction or similar manual materials jobs while the other 7 reported between 30 and 800 hours of such experience. All 20 were right-handed per self-report. They were 26.8 ± 4.6 (mean ± SD) years old, 1.75 ± 0.07 m tall, and weighed 76.1 ± 12.0 kg.

C. Study Protocol

The study was approved by the University of Wyoming Institutional Review Board (protocol # 20220429YS03302). All participants gave written informed consent and took part in a session in the University of Wyoming Biomechanics Lab.

All participants wore spandex shirts and pants as well as gloves and steel-toe boots. The exoskeleton was first sized to each participant following the manufacturer's instructions. Assistance was engaged, and participants were allowed to practice using the exoskeleton for lifting and carrying objects around the lab until they felt reasonably familiar with the device (usually ~5 minutes). Sensors were then applied and MVC tests were performed for the ES and RA as in our previous study [7].

Data collection was done in three blocks: first without the exoskeleton, then with the engaged exoskeleton, then without the exoskeleton again. A similar study design was used in previous exoskeleton work [7], [8], [19]. Within each block, participants performed five tasks in random order:

- Carrying one lumber board (mass 6 kg, dimensions 265 x 14 x 4 cm) over a distance of 9 m at a self-selected speed. The board was held at waist level on the participant's right side, with the right hand below the board.
- Carrying three lumber boards (total mass 18 kg, same size as above) over a distance of 9 m at a self-selected speed. They were similarly held at waist level on the participant's right side.
- Lifting one lumber board (same size & mass as above) from the ground to waist level, holding it there for 2 seconds, and lowering it back to the ground. Participants gripped the middle of the board and held it horizontally for the duration. A photo of this task is shown in Fig. 1.
- Lifting and lowering three lumber boards (same as previous task, but with 3 boards).
- Raising three lumber boards: The participant held the boards (total mass 18 kg, same size as above) at one end and then raised that end above their head, with the other end of the boards staying on the ground. A photo of this task is shown in Fig. 2.

Fig. 1. Participant lifting one lumber board.

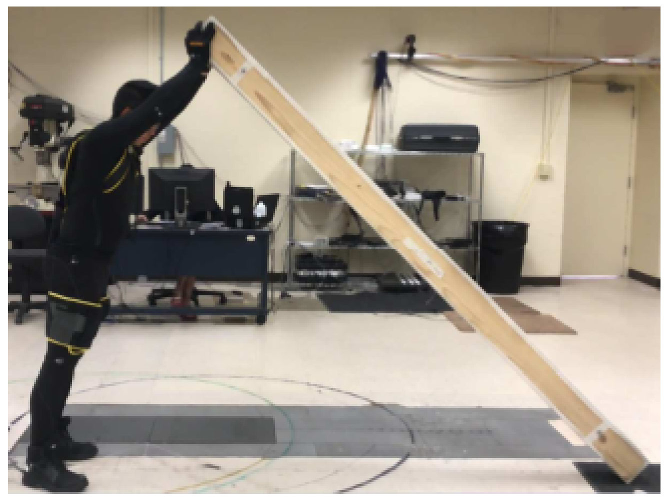

Fig. 2. Participant raising three lumber boards.

Three consecutive trials of each task were done within each block: one practice trial and two trials where measurements were taken. Exoskeleton and sensor adjustments were made during the blocks as needed to address comfort issues and sensor detachment.

D. Data Analysis

The blocks were segmented into individual task trials. For carrying tasks, a single gait cycle midway across the room was analyzed. For raising tasks, a segment was defined as being from the initiation of motion of the lumber boards to the maximal height of the boards. For the lifting and lowering tasks, a lifting segment was defined as being from the initiation of upward motion of the lumber boards to the maximal height of the boards while a lowering segment was defined as being from the initiation of downward motion of the boards to the minimal height of the boards. Thus, from the perspective of data analysis, there were 7 tasks: carrying 1 board, carrying 3 boards, lifting 1 board, lifting 3 boards, lowering 1 board, lowering 3 boards, and raising 3 boards.

EMG in each trial was first filtered with a 20-450 4th-order Butterworth bandpass filter, then rectified and filtered with a 10-Hz 4th-order Butterworth lowpass filter. This produced the linear envelope, which was then normalized by the maximum value obtained during that muscle's MVC tests. For each task segment, mean values of each muscle's EMG (expressed as percentages of MVC value) were used as outcome variables.

For kinematics, trunk ranges of motion (ROM) in flexion/extension, left/right bending, and left-right rotation as well as hip flexion ROM (between trunk and thigh vectors) and knee flexion ROM were calculated from marker data via the same technique used in our previous exoskeleton work [7]. For each task segment, these five ROM (3x trunk, hip, knee) were used as outcome variables.

Statistical analysis was done separately for each outcome variable (EMG and kinematics) and task. For each variable and task, a one-way repeated-measures analysis of variance with Greenhouse-Geisser corrections was used to calculate the linear contrast comparing block 2 (exoskeleton) to blocks 1 and 3 (no exoskeleton). The contrast was compared to zero using a one-sample t-test to determine whether the difference between wearing and not wearing the exoskeleton was significant. For each contrast, the significance (two-tailored p-value) and effect size (Cohen's d) are reported.

III. Results

For RA EMG, all contrasts had $p > 0.3$, and RA results are thus not reported in detail. Contrasts for ES EMG are shown in Table 1, and an example of left ES EMG in three different tasks is shown in Fig. 3. Contrasts for the three trunk ROM are shown in Table 2 while contrasts for hip and knee ROM are shown in Table 3. An example of hip ROM In three different tasks is shown in Fig. 4.

TABLE I. Erector spinae electromyogram results: Significance (p) and effect size (Cohen's d) for linear contrasts in different tasks for the left and right erector muscle.

Task	Left muscle		Right muscle	
	p	*d*	*p*	*d*
carry 1 board	.004	-.412	.921	.015
carry 3 boards	.003	-.415	.425	.126
lift 1 board	.003	-.372	.001	-.481
lift 3 boards	.097	-.208	.073	-.271
lower 1 board	.008	-.531	.002	-.500
lower 3 boards	< .001	-.560	.005	-.451
raise 3 boards	.018	-.234	.381	-.128

TABLE II. Trunk range of motion results: Significance (p) and effect size (Cohen's d) for linear contrasts in different tasks for three dimensions: flexion/extension, lateral bend, and left-right rotation.

Task	Flexion / extension		Lateral bend		Left-right rotation	
	p	*d*	*p*	*d*	*p*	*d*
carry 1 board	.472	.224	<.001	.62	.324	-.194
carry 3 boards	.165	.416	.011	.438	.021	.431
lift 1 board	.016	-.304	.464	.116	.047	-.435
lift 3 boards	.003	-.430	.071	-.411	.001	-.567
lower 1 board	.001	-.374	.568	-.101	.386	-.170
lower 3 boards	.002	-.391	.376	-.175	.003	-.463
raise 3 boards	.005	-.448	.587	.148	.421	.162

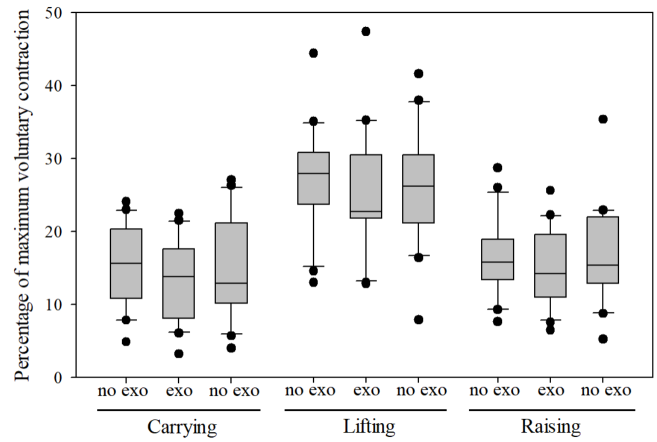

Fig. 3. Left erector spinae electromyogram in three different tasks: carrying 3 boards, lifting 3 boards, and raising 3 boards. For each task, subplots indicate the three blocks: first without the exoskeleton, then with the exoskeleton, then without the exoskeleton again.

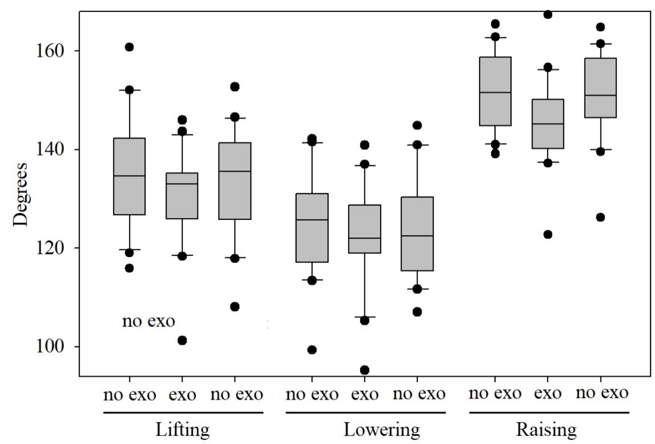

Fig. 4. Hip range of motion in three different tasks: lifting, lowering and raising 3 boards. For each task, subplots indicate the three blocks: first without the exoskeleton, then with the exoskeleton, then without the exoskeleton again.

TABLE III. Hip and knee range of motion results: Significance (p) and effect size (Cohen's d) for linear contrasts in different tasks for the hip and knee.

Task	Hip range of motion		Knee range of motion	
	p	*d*	*p*	*d*
carry 1 board	< .001	-.582	.038	-.260
carry 3 boards	< .001	-.433	.476	-.084
lift 1 board	.063	-.265	.112	.181
lift 3 boards	.032	-.344	.027	.271
lower 1 board	< .001	-.517	.094	.177
lower 3 boards	.140	-.191	.006	.361
raise 3 boards	< .001	-.748	.476	.109

IV. Discussion

A. Electromyography

The exoskeleton reduced left ES EMG in all tasks, with effect sizes ranging from -0.2 (small) to -.0.56 (medium). Right ES EMG was also reduced in lifting and lowering tasks but notably not in the carrying tasks. We had originally not expected reductions in carrying tasks at all, as our previous study found no benefit of the Apex while carrying a box [7].

Asymmetric effects of the exoskeleton in carrying tasks can be explained by the fact that participants were all right-handed and carried the load on the right side of the body, resulting in a heavier load on the left ES than the right ES and consequently more potential for the exoskeleton to reduce load on the left ES. This can also be seen in a comparison of left and right ES EMG levels. For example, when carrying 3 boards, left ES EMG is approximately 15% of MVC value without the exoskeleton and 13% with the exoskeleton while right ES EMG is approximately 8% of MVC value both with and without the exoskeleton. This difference between sides is much smaller in the lifting tasks, which are more symmetric. For example, when lifting 3 boards, left ES EMG is approximately 27% of MVC value without the exoskeleton and 25% with it while right ES EMG is approximately 29% of MVC value without the exoskeleton and 26% with it.

Overall, the mean reduction in left ES EMG by the Apex exoskeleton ranges from about 5% of the no-exoskeleton value (when lifting 3 boards) to about 25% of the no-exoskeleton value (when lowering 1 board). For the right ES EMG, if carrying tasks are excluded, reductions similarly range from about 5% (raising 3 boards) to about 23% (lowering 1 board). This is in line with previous Apex results in more "generic" tasks such as lifting boxes [6], [7] – for example, Lamers et al. reported a 14-16% reduction during cycles of lifting and lowering boxes; while they did not separately analyze lifting and lowering segments, the reduction appeared to be greater during lowering segments [6].

Since these are short-term results, it remains to be seen whether the decrease in ES EMG would have a practical effect. Lamers et al. [6] posited that even small reductions may have meaningful cumulative effects over the course of a workday, and the exoskeleton is not very expensive or uncomfortable, so it does not appear to have significant downsides. On the other hand, Motmans et al. [18] also found EMG reductions of about 10%, but described this as a "rather small benefit" that should not be the only measure taken to relieve workers. We plan to explore this further in the future by first recruiting actual construction workers (who may have different reactions to the exoskeleton), then conducting longer-term evaluations.

B. *Kinematics*

The exoskeleton reduced trunk flexion/extension ROM in lifting, lowering and raising tasks, with effect sizes ranging from -0.3 to -0.45. It also increased trunk lateral bend ROM in carrying tasks and reduced trunk left/right rotation ROM in most lifting and lowering tasks. Furthermore, it reduced hip ROM in all tasks (with effect sizes ranging from -0.2 (small) to -0.75 (large)), decreased knee ROM in carrying tasks, and increased knee ROM in lifting and lowering tasks.

Increased knee ROM and reduced trunk and hip ROM in lifting and lowering tasks are likely beneficial. The result implies that participants lifted more with their legs (increased knee ROM) than with their back (reduced trunk/hip ROM), which is a more ergonomic lifting strategy [20]. Our previous Apex study did not find significant ROM changes [7], but used more controlled (less realistic) tasks and did not investigate hip or knee ROM. In the future, we will conduct a more detailed kinematics analysis with workers to identify possible postural changes.

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