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FIELD-BASED ASSESSMENT OF JOINT MOTIONS IN CONSTRUCTION TASKS WITH AND WITHOUT EXOSKELETONS IN SUPPORT OF WORKER-EXOSKELETON PARTNERSHIP MODELING AND SIMULATION

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ABSTRACT

Construction workers are required to perform repetitive, physically demanding manual handling work which may pose severe risks for work-related musculoskeletal disorders and injuries. Exoskeletons have substantial potential to protect worker safety and well-being and increase construction productivity by augmenting and complementing workers' physical abilities. However, a key barrier for their adoption in construction is the lack of rigorous research-based real-world evaluation of the beneficial impact of exoskeleton use in practice. As the foundational step to address this issue, this paper presents a field-based assessment to reconstruct and analyze worker joint motions with and without back- and shoulder-assisted exoskeletons in two construction tasks: pushing/emptying gondolas and installing/removing wooden blocks between steel studs. The findings from this research will inform future investigations on worker-exoskeleton partnership to model and simulate the impact on worker and work performance from various perspectives including biomechanics, ergonomics, productivity, and profitability.

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1 INTRODUCTION

The construction industry is labor-intensive, where workers are heavily involved in physically demanding tasks, including material lifting or hauling, plastering, paving and surfacing, scaffolding, etc. These tasks require sustained and repeated work performance in difficult postures (e.g., kneeling, crouching, stooping), which exposes workers to a severe risk for work-related musculoskeletal disorders (WMSDs) resulting in occupational injuries and illnesses (Zhu et al. 2021). According to reports from the Bureau of Labor Statistics (BLS), the average injury and illness incidence rate in 2011-2018 reached nearly 51 cases per 10,000 full-time construction workers (BLS 2020). This statistic is still a conservative estimate since it excludes unreported cases and incidents not resulting in loss of working days.

Exoskeletons are external frames that can be worn to support human bodies and help to alleviate muscle overloading and fatigue from repetitive tasks. In addition to improving construction labor productivity, they are expected to protect workers' health and safety, reduce their risk of getting WMSDs and injuries, extend their career life expectancy, and broaden the overall workforce participation in the construction industry. On the other hand, exoskeletons can place different, unexpected, or incompatible interaction loads on workers, potentially constraining their motion and causing discomfort when wearing exoskeletons to perform construction tasks.

To provide a better understanding of exoskeleton use in construction and create effective worker-exoskeleton partnerships, this paper focuses on a foundational step of using wearable sensors for quantitative, field-based assessment of worker joint motions in common construction tasks with and without exoskeletons. The goal is to inform modeling and simulation approaches to understanding and predicting the effects of exoskeletons on future construction operations.

2 RELATED WORK

2.1 Industrial exoskeletons and their potential in construction

Industrial exoskeletons are designed to support tasks such as overhead work, lifting, carrying, and static holding (CDC 2020). They help wearers augment their strength, increase their endurance, minimize high muscular activation, and improve overall work efficiency. Active exoskeletons use batteries or electric cable connections to run sensors and actuators, while passive exoskeletons do not have any electric power source but are "powered" by natural human movement through springs and counterbalance forces (ExR 2015). Upper extremity exoskeletons, such as Ekso EVO (Ekso Bionics 2021) and Hilti EXO-01 (Hilti 2020), provide support to the upper body, including arms, shoulders, and torso; lower extremity exoskeletons, such as HeroWear Apex (HeroWear 2022) and BackX (suitX 2022), provide support to legs, hips, and lower torso; and full body exoskeletons, such as Guardian XO (Sarcos 2019), provide support to the whole body.

The potential use of exoskeletons in construction has been briefly discussed by Kim et al. (2019). They conducted phone interviews with 26 construction industry representatives to gather their perspectives on exoskeleton adoption in practice. It was noted that exoskeletons were beneficial for repetitive tasks or the ones involving heavy material handling and overhead work; however, adoption barriers still exist due to concerns regarding health, safety, usability, and return on investment (Kim et al. 2019). Also, Zhu et al. (2021) reviewed and analyzed the benefits and challenges of exoskeleton use in construction at the trade level by mapping the potential exoskeleton type to each construction trade based on the top three body part injuries that the trade sustains. Both studies provided the conceptual and qualitative analysis of exoskeleton uses in construction. To provide construction professionals with comprehensive insights and guidelines on exoskeleton adoption, it is necessary to model and simulate the worker and work performance when exoskeletons are integrated into current construction processes.

Existing research on assessment of exoskeletons in construction have focused primarily on exoskeleton effects in reducing muscle fatigue, perceived exertion, and metabolic costs in controlled laboratory environments (Antwi-Afari et al. 2021; Gonslaves et al. 2021; Ye et al. 2022). Such tests are informative, but are not representative of the real workplaces and workers, hence inadequate for credible modeling and simulation of worker-exoskeleton partnerships in construction, on accounts of the potential discrepancy of biomechanical performances between real construction settings and laboratory simulations. One critical step towards the modeling and simulation of the worker and work performance with exoskeletons is to conduct field-based exoskeleton assessment to collect and analyze their real-world performance data.

2.2 Industrial exosuits/exoskeletons investigations in other industries

Compared with the construction industry, the effectiveness of industrial exosuits/exoskeletons has been extensively investigated in the manufacturing, automotive assembly, warehousing, and agriculture industries. Again, most studies were performed in laboratories (e.g., Koopman et al. 2019; Kim et al. 2020; Bosch et al. 2016). In these studies, the test subjects are typically not professional workers with years of working experience, the number of test subjects is limited, and the test period is short. A second category of studies were performed in real workplaces, such as with American automotive workers (Graham et al. 2009), Belgian machine shop workers (Amandels et al. 2018), order fulfillment workers (Motmans et al. 2018), German automotive workers (Hensel and Keil 2019), and workers in a French COVID intensive care unit (Settembre et al. 2020). The investigation results provided insights regarding exoskeleton usability in practice, which sometimes conflicted with the claims of exoskeleton manufacturers.

Overall, existing exosuits/exoskeleton investigation results have helped researchers and professionals gain a better understanding of occupational biomechanics (e.g., Chaffin et al. 2006), industrial ergonomics (e.g., Kodak and Jacobs 2004), anthropometry (e.g., Pheasant and Haslegrave 2018), and workplace tasks such as symmetric (e.g., Marras et al. 1993) and general lifting (e.g., Gallagher and Marras 2012) with exoskeletons. However, this level of understanding is still incomplete, especially considering that there is such a broad range of workers (anthropometry, strength, age, disability), situations (work conditions, survivor bias, external stressors) and diversity of tasks. Further, the findings from other industries cannot necessarily be applied in the cluttered, unstructured, and dynamic construction workplace.

2.3 Field-based collection during real-life movements

Accurately understanding the effects of exoskeletons on real-world construction tasks requires collection of data in the field, with real construction workers performing actual construction tasks. Fortunately, methods have been gradually improving to measure and record data during real-world activities. Inertial sensors can be used with advanced motion reconstruction algorithms to estimate movements of multiple body segments or even the whole body. For purposes of understanding movement, kinematic measures center on joint angle kinematics, while certain kinetic aspects such as center-of-mass (COM) acceleration can also be estimated using these systems. Recent efforts have advanced the application of such wearable systems to ever more demanding real-world tasks, such as estimating COM acceleration and knee angle during cutting maneuvers in competitive ultimate frisbee games (Slaughter and Adamczyk 2020) or combining knee and ankle angle estimates with kinetic measures to feed model-based analysis of muscle-tendon load and power on real-world slopes (Harper et al. 2022). Certain wearable systems can even estimate the path of a wearer (Ojeda and Borenstein 2007), allowing analysis of distance traveled and specific location-based behaviors (Wang and Adamczyk 2019). While the kinematic measurements do not perfectly reproduce laboratory motion capture, their accuracy and precision are surprisingly good (Schepers et al. 2018); and as the only viable choice for real-world, large-volume capture, these systems are in a unique position to contribute to analyses of construction task work in-situ. In this research, we apply a wearable inertial motion capture system to record construction workers doing different construction tasks in the workplace and compare how their body kinematics are affected by using passive shoulder/arm exoskeletons and lower-back exoskeletons.

3 RESEARCH OBJECTIVES

The specific objective of this study is to quantify the range and distribution of workers' joint motions when performing specific construction tasks and to compare these motion behaviors with and without the use of passive exoskeletons for the arm and the lower back. Specifically, we investigate, in real-world settings, how a passive lower-back exoskeleton affects pelvis movement (sagittal tilt angle) in a pushing task and how two passive shoulder exoskeletons affect arm-raising movements (shoulder flexion and abduction angles) in a task working on a wall and ceiling. The findings from this study provide critical input data for modeling and simulating the ergonomic effects (increase or decrease in injury risk factors, fatigue, etc.) and work performance effects (productivity, endurance, altered task design requirements, etc.) likely to be caused by exoskeleton use. Characteristics of joint motions in real construction tasks can be combined with task allocation or management planning to model how exoskeletons can transform work in construction.

4 METHODS

Two tasks representative of activities commonly performed in construction sites were selected (Figure 1). Both tasks were set in the equipment yard warehouse of a construction company, which was the workers' daily workplace and an environment similar to construction sites in that the same equipment, tools, materials and safety precautions were used along with cluttered and dynamic work conditions. This location was chosen as the first pilot test to assess the methods before future tests on active construction sites.

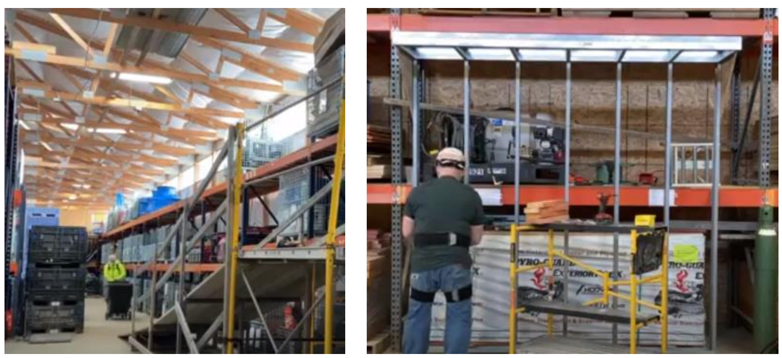

Figure 1: Two construction tasks: pushing/emptying gondolas (left) and installing wooden blocks (right).

The field tests consisted of two tasks: Task-1, pushing and dumping out gondolas and Task-2, installing wooden blocks in a metal stud wall. These tasks are detailed in Sections 4.1 and 4.2 below. Four male workers, aged 25 to 61 with four to thirty-five years in their current jobs, participated in Task-1. Three of these four then participated in Task-2. All subjects gave their written informed consent according to procedures approved by the University of Wisconsin Minimal Risk Research IRB (protocol 2021-1608).

In the field test, the XSens MVN Awinda system (XSens 2022) was used for motion capture. The MVN Awinda is a set of wireless inertial-magnetic sensors that provides accurate motion capture without the limitations of a wired or camera-based system. For all tests, the full-body system was used (17 sensors placed on the individual's torso, head, pelvis, and extremities). The sensors have a stated dynamic orientation accuracy of 0.75 degree RMS (Roll/Pitch), 1.5 degree RMS (Heading) and a static orientation accuracy of 0.5 degree RMS (Roll/Pitch), 1 degree RMS (Heading) (XSens 2022). The sensors were placed as close to the skin as possible and checked routinely throughout the test to ensure they remained in place. The head sensor was attached directly to hardhats worn during the test. Motion capture data was recorded using XSens MVN Analyze Pro software (Version 2020.2.0), with an Awinda Station at a sampling rate of 60Hz (XSens 2022).

Three commercially available passive exoskeletons (Figure 2) were tested in this study. The HeroWear Apex is an elastic lower-back exosuit with a manual on/off switch providing adjustable locking for the neutral length of the elastic bands which support the load; it has been shown to reduce muscle activity 20-30% during lifting tasks (HeroWear 2022). The Hilti EXO-01 and Ekso Evo are both passive shoulder exoskeletons designed to help reduce arm/shoulder muscle fatigue during long periods of overhead work

(Hilti 2020; Ekso Bionics 2021). The Hilti EXO-01 uses one or two internal elastic bands (bungee cord loops) acting about each shoulder joint through an adjustable moment arm mechanism. The Ekso Evo uses interchangeable spring cartridges to change assistance strength and an internal linkage system to convert spring compression into shoulder moment. Both shoulder exoskeletons have a nonlinear torque profile that provides maximum torque when the upper arm is held near a right angle to the body. The Ekso Evo also has a lockout mechanism to disengage its springs if the user desires.

Figure 2: Three exoskeletons for tests: HeroWear Apex (Left), Hilti EXO-01 (Center), and Ekso EVO (Right). The subject also wears a full suite of sensors (e.g., in t-shirt pouches, on wrists, etc.).

Individuals were measured and fitted according to the manufacturer's instructions to make sure that the exoskeletons were worn appropriately. For the HeroWear Apex, this meant fitting the proper shoulder strap and thigh strap size, and ensuring the elastic band was the correct length. Two band strengths are provided, and the normal strength band was used for all cases. The Hilti EXO-01 was adjusted according to the manual (Hilti 2022) to ensure the shoulder mechanism aligned properly with the body, and then the individual adjusted the strap system to a setting that was comfortable for them. The elastic band system was set to engage one band (rather than two) at the maximum moment arm setting. For the Ekso Evo, the waistband size, vertical dorsal pillar height, and arm band size were selected to fit each individual. The Evo's interchangeable spring cartridges are for nominal lifted loads of: 5 lb., 7 lb., 10 lb., 12 lb., and 15 lb. In this field test, one individual opted to use the 10 lb. cartridge, while the others used the 7 lb. cartridge.

4.1 Task-1: Pushing and dumping out gondolas

Task-1 consisted of pushing and emptying construction gondolas (tilting wheeled refuse carts) with and without the HeroWear Apex lower-back exosuit. The task was conducted in a warehouse with a scaffolding platform and ramp to emulate conditions on a construction site (Figure 3). The platform was 14 ft long, 57 in. wide, and 63 in. above ground level and a ramp, made of two 16 ft x 57 in. sections with an average incline of 8.7 degrees, was used to go between the ground level and the platform. Each construction gondola weighed 63.5 kg when empty and 120 kg when filled. The participant's tasks and movement path followed a specific sequence. The participant started with the loaded gondola at the start/end point shown, and the other empty gondola was placed on the ground level next to the raised platform. The loaded gondola was pushed up the ramp and to the end of the platform, where the contents were dumped into the empty gondola sitting on the ground below. The newly empty gondola was then taken down the ramp and pushed on the flat ground, and then exchanged for the loaded gondola. Finally, the loaded gondola was pushed following the rest of the path and brought back to the start/end point. Workers performed this cyclic task 10 to 15 times.

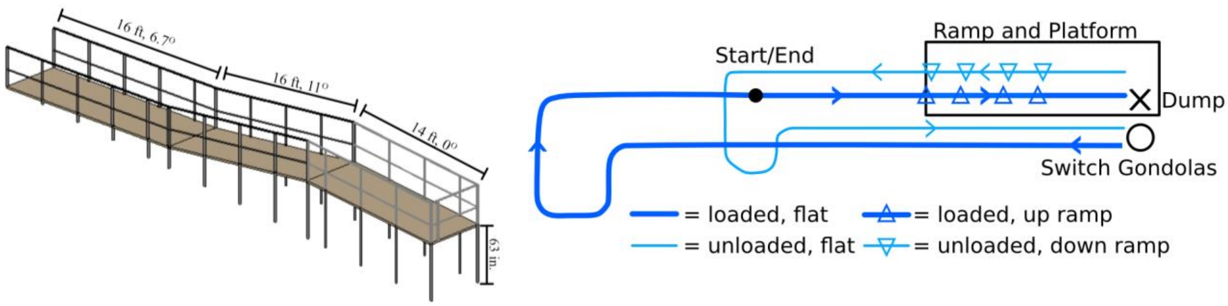

Figure 3: Work settings for Task-1: ramp and platform (left) and movement path (right).

Four individuals completed Task-1. Every participant first completed the task without wearing an exoskeleton and then with the HeroWear Apex exosuit. There was a break of at least 10 minutes between the no-exo test and the exosuit test during which the participant was measured and fitted with the HeroWear Apex. The XSens motion capture system was calibrated immediately before each test, both with and without the exosuit, using the Neutral pose calibration within XSens software. Each participant was instructed on how to activate the exoskeleton's locking mechanism, but they were given free choice on when during the task to have the exoskeleton on and off.

4.2 Task-2: installing/removing wooden blocks

Task-2 was to install and remove wooden blocks between metal studs in a wall and soffit to be mounted to the wall. The work setting for this task is illustrated in Figure 4, where a model of a single block installation is highlighted. The wooden blocks used have dimensions 2×6×16 in. with a mass of 0.91 kg, and were cut to interlock with the studs. A metal stud wall was constructed with 6 columns, roughly 8 ft (2.4 m) by 8 ft (2.4 m) with a roughly 2 ft (0.6 m) soffit. Each test consisted of installing eighteen of these blocks in two columns from floor to soffit: six in the wall and three in the soffit, per section. Participants were given no instruction on what order to install the blocks, but the blocks were installed in the same locations by each worker.

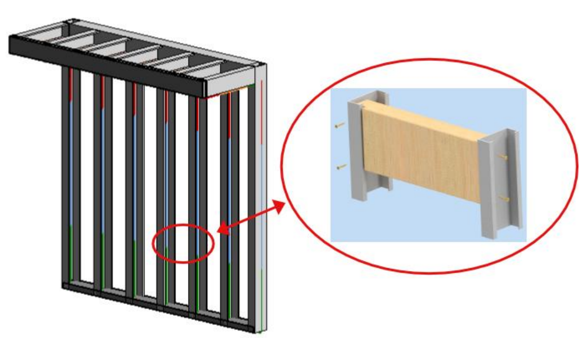

Figure 4: Work settings for Task 2: metal stud walls and block installation.

The three test cases were done in the same order for each individual: first with no exoskeleton, then with the Ekso Evo, and finally with the Hilti EXO-01. Between tests, a break of at least 10 minutes was taken to fit the next exoskeleton and verify the wearable sensor positions. Calibration of the XSens system was done immediately before each test condition, after donning the exoskeleton, to ensure that any small changes in alignment were properly accounted for. The calibration was done within the XSens software using the Neutral pose calibration procedure. Each test took between 25 and 31 minutes.

5 ANALYSIS

Motion capture data was processed by XSens MVN Analyze Pro Version 2020.2.0. The software calculates joint angles defined using the MVN convention, which matches ISB recommendations for all joints except the shoulder. Shoulder angles are reported as the relative orientation between the shoulder segment (approximately the clavicle and scapula) and the upper arm segment, using a ZXY (flexion/extension, abduction/adduction, and axial rotation, respectively) Euler angle sequence (XSens 2021).

For Task-1, data for the sagittal pelvis tilt angle from global vertical were analyzed. For each individual, the data were partitioned into four sections of interest for both no exoskeleton and Herowear Apex conditions: loaded gondola up-ramp, unloaded gondola down-ramp, unloaded gondola on flat ground, and loaded gondola on flat ground. Normalized histograms (similar to probability density plots) of pelvis tilt angle were created for each section to compare the two conditions. The mean, standard deviation, inter-quartile range (IQR) and 5-95% range of motion (ROM) were calculated for every section of each condition, and Wilcoxon signed-rank tests were performed to find whether the conditions differed systematically.

For Task-2, shoulder angle data were analyzed for the no-exoskeleton, Hilti EXO-01 and Ekso Evo Outcomes were the shoulder angles given by the software: Flexion/Extension and Abduction/Adduction angles for the right (tool-holding) shoulder. Normalized histograms were created for these joint angles to compare the conditions. The mean, standard deviation, IQR, 5-95% ROM, and percentage of angles below zero degrees (i.e., shoulder extension or adduction angles) were calculated for each joint angle in each case. Wilcoxon signed-rank tests were again performed to find whether the conditions differed for these metrics.

6 RESULTS

Table 1 illustrates the effects of HeroWear Apex exosuit on the test subjects' pelvis angles when pushing gondola uphill loaded and downhill unloaded in Task-1. Although the mean shows no difference due to these dramatically contrasting effects on individuals, the HeroWear Apex led to reduced mean pelvis angles in both down ramp and up ramp sections for three of four subjects. Figure 5 shows the changes of the probability densities of pelvic lean for one test subject (Subject #3). Table 2 illustrates the effects of HeroWear Apex exoskeleton on the test subjects' pelvis angles in the loaded and unloaded flat sections. Two subjects saw a decrease in mean angle with the use of the HeroWear Apex, as shown in Figure 6. One subject saw an increase in the mean pelvis angle. One subject did not activate the exoskeleton during these sections and saw no difference between the two cases. As above, no overall mean difference appeared due to opposite effects on individuals in Table 2.

Table 1: Effects of HeroWear Apex exoskeleton on pelvis angles when pushing gondolas uphill and downhill across all subjects.

	Pelvis Angle, Uphill Loaded with/without EXO		
Condition	**Mean (deg)**	**IQR (deg) 25-75%**	**ROM (deg) 5-95%**
No EXO	40 ± 10	6 ± 2	16 ± 6
HeroWear Apex	40 ± 6	6 ± 1	15 ± 5
P-val: Hero<None	0.875	**0.25**	**0.25**

	Pelvis Angle, Downhill Unloaded with/without EXO		
Condition	**Mean (deg)**	**IQR (deg) 25-75%**	**ROM (deg) 5-95%**
No EXO	7 ± 11	5.1 ± 5.2	16 ± 5
HeroWear Apex	7 ± 13	5.3 ± 0.9	13 ± 2
P-val: Hero<None	0.875	0.625	0.625

Data are Mean ± SD across subjects. P-values are from paired Wilcoxon signed-rank test on subject means.

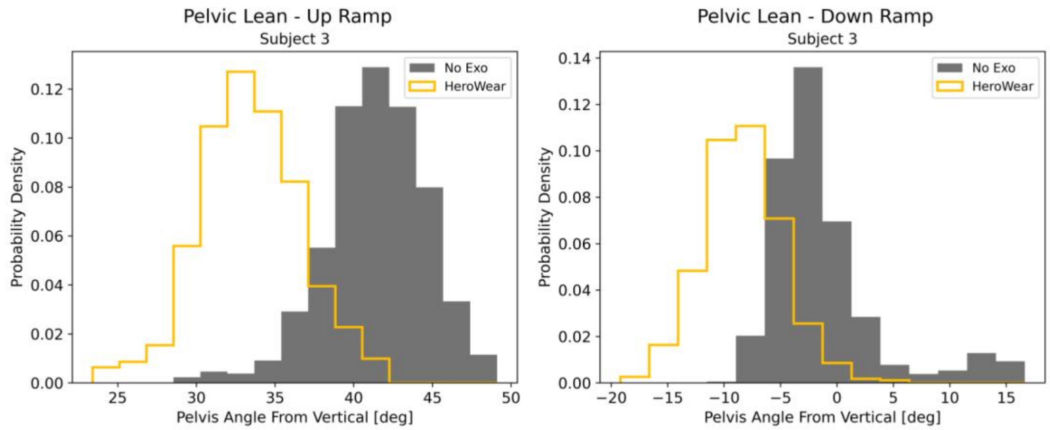

Figure 5: Probability densities of pelvic lean for Subject 3 during the up ramp (left) and down ramp (right) sections of Task-1.

Table 2: Effects of HeroWear Apex exoskeleton on pelvis angle when pushing gondolas on flat ground across all subjects.

	Pelvis Angle, Flat Ground Loaded with/without EXO		
Condition	**Mean (deg)**	**IQR (deg) 25-75%**	**ROM (deg) 5-95%**
No EXO	20 ± 8	5.6 ± 1.4	14 ± 4
HeroWear Apex	22 ± 8	5.3 ± 1.4	14 ± 3
P-val: Hero<None	0.875	0.625	1

	Pelvis Angle, Flat Ground Unloaded with/without EXO		
Condition	**Mean (deg)**	**IQR (deg) 25-75%**	**ROM (deg) 5-95%**
No EXO	14 ± 6	5.2 ± 1.8	13 ± 5
HeroWear Apex	16 ± 7	5.2 ± 1.7	12 ± 4
P-val: Hero<None	0.875	0.875	0.875

Data are Mean ± SD across subjects. P-values are from paired Wilcoxon signed-rank test on subject means.

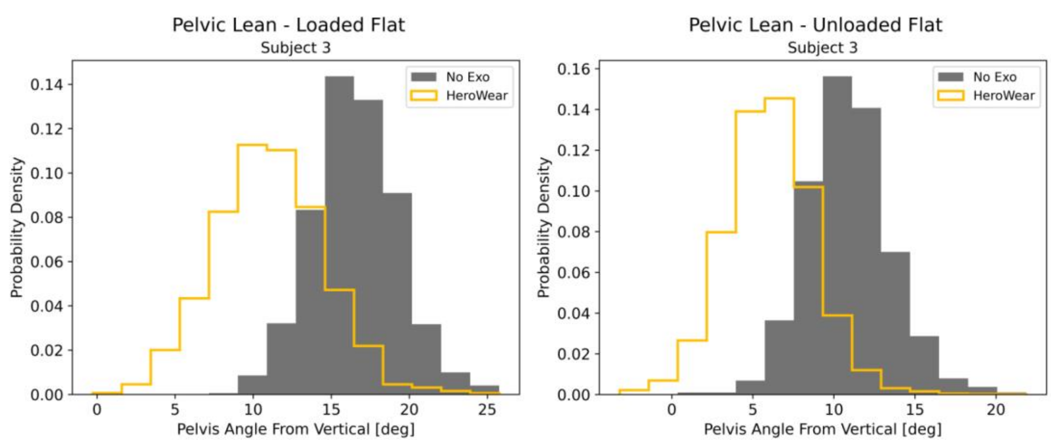

Figure 6: Probability densities of pelvic lean for Subject 3 during loaded (left) and unloaded (right) flat pushing in Task-1.

Table 3 compiles the effects of Hilti EXO-01 and Ekso Evo exoskeletons on shoulder flexion and abduction and Figure 7 shows the probability densities of right shoulder angles for one subject over all samples recorded in Task-2. It could be seen from the table and figure that the Hilti EXO-01 and Ekso Evo both led to reduced range of motion (5-95% range) in both flexion and abduction as well as a larger angle on the most significant peak in shoulder flexion angle. The Ekso Evo led to a larger reduction in flexion ROM than the Hilti EXO-01 while the Hilti led to a larger reduction in abduction ROM than the Ekso. Both exoskeletons led to significantly reduced shoulder extension postures. The Ekso Evo led to an increase in mean angle for both flexion and abduction while the Hilti EXO-01 led to an increase in flexion mean only.

Table 3: Effects of Hilti EXO-01 and Ekso Evo exoskeletons on shoulder flexion and abduction in Task 2.

	Shoulder Angle with different EXO conditions, Wall Blocking task						
	Flexion (arm raised to front)				Abduction (arm raised to side)		
Condition	**Percent < 0 deg**	**Mean (deg)**	**IQR (deg) 25-75%**	**ROM (deg) 5-95%**	**Mean (deg)**	**IQR (deg) (25-75%)**	**ROM (deg) 5-95%**
No EXO	20 ± 18	33 ± 11	55 ± 18	112 ± 6	21 ± 6	11 ± 3	33 ± 9
Hilti EXO-01	10 ± 11	34 ± 5	55 ± 6	103 ± 10	21 ± 7	10 ± 4	29 ± 8
EksoWorks Evo	4 ± 4	34 ± 10	35 ± 5	94 ± 20	26 ± 6	11 ± 4	30 ± 8
P-val: Hilti≠No	0.5	1.0	1.0	**0.25**	1.0	0.5	**0.25**
P-val: Ekso≠No	**0.25**	1.0	**0.25**	**0.25**	**0.25**	0.75	0.5

Data are Mean ± SD across subjects. P-values are from paired Wilcoxon signed-rank test on subject means.

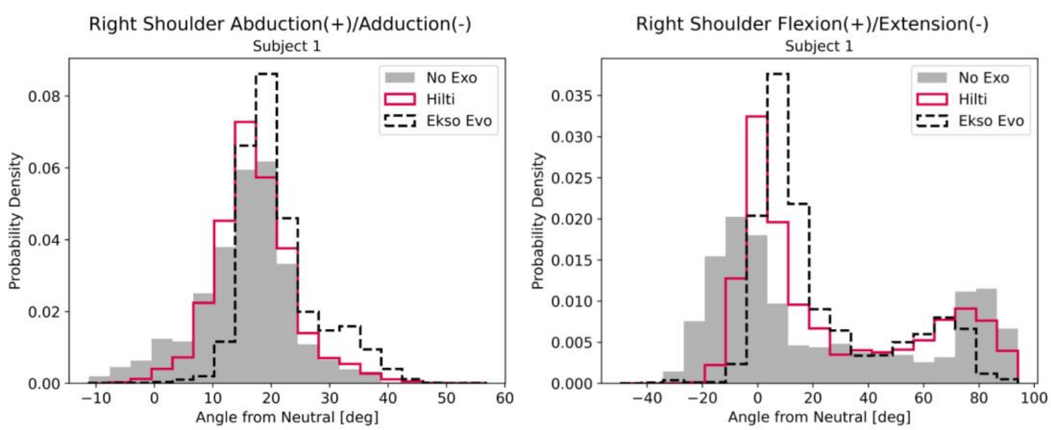

Figure 7: Probability densities of right shoulder angles for Subject 1 over all samples recorded in Task-2.

7 DISCUSSION

This study presented a foundational step of using wearable sensors for quantitative, field-based assessment of worker joint motions in construction tasks with and without exoskeletons. There are several lessons learnt in terms of using the collected data to support the modeling and simulation of worker kinematics and the understanding and prediction of the effects of exoskeletons on future construction operations.

7.1 In-situ data collection – benefits and pitfalls

One of the potential pitfalls of in-situ, real-world data collections is the potential variability in tasks and task performance behaviors that people may exhibit. Observed changes in ROM and posture do not necessarily imply that those changes are unavoidable. Behavior and preference can shift in response to subtle influences, such that observations may reflect behavior as well as physical constraints. Therefore, we cannot strictly say that the exoskeletons limit motion, only that certain outcome measurements were different with the exoskeletons than without.

On the positive side, the real-world wearable data collection approach provides enormous amounts of data that are rich enough to characterize statistically. And, in the sense of a pragmatic trial, it may not always matter why the observed changes occurred, for some questions it may suffice to know that the shift occurred, and therefore how the inputs to the system – exoskeleton or not, or parameter settings – can be used to affect an outcome. This is the core of a machine-learning approach to making use of these data, and it fundamentally requires the kinds of large datasets that can be collected by in-situ wearable recording.

7.2 Using the collected data to seed modeling and simulation of construction operations

Data like those collected in this research can help inform future studies in modeling and simulation of both construction operations and ergonomic risk exposure. As exploration of exoskeleton use and possible adoption in construction is in its infancy, much knowledge regarding translation barriers and enablers in the context of project management and risk control of exoskeleton-enabled work is still lacking. Future studies which incorporate field data into operations simulation models can greatly enhance our understanding of how exoskeleton use impacts resource allocation, job duration, and shift planning. For example, the augmented capabilities can enhance the productivity of individual workers, which would alter the allocation of workers (one type of construction resources) and estimation of activity durations (directly associated with project duration and cost). Simulation models can provide cost savings projection based on the extent of the enhanced production estimated through data fitting of the measurements collected in the field. The simulation models can also enable return-on-investment analysis and justification by comparing the cost savings to the investment cost for exoskeleton installation, maintenance, and staff training. The field data can also aid in the development of accurate biomechanical models to understand the impacts and potential residual safety risks of long-term exoskeleton use. Thus, field data-based simulation modeling and analysis can inform best practices to facilitate exoskeleton adoption and implementation in construction.

7.3 Limitations and future work

A limitation of the lower back exosuit tests is that the system did not include measurement of when subjects locked and unlocked the support bands, nor of how much slack was left in the cable. Variability in this usage was intentionally allowed to avoid biasing the subjects' behavior, but it does add uncertainty in interpretation. In future work, we may implement a sensor to detect the locking/unlocking behavior.

Another limitation is the interaction of the exoskeletons with the motion sensors, and the mounting of those sensors in a field-based test. Sensors on the thighs were worn over the pants for convenience of the construction workers (to avoid the need for a changing room), but as a result their straps tended to loosen and slip, requiring readjustment and recalibration of the motion model. Also, some sensors were in positions that coincided with exoskeleton/exosuit parts (thigh and arm cuffs), requiring special care in placement. We will continue improving how we secure those sensors to ensure good data with maximum convenience.

This pilot test was in a construction company's facility and enrolled construction workers, but it was not, strictly speaking, on a construction site. The next step is to implement a similar test on active construction sites. We anticipate tighter time constraints and a greater variety of movements and tasks on a real construction site. Real sites may add variability, so we will address this by further segmenting the activities based on the location of different tasks in the workplace (e.g. Wang and Adamczyk 2019). We plan to add a position tracking tag system to ensure that absolute position remains reliable.

Finally, the conditions of this test were performed in a fixed order, so the interpretation may be biased by an order effect; future work will continue to attempt to minimize and understand the effect on the results.

8 CONCLUSIONS

This pilot study illustrates and validates the approach of using wearable movement sensors to evaluate the effects of exoskeletons and exosuits during in-field construction tasks. These effects need to be evaluated using task-specific metrics, such as trunk lean in pushing and shoulder flexion and abduction for overhead work. Ongoing and future efforts to assess exoskeletons and exosuits in active construction sites should focus on improving the convenience and reliability of sensor mounting and on ensuring the ability to segment complex tasks into constituent movements of interest. Data from in-field studies will seed modeling studies to optimize the use of exoskeletons and construction operations incorporating them.

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