Upper extremity exoskeletons in construction, a field-based study

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***Abstract*— The construction trade requires repetitive, physically demanding manual tasks which can over time pose severe risks for work-related musculoskeletal disorders (WMSDs) [1]. Exoskeletons and exosuits (collectively called "EXOs" in this work) have substantial potential to protect workers and to increase worker productivity by reducing exertion and fatigue. Despite these potential benefits, EXOs are uncommon in the construction industry. We present preliminary results from a pilot study investigating the knowledge gaps and barriers to EXO adoption.**

The overall objective of this work is to establish a foundational understanding of how EXOs can transform the future of construction trade work. The described work focuses on industry collaboration and field-based kinematic evaluation of three subjects performing a real-world construction task, removing wooden blocks from a steel-frame wall. We demonstrate the range of motion of the upper extremities of the subjects performing the task unassisted, followed by performing the task wearing two upper-extremity EXOs. This work is a presented in parallel with our separate study (evaluating the effects of a lower back EXO while dumping a gondola of refuse) also presented at this workshop. Our preliminary findings build a foundation of understanding of EXO-enabled construction tasks. This will foster EXO adoption and yield benefits including but not limited to improving the productivity of construction trades, reducing the risks of WMSDs and injuries of trade workers, broadening the workforce participation in construction trades, and extending the career life expectancy of existing trade workers.

I. Introduction

Since the industrial revolution (and arguably long before that), tremendous effort has been made to evaluate work and work tasks, and to present possible improvements for the worker, their productivity, and for the organization as a whole. Ranging from new machinery, to formation of unions, to the widespread incorporation of Personal Protective Equipment (PPE), there have been widespread efforts to make the worker safer, more comfortable, and more productive. Through all of these efforts (and many non-industrial efforts), we have gained great understanding of occupational biomechanics [1], industrial ergonomics [2]–[4], anthropometry[5], [6], and workplace tasks such as symmetric [7] and general lifting [8] in both industrial and general tasks. Gaining this level of understanding took countless studies over many years, yet our knowledge is incomplete, and workplace musculoskeletal injuries remain the second most common cause of absenteeism after the common cold. There is such a broad range of workers (anthropometry, strength, age), situation (work conditions, survivor bias, external stressors) and tasks (myriad industries requiring countless tasks) that a comprehensive evaluation of industrial work remains essentially impossible. Adding exoskeletons to these work scenarios holds a great deal of promise but makes the problem even more challenging.

Many administrative and engineering solutions have been implemented to reduce workplace injury with varying levels of success. Safety and assistive devices such as overhead supported lifts for tools and packages have been installed in industrial settings such as automobile assembly plants. Box lifts and conveyors are widespread in material handling locations such as order fulfillment centers and delivery warehouses such as the US postal service. These devices, often rigidly bolted to the floor of a material handling center or suspended from above in a manufacturing plant, have dramatically reduced industrial injuries [9], [10]. In unstructured environments, such as construction sites, these rigidly mounted devices are limited to areas around work vehicles. For most job tasks, often high in the air, remote, or requiring high mobility, these assist devices remain largely impractical.

Exoskeletons have been developed over many years for many applications [11]–[13], including several by our team [14]–[17]. Since Ralph Mosher introduced the Hardiman at General Electric Research in 1968, (and long before that in the entertainment/science fiction domain) there has been considerable interest in exoskeletons to assist humans with various assistance, augmentation, rehabilitation, and evaluation tasks [18], [19]. Exoskeletons have been developed, in both passive (unpowered, relying on pulleys, springs, elastic straps for energy storage) and active (using stored energy such as batteries and motors or compressed gas and pneumatic actuators) forms, by academic groups for research and by the private sector as products. Many EXOs have been developed for medical applications (to evaluate or rehabilitate motion, correct gait, augment those with reduced ability). Another type of EXO, largely funded by the military, aims to reduce the metabolic cost of walking or reduce effort needed to carry heavy backpacks long distances. While members of our team have developed both types of EXOs, here, we do not cover medical or backpack-carrying devices,

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and instead focus on EXOs primarily used to assist able-bodied wearers in occupational tasks.

The construction industry, comprised of highly variable tasks in fast-changing environments, often in temporary/short-term jobsites do not lend themselves well to traditional automation devices such as overhead lift-assist, industrial robots, and conveyor systems. Thus, the construction trades rely largely on the strength and skill of able-bodied workers. It is our hypothesis that EXOs are better suited to assisting workers than traditional industrial automation tools. It is our long-term goal to study the tasks performed by construction tradesmen, and better understand the potential role that EXOs may play, including most appropriate tasks, potential for augmentation and injury reduction, and limitations of EXOs on the worksite.

II. Method

A. *Defining EXOs*

This work describes a task performed in three configurations: First unassisted, then wearing each of two EXOs (EXO 1: Hilti EXO-01, and EXO 2: Ekso Evo). Both EXOs are passive shoulder exoskeletons as shown in Figure 1. For this study, passive EXOs were selected (vs. active EXOs), as they are less complex, require no charging/charge monitoring, and several models are now commercially available [20]. Many EXOs have been developed in laboratory settings. These devices are often faced with user complaints including poor fit, chafing, uncomfortable contact stress from high assistive force, and little perceived assistance [21]–[23]. Further, in the construction trades, any device which limits worker speed or range of motion could be seen as reducing productivity, and may face an insurmountable barrier to acceptance [24], [25]. The two EXOs selected for this work have undergone extensive evaluation and testing for ergonomics, fit, and comfort during the development process from laboratory prototypes to commercial systems, giving them greater promise for user acceptance.

B. *Defining the Task*

Often, EXO evaluation studies focus on an EXO's ability to reduce muscle activation level (as measured via change in electromyographic data), reduce metabolic cost (as measured via change in oxygen consumption), and increase overall satisfaction (as measured via survey responses). These changes are generally evaluated on subjects wearing EXOs while performing tasks in controlled laboratory environments [26], [27]. To perform consistent evaluations, tasks are often reduced and experimentally controlled, such as maintaining specific postures or repeated lifting and lowering of a package in the sagittal plane. Such tasks are generally designed to isolate parameters (e.g., activation level of specific muscles in the back, shoulder, etc.), rather than to emulate real-world construction tasks. While these simulations are valuable for initial explorations of prototype EXO effectiveness, real-world demonstrations of effectiveness are necessary if the broader industry is to adopt EXOs on the worksite. Previous evaluations have found that EXOs are quite effective in reducing activation levels in specific targeted muscles during highly structured predefined tasks. However, when evaluating the effects of an exoskeleton on muscles which it was NOT designed to assist, one study showed an increase of mean and peak muscle activation in most cases [28]. Thus careful analysis of the EXOs in real-world tasks, and the overall effectiveness of the EXOs is critical.

C. *Experimental Procedure*

We partnered with a prominent local construction contractor to evaluate workers as they performed typical construction tasks. Worker motion data was collected in the unassisted case as well as while wearing each of the two EXOs shown in Figure 1. Workers installed and later removed wooden blocks from a metal support structure. For this experiment, we analyzed the block removal operation to investigate the highly non-neutral postures required to remove screws in various locations in the framework. This task required working at or above shoulder height, supporting a wooden block (50 mm x 150 mm x 400 mm, mass of 910 gram) in one hand and a power screwdriver in the other. After removing four screws holding the block in place, the block is removed from inside the sheet-metal studs and placed on a pile of blocks.

Three workers (male, age 25 to 61 with 4-35 years in their current jobs) participated in the task. Each worker initially performed their task in an unassisted state (no EXO). To reconstruct full-body kinematics, video was recorded through the duration of the experiment. Additionally, subjects performed all tasks while wearing a suite of movement sensors (XSens MVN Awinda). Each subject removed 18 blocks over

Figure 1. The two passive shoulder exoskeleton systems, and evaluation of the block removal task. A. Hilti EXO-01 (left) and Ekso Evo (right). B Still image from video data of a worker performing the block removal task (left), and a still from motion capture data from the sensor suit (right).

roughly 15 minutes without EXO. Next, the subject donned the first EXO (still wearing the suite of motion sensors) and installed then removed an additional 18 blocks. Finally, the worker switched to the second EXO and installed then removed an additional 18 blocks (still wearing the suite of motion sensors). All subjects completed a survey on comfort, pain, and perceived effectiveness of using EXOs.

III. Results

Results from the block removal tests by three subjects suggested changes in body kinematics from using the EXO versus performing the same task unassisted. The results are summarized with mean ± SD in Table 1. Shoulder flexion/extension and shoulder abduction/adduction are given as combined results for the three subjects. Flexion/extension data shows little change based on EXO use vs unassisted task performance, but shoulder abduction/adduction showed more difference between the three cases (unassisted, Hilti EXO-01, and Ekso Evo). The Ekso Evo showed the greatest difference in shoulder abduction/adduction of the three cases. In order to explore data for individual subjects, shoulder abduction/adduction data is shown in Figure 2 for left and right arms for each of the three subjects. Because the exo is providing a restoring force (assisting in attaining elevated shoulder postures with reduced muscle activation), we can no longer say that increased shoulder flexion or abduction is necessarily an undesirable result. Note how in several cases (especially notable with subject 2), the most common posture (highest probability density) is "shifted" toward non-neutral. That may simply be the EXO restoring force causing an at-rest shoulder posture to be slightly abducted.

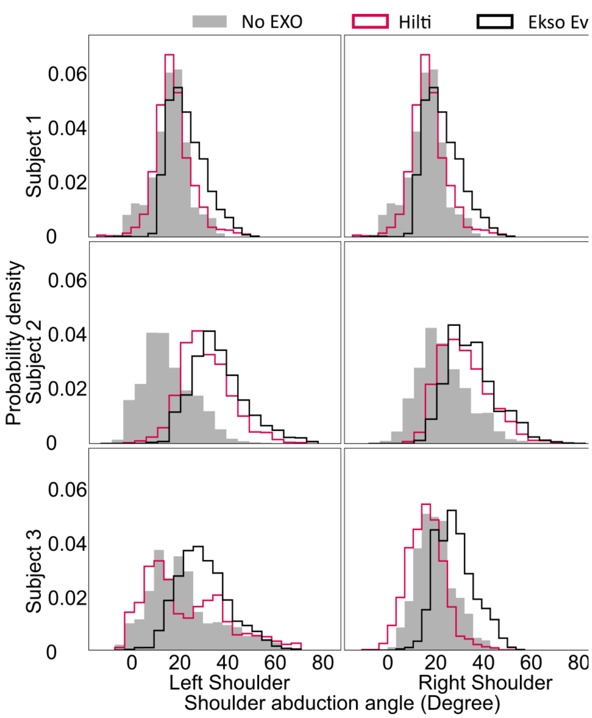

Figure 2. Results for 3 subjects, shoulder abduction (adduction shown as negative) during block removal task. Comparing unassisted vs. two EXOs. Both EXOs (and especially Ekso Evo increased abduction angle through most of task duration. Fraction of task duration recorded as probability density. For all curves, Overall probability (area under curve) equals one.

TABLE I. Range of motion, Flexion/Extension

	Condition	Shoulder Flexion/Extension		
		Mean± S.D.	***IQR (25-75%)***	***ROM (5-95%)***
Left	No EXO	51.1 ± 1.1	52 ± 3	92.7 ± 0.9
	Hilti EXO-01	45 ± 6	45 ± 3	91 ± 8
	Ekso Evo	48 ± 7	47 ± 10	90 ± 25
Right	No EXO	42 ± 6	61 ± 13	103 ± 3
	Hilti EXO-01	37 ± 4	47 ± 12	90 ± 11
	Ekso Evo	41 ± 15	46 ± 5	87 ± 12

TABLE II. Range of motion, Abduction/Adduction

	Condition	Shoulder Abduction/Adduction		
		Mean± S.D.	***IQR (25-75%)***	***ROM (5-95%)***
Left	No EXO	17 ± 4	15.5 ± 1.4	42 ± 8
	Hilti EXO-01	24 ± 6	19 ± 6	44 ± 11
	Ekso Evo	33 ± 3	17 ± 5	39 ± 3
Right	No EXO	20 ± 4	11 ± 3	30 ± 5
	Hilti EXO-01	22 ± 9	11 ± 3	28 ± 6
	Ekso Evo	29 ± 6	11.8 ± 1.2	29 ± 5

IV. Discussion

The critical overall finding is that results from both exoskeletons suggest systematic changes in body kinematics during the construction tasks tested. Data in Figure 2 demonstrates that not all subjects changed their kinematics equally. This phenomenon of responders and non-responders is common in human-subjects research, including with exoskeletons in laboratory tests; it nevertheless impedes us from drawing consistent conclusions. Issues such as discomfort or imperfect fit could cause certain individuals to reject the available assistance or fight against it. Certain devices may be inappropriate for these individuals, or they might just take more time to adapt [29].

During the block removal task, the major finding was that both the Hilti EXO-01 and Ekso Evo exoskeletons both led to a reduced 5-95% range of motion in shoulder flexion/extension on the right arm. It is interesting to note that the effect appears unilateral. While the EXO is symmetrical in its assisting force, the task itself is not symmetrical, and so certain motions might not happen on both arms. The change in probability density (particularly in abduction/adduction) is more pronounced with the Ekso Evo than for the Hilti EXO-01. This finding offers the opportunity to contrast the two designs. One notable difference is that the support columns along the back of these exoskeletons are attached in very different ways. On the Ekso Evo, they are mounted rigidly to the waist belt at a relatively medial location, whereas on the Hilti EXO-01 they are mounted to a free-moving ball joint on the belt at a relatively lateral location. It could be that the movement or lack of movement in these uprights could impede the motion more in the Ekso Evo. Alternatively, the Ekso Evo has a multi-link folding mechanism concealed inside the textile pouch along the upright; this could restrict movement.

Or, it could be that the shoulder joint itself could produce torque in a way that pushes the arm into different directions, even if it does not actually restrict movement. One observation about the task itself is that overall hand height is largely dictated by shoulder flexion; thus, shoulder flexion/extension may be less affected by the use of an EXO and more affected by task design. Given the various possible reasons for the observed behavioral change in angles and range, further investigation of the mechanisms of the two exoskeletons is needed.

Shoulder abduction/adduction results are also interesting. The main finding is that the Ekso Evo caused an increase in the mean shoulder abduction angle, in this case bilaterally. The users' experience was that the spring force tended to lift the arms away from neutral into abduction even when the user had no specific intention to do so. Perhaps this considerable increase in shoulder abduction is an indication that the compensating force of the EXOs allows subjects to more comfortably sustain non-neutral postures during tasks.

A secondary finding is that the Hilti EXO-01 may reduce the shoulder abduction 5-95% range of motion. These results provide encouraging preliminary data, motivating us to continue our investigations. Future testing can include additional sensors such as electromyography (EMG) sensors to sense muscle activation, instrumented insoles to record gait and stance variations, and perhaps even VO2 measurements to record metabolic cost of performing the tasks.

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