Exoskeletons in construction and their role in the Future of Work*

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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 four subjects performing a real-world construction task, namely dumping a gondola of refuse into a bin. 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

The context for our research is the construction industry, specifically the occupation categories within Construction Trades Workers ("47-2000"), with a focus on "47-2061.00 - Construction Laborers", "47-2031.00 - Carpenter", "47-2111.00 - Electricians", "47-2152.00 - Plumber, Pipefitter, and Steamfitter", and "47-2171.00 - Reinforcing Iron and Rebar Workers". These trades represent around 2.76 million workers under the occupation category of Construction and Extraction ("47-0000") [1]. Workers in these trades are typically required to perform physically demanding job tasks, such as digging holes or trenches, loading/unloading materials, removing debris and garbage, installing doors and windows, building frameworks, installing plumbing or piping, etc. These common tasks require sustained and repeated extreme postures (kneeling, crouching, stooping), which exposes them to a severe risk for WMSDs resulting in occupational injuries and illnesses [2]. According to the reports from the Bureau of Labor Statistics (BLS), the average injury and illness incidence rate in 2011-2018 reached up to 50.7 cases per 10,000 full-time construction workers [3]. This statistic is a conservative estimate since it excludes unreported cases and incidents not resulting in loss of working days.

On the other hand, although the trades workers primarily do physical work, they continually solve unique challenges while performing highly varying tasks in dynamic, unstructured, and unpredictable work environments. As a result, much of their work has a low potential for automation and is infeasible to be replaced entirely by robots [4]. In this regard, EXO technology shows great promise for making construction tasks more efficient, safer, and accessible to a broader set of workers.

The benefits envisioned with EXO-enabled construction work are manyfold. First, it can extend the career span of existing midcareer tradespeople, protecting them from potential WMSDs and/or acute injuries resulting in loss of working days. Second, it can expand the skilled trades workforce by attracting candidates into the trades who may otherwise not consider such jobs due to their physically demanding nature. Women represent only about 2.5% of tradespeople [5], which could be greatly increased by the adoption of EXOs in trade jobs. Third, the performance gains achieved by EXO-enabled work can help increase productivity in the construction industry. Over the past two decades, global productivity has grown by 2.8% annually; the construction industry, however, has only grown by 1% [6]. The construction industry accounts for a significant portion of the economy and it is still booming. Growth of nearly 35% to $5.8 trillion worldwide by 2030 is anticipated despite the coronavirus pandemic, and the U.S. would contribute ~12% of that growth [7]. The construction industry faces an increasingly severe shortage of qualified workers against a rapidly increasing demand. 44% of construction firms reported that projects have taken longer than originally anticipated, and 43% reported that costs have been higher due to workforce shortages [8]. Also, many current skilled workers were asked to work more, increasing their risk of WMSDs, injury, and illness [9]. In a recent survey conducted by McKinsey & Company, 87% of the respondents believed that the shortage of skilled workers had a high impact on the construction industry, and almost 50% of respondents expected this to worsen over the next decade [10]. With the passing of the $1 Trillion Infrastructure Bill in 2021 [11], it has become imperative that we address the need for growing the trades workforce and improving industry productivity.

Although EXOs promise many significant benefits, their adoption currently in the construction industry is minimal,

*Research supported by the National Science Foundation.

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primarily due to a lack of understanding of how EXOs can transform construction tasks and the associated benefits and broader impacts. Our research based on field experiments at construction sites aims to address this critical knowledge gap, and thereby help improve EXO-worker partnership and promote EXO usage in construction.

II. Method

A. Defining EXOs

This work describes a task performed unassisted and assisted using a passive lower-back EXO (HeroWear, Apex, passive lower-back exosuit), more suited for the construction industry, compared with active EXOs [12]. Through these experiments, our aim was to gain insights into how EXOs impact the task and the worker and to develop a deeper understanding regarding incompatibility between construction task requirements versus EXO form factor and capabilities. Most existing EXOs rely on the fixed-axis rotation hinges for joints, which do not accurately mimic how worker limbs move in construction settings. As a result, the worker's mobility in an EXO does not reflect natural movement and has limited versatility. Both discomfort and limited range of motion can make some EXOs unappealing to workers for some tasks, and therefore pose a barrier to EXO use by construction trade workers [13, 14].

B. Defining the Task

Previous EXO evaluation studies in construction have focused primarily on EXO functionalities to reduce muscle fatigue, perceived exertion, and metabolic cost. They measured test subjects' oxygen consumption, muscle activities, etc., when subjects wear EXOs and perform simple tasks (e.g., static holding and lifting) in controlled laboratory environments (e.g., [15, 16]). In these studies, test subjects are typically not professional workers with years of working experience, and the test period is short. Therefore, the process of executing construction tasks and the postures assumed during these tasks are not representative of the real workplace. Field-based evidence is critical to support the safe adoption and use of EXOs in practice, as it provides an understanding of EXOs' true effectiveness, practicality, safety, and user acceptance [17, 18]. However, existing EXO field tests are limited to automotive assembly (e.g., [19 – 22]), manufacturing (e.g., [23]), warehousing (e.g., [24, 25]), and agriculture (e.g., [26, 27]) settings. Compared with these field test settings, construction workplaces are more cluttered, unstructured, and dynamic.

C. Experimental Procedure

We partnered with an industry-leading construction contractor to evaluate workers as they performed a typical construction task with and without an EXO. The task consisted of dumping a loaded gondola (wheeled cart) from an elevated platform into another cart. The loaded cart had a mass of 120 kg (265 lb), and the unloaded cart had a mass of 64kg (140 lb). This task required repetitive high-force operations on the lower back. This task is common on construction sites, as gondolas loaded with construction refuse are dumped into trash receptacles throughout the construction process.

Figure 1. Worker wearing the Hero Wear Apex EXO (Left), pushing then dumping (middle), screen capture from video of motion capture (Right).

Four workers (male, age 25 to 61 with 4-35 years in their current jobs) participated in the task. Workers performed their tasks in an unassisted state (no EXO) and with an EXO for assistance (Fig. 1). To reconstruct full-body kinematics, the test subject donned a suite of wearable movement sensors (XSens MVN Awinda). Videos were also recorded. For the dumping task, each subject performed ten full cycles over roughly 15 minutes without EXO. Next, the subject donned the EXO and performed an additional ten cycles. All subjects were requested to complete a survey on comfort, pain, and perceived effectiveness of using EXOs.

III. Results

Results from these tests suggested changes in body kinematics from using the EXO while performing the dumping task versus performing the same task without EXO assistance. The results are summarized with mean ± SD in Table 1. Pelvic forward inclination data for four subjects is shown in Figure 2. Angle is presented as pelvis deviation from vertical (0°), viewed in the sagittal plane. Forward bending is positive and leaning backwards is negative. These are roughly equivalent to trunk flexion and extension if the legs were constraint to a neutral posture. While the mean pelvic angle during the dumping process showed little change (19° for both Herowear and no Exo cases), standard deviation was greatly reduced for workers wearing the Herowear EXO (8° vs 4°). Inner quartile range (IQR) and 5-95% range of motion (ROM) data similarly show sizeable drops in standard deviation while workers wore the Herowear EXO. This preliminary data suggests that wearing the EXO may not reduce the mean trunk incline angle. However, the preliminary results suggest that wearing the Herowear EXO may reduce the occurrence of very extreme postures during the dumping task.

Further, the EXO enabled three of four subjects to reduce their mean forward trunk lean angle during the dumping activity (Fig. 2). Reduced forward trunk lean may indicate reduced exertion of the hip and lower back muscles, consistent with the EXO's intended effect. Because the EXO also provides a hip extension moment to assist the lift, the reduced exertion may be further compounded.

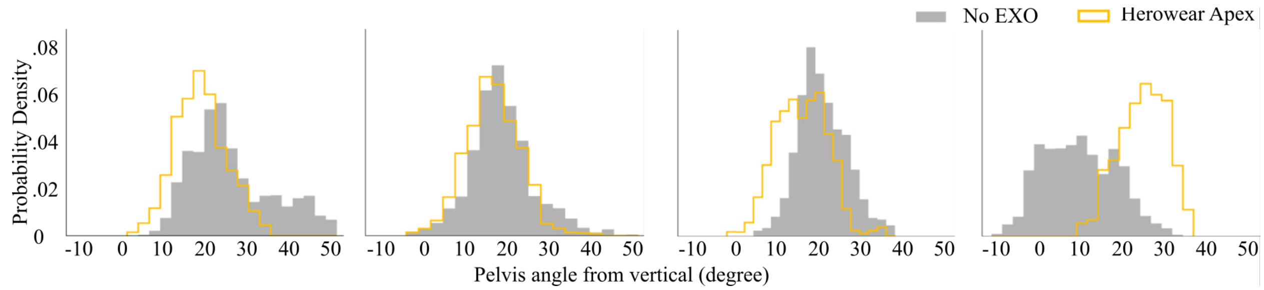

Figure 2. Results for 4 subjects. Changes in movement kinematics, unassisted and while wearing an exoskeleton while dumping a gondola of refuse into a larger cart.

These results validate the approach of using wearable movement sensors to evaluate the effects of EXOs during in-field construction tasks. These effects should be evaluated using task-specific metrics, such as trunk lean in lifting or pushing and shoulder flexion and abduction for overhead work, to minimize the presence of non-targeted movements in the data. Because our approach uses whole-body movement reconstruction along with task video, we can isolate specific portions of a task for analysis. Similar approaches for assessing specific tasks captured in long-term real-world monitoring have proven to reduce variability in the data and strengthen results [28].

TABLE I. RANGE OF MOTION

Condition	Pelvis Angle from Vertical (degree)		
	Mean± S. D.	***IQR (25-75%)***	***ROM (5-95%)***
No EXO	19 ± 8	11 ± 3	27 ± 6
HeroWear Apex	19 ± 4	8.7 ± 0.3	19.9 ± 0.8

The workers completed a survey asking on a scale of 1 (strongly disagree) to 5 (strongly agree) regarding satisfaction with the EXO and intent to use the EXO in the future. Satisfaction yielded an average score of 2.4, and intent to use in the future yielded a score of 2.2 (Table 2). No worker answered 5 for either question, and one worker responded 1 to each question. The workers most liked the support provided by the EXO when performing the task. They mentioned that the EXO helped them keep their backs aligned and under less perceived stress. On the other hand, the workers disliked the movement restraints imposed by the EXO as well as uncomfortable feelings due to the tightened straps on legs when wearing EXOs. One worker reported pain, soreness, or discomfort when wearing the EXO.

TABLE II. SURVEY RESULTS

	Number of Responses	
	Satisfied	***Intend to use***
(Strongly Disagree) 1	1	1
2	0	0
3	1	2
4	2	1
(Strongly Agree) 5	0	0
Mean Score:	**2.4**	**2.2**

IV. Discussion

Preliminary results have established the feasibility of executing a quantitative assessment of the effects of EXOs through controlled observational field testing in real construction tasks. Hence, in our future work, we plan to execute such tests in a variety of construction settings and tasks and evaluate outcomes measuring the effects of EXOs on biomechanics, performance, and productivity, in conjunction with traditional user experience outcomes. Potential tasks may include installation or removal of carpet squares or framing of wall segments laid on the floor. Finally, we will explore ways to instrument the EXOs themselves to further clarify their function. For example, we may measure the displacement of the clutched cable in the HeroWear Apex lower-back EXO with a string potentiometer, to understand how the user uses its locking/unlocking feature. Further instrumentation, such as instrumented insoles and electromyographic (EMG) sensors, can be employed to obtain valuable force and muscle activation data. Results from these further tests will serve as valuable tools for EXO manufacturers and construction organizations for improving future EXO designs and for planning EXO-enabled tasks.

Acknowledgment

This research was supported by the National Science Foundation via grants #CNS-2128823 and #CNS-2128716. The authors also acknowledge M.A. Mortenson Company for their collaboration on this research.

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