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Usability and Biomechanical Testing of Passive Exoskeletons for Construction Workers: A Field-Based Pilot Study

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Abstract: The labor-intensive nature of the construction industry requires workers to frequently perform physically demanding manual work, thereby exposing them to the risk of musculoskeletal injury (approximately 31.2 cases per 10,000 full-time equivalent workers). Exoskeletons and exosuits (collectively called EXOs here) are designed to protect workers from these injuries by reducing exertion and muscle fatigue during work. However, the usability of EXOs in construction is still not clear. This is because extant EXO assessments in construction were mainly conducted in laboratory environments with test participants who are not construction professionals. In this research, we conducted a pilot study to investigate the usability of EXOs in a real construction workplace. Four experienced workers were recruited to push/empty construction gondolas with and without a Back-Support EXO, HeroWear Apex. Three workers were recruited to install/remove wooden blocks between steel studs with and without two Arm-Support EXOs, i.e., Ekso EVO and Hilti EXO-001. Their motions, postures, heart rates, and task completion times were recorded and compared. The workers were also surveyed to gather their attitudes toward the EXO's usefulness and ease of use. The study results demonstrated that the workers responded to the use of EXOs differently and consequently were not unanimously in favor of EXO adoption in practice. The preliminary results and findings from this pilot study help in building a foundation of understanding to improve EXO products to fit the needs of construction workers and foster EXO-enabled construction tasks in the future.

Keywords: passive exoskeletons; exosuits; usability testing; field tests; construction workers

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1. Introduction

The construction industry is labor-intensive and construction workers are frequently involved in manual handling tasks for material lifting or hauling, plastering, paving, surfacing, scaffolding, etc. The continual engagement in such physically demanding tasks exposes the workers to significant risk for work-related musculoskeletal disorders (WMSDs). It was reported that the rate of WMSDs in construction was 31.2 cases per 10,000 full-time equivalent (FTE) workers and the median days away from work due to WMSDs reached up to 13 days in 2017 [1]. They result in a sizable economic burden on workers and contractors, considering that MSDs are one of the most common and costly injury categories in the United States [2]. Liberty Mutual Insurance [3] estimated that the construction worker compensation costs brought on by WMSDs were more than $2 billion annually. In those WMSD incidents, the back and shoulder were the most impacted body regions; back injuries accounted for 43% of nonfatal occupational injuries in construction in

2018, with a median of eight lost workdays, and shoulder injuries accounted for 16%, with a median of 25 lost workdays [4–6].

Recently, a variety of exoskeletons and exosuits (collectively called EXOs in this paper) have become available in the market [7]. They are designed to provide support and protect workers from potential WMSDs [8,9]. Depending on whether external power is used, EXOs can be classified into active, passive, and semi-active EXOs [10]. Active EXOs have powered components that help power movement, and they require batteries, pneumatic, or other sources of stored energy, or a tether to remote electric or other energy sources to function. Passive EXOs do not have actuators or use stored power sources. Instead, they utilize springs and/or locks, and counterbalance forces for weight redistribution, damping, etc. Semi-active EXOs use low-power actuation units to enable passive exoskeletons with a certain degree of adaptivity through modification of a spring-based actuation system of passive exoskeletons. Depending on which human body parts are protected, EXOs can be classified into upper extremity, lower extremity, and full-body categories. The upper extremity EXOs provide support to the arms, shoulders, and upper torso. The lower extremity EXOs provide support to the legs, hips, and lower torso. The full-body EXOs provide support to the whole body.

With the emergence of these EXOs, one critical question to ask is: what is the efficacy of EXOs and/or their impacts on workers performing tasks? To answer this question, multiple EXO assessment studies have been conducted in the context of various industries. These studies have assessed EXOs either in laboratory environments or field settings. In the laboratory environments, students and/or workers were recruited to conduct simple tasks, such as repetitively lifting or statically holding, while different types of sensors were used to monitor their physical fatigue, muscle activity, and metabolic costs [11,12]. In real field settings, professional workers were requested to wear EXOs and perform their routine jobs. In these studies, they focused on workers' perceived strain [13], work intensity with EXOs [14], wearing comfort, practicality, safety, user acceptance, etc. [15,16].

So far, most of the existing field-based EXO assessments have been performed in the context of automotive assembly, manufacturing, warehousing, and agriculture industries. EXO assessments in construction are still at the infancy stage partly because the construction industry, in comparison to other industries, is generally more conservative and slower in the adoption of new technologies, materials, and tools [17,18]. Existing EXO assessment work in construction was mainly conducted in controlled laboratory environments, and thereby subject to several limitations. For example, the test participants in the assessment studies are not professional construction workers [19]. The test environments may not be fully representative of real construction workplaces or job sites [11,19]. As a result, the impact and/or efficacy of the use of EXOs on construction workers are still not clear.

To fill this gap, this paper presents a pilot study for investigating the two types of passive EXOs (i.e., a lower back exosuit and two shoulder exoskeletons) in construction workplaces. Multiple passive EXO products are readily available in the market. They are lightweight, affordable, and easily deployable without the need for power. For these reasons, they are more commonly used relative to active EXOs in construction and other industries [20]. Two objectives will be achieved through the study. First, the study aims to investigate, in field settings, the potential usability issues of a passive back-support EXO (BSE) for completing the task of pushing and emptying a gondola. Second, the study will investigate, in field settings, the potential usability issues of two passive arm-support EXOs (ASEs) for the task of installing and removing wooden blocks. This study partnered with M.A. Mortenson Company, an industry-leading construction contractor. The tasks selected for tests were based on the recommendation of their safety director, considering that they are common in construction fields and closely related to the applications targeted by the EXO manufacturers. Professional workers were recruited to perform the tasks with and without EXOs. Their motions, heart rates, and task completion times were recorded and compared. In addition, the workers were surveyed about their perceived task load, EXO usefulness, comfort level, and satisfaction. The pilot study helps establish a foundational understanding of the potential usability issues when passive EXOs are used by construction workers and provides valuable insights regarding the future of EXO-enabled construction tasks.

The rest of the paper is organized as follows. Section 2 introduces the related work on the potential of EXO use and assessment in construction and other industries. Section 3 describes the tasks performed in our pilot study, the participants involved, the detailed experimental procedures, and the adopted analysis techniques. The results and findings of the pilot study are discussed in Section 4. Conclusions and future work are found in Section 5.

2. Related Work

Related work is divided into three parts. First, the potential for EXO use in construction is introduced, which provides insights into the benefits of using EXOs for construction workers and contractors. The second part introduces existing EXO assessment studies conducted by researchers in construction. It was noted that most of them were laboratory-based. In addition, the EXO assessment work in other industries is mentioned to highlight the importance of field-based EXO assessment studies.

2.1. Potential for EXO Use in Construction

Researchers have performed conceptual and qualitative analyses of the potential for EXO use in construction. Kim et al. [7] phone-interviewed 26 construction industry representatives and collected their opinions on the benefits and barriers of EXO adoption in construction practices. Two main benefits were envisioned with EXO-enabled construction work. First, EXOs are useful for repetitive tasks or ones involving heavy material handling, overhead work, etc. [7]. They can help protect workers from potential WMSDs and/or acute injuries resulting in loss of working days and extend their career spans. Second, EXOs are expected to increase labor productivity in the construction industry. The construction industry has been criticized for low productivity [21] and much labor work is not suitable for full automation [22]. EXOs would improve overall work efficiency and productivity by augmenting workers′ strength, increasing their endurance, and minimizing high muscular activation that may lead to WMSDs.

Zhu et al. [23] reviewed and analyzed the benefits and challenges of EXOs in construction and extended the EXO use to the construction trade level. They created a map that associated EXO types to construction trades based on the top three body part injuries that the trades sustain. The map is expected to provide the construction community with a better understanding of the status quo of existing EXO technologies in manual handling tasks, and their benefits and limitations for being adopted in construction trades.

Mahmud et al. [24] identified the facilitator, barriers, and corresponding solutions to overcome the barriers for adoption of EXOs in construction workplaces through a sequential multistage Delphi study. Eighteen experts from academia, industry, and government participated in a workshop to provide insights regarding facilitators, barriers, and potential solutions from a holistic view with respect to business, technology, organization, policy/regulation, ergonomics/safety, and end users. The outcomes of the study led to greater understanding of the benefits, risks, and opportunities of EXO use in construction, while shedding light on the developments and endeavors needed towards a viable roadmap for adoption of EXO technologies in construction workplaces.

In addition to the benefits, risk and/or safety concerns on the EXO use in practice have also been identified. For example, wearers' skin irritation, allergic reactions, and hygiene issues have been noted [25]. Passive EXOs do not reduce the total load on the wearers. Instead, they try to shift the load from one body part to another (e.g., from the shoulders to the waist), which could lead to wearing discomfort and loss of balance due to changes in the center of gravity [26]. If an EXO does not fit the wearer properly, it may exert pressure on unintended body parts, increasing the risk of MSDs, and can cause muscle atrophy due to continuous support from EXOs, such as back belts [24].

2.2. EXO Assessments in Construction

To provide construction researchers and professionals with comprehensive insights and guidelines on EXO use, it is necessary to assess the EXO impacts and/or efficacy in a quantitative way. So far, most of the existing EXO assessment work in construction is still limited to laboratory-based tests, where the assessment focus was placed on measuring the EXO functionalities to reduce muscle activity, as well as perceived exertion and discomfort. For example, the lower extremity EXOs. Antwi-Afari et al. [11] examined the effects of a lower extremity passive EXO on the worker's spinal muscle activity when lifting a standard wooden box (30 cm × 30 cm × 25 cm) under loads of 5 kg, 15 kg, and 25 kg. Based on the signals measured by surface electromyography (sEMG) electrodes, the study found that EXO use could reduce the Lumbar Erector Spinae (LES) muscle activity at the L3 vertebrae level by 11% to 33% of Maximum Voluntary Contractions (MVCs). The test participants also reported a reduced level of perceived discomfort scores for their lower back regions [11].

Gonsalves et al. [19] assessed the participants' physiological conditions when using a lower extremity passive EXO in the simulated rebar placing and tying task. It was noted that the EXO could reduce the latissimus dorsi (LD) muscle activities by 3% to 11%, but induce greater muscle activation in the erector spinae regions [19]. In addition, a reduction in the perceived discomfort in the back was reported, but discomfort in the chest region was noted. The findings of reduced discomfort on the back and increased discomfort due to the wearing of a passive back-support EXO were also reported by Ogunseiju et al. [27] in their simulated flooring task.

As for the upper extremity EXOs, de Vries et al. [28] investigated the effectiveness of a passive arm-support exoskeleton in plastering work, including the tasks of "applying gypsum", "screeding", and "finishing with a plastering spatula", which are similar to the work performed by plasterers. They recruited active plasterers rather than test subjects with no or little construction experience. The recorded EMG signals indicated that the muscle activity of the plasterers was reduced with the wearing of an EXO, and the perceived exertion was also reduced for all tasks except for the task of applying gypsum on the wall [28].

In addition, Chen et al. [29] developed a wearable knee assistive device to help construction workers reduce knee pain, injuries, and osteoarthritis when performing tasks in awkward kneeling postures for prolonged time periods. When assessing their device, the motion capture suite, pressure mats, and wireless EMG sensor suite were used to measure participants' kinetics, kinematics, and physiological conditions. The results indicated that the muscle activation of knee and hip extensor muscles was reduced from standing to kneeling and from kneeling to standing.

2.3. EXO Assessments in Other Industries

Compared with the initial, laboratory-based EXO assessments in construction, the EXO impacts and/or efficacy have been more extensively assessed in other industries, such as manufacturing, automotive assembly, warehousing, and agriculture, using both laboratory and field-based assessment. For example, several controlled laboratory studies indicate that EXO use could reduce muscle activity levels, perceived exertion, and metabolic costs during repetitive lifting [30,31], overhead lifting [12], and simulated overhead drilling [32]. Furthermore, undesirable effects associated with EXO use were noted, such as elevated contact pressure between the EXO and the human body [15,33] and a restricted range of joint motions [34].

In addition to the laboratory-based studies, field-based EXO assessments have been conducted. For example, Hefferle et al. [13] revealed muscle activity reductions in the upper limbs, shoulders, neck, and spine while using EXOs in the assembly department of an automobile manufacturer. Kim et al. [14] conducted an 18-month field study at nine automotive manufacturing facilities and reported no longitudinal effects of arm-support EXO to use on perceived physical demands during overhead work. Motmans et al. [35] investigated the effect on muscle activity and posture of the back and shoulders of order pickers when performing the task of order picking cheese. In addition, Omoniyi et al. [16] reported the perceptions of diverse farmers regarding the feasibility and practicality of EXO use in Canadian prairie grain and livestock farm operations. Overall, the EXO effects in a field setting were different from the ones noted in a controlled laboratory environment [16,36].

3. Materials and Methods

Figure 1 illustrates the overall flowchart of the pilot study. It starts with the experimental setup, including the experiment introduction, sensor calibrations, and body measurement for EXO fittings. After the setup, the recruited workers were asked to complete the assigned tasks first without EXOs and then with EXOs. In addition, the workers' opinions on the use of EXOs were surveyed and the collected sensory data analyzed and compared to identify the impacts of using EXOs in terms of joint motions, heart rates, and task completion time.

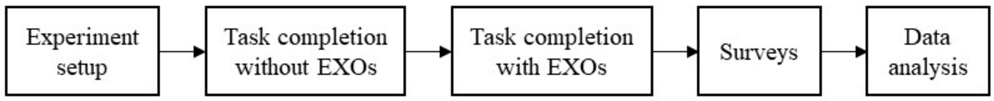


Figure 1. Pilot study flowchart.

It is worth noting that the participants in the study were all professional construction workers with years of working experience and the investigation was conducted in their daily workplace rather than in a controlled laboratory. The tests in this study were not fully controlled. The test participants were told what they needed to do. However, they were allowed to perform the tasks based on their individual preferences and approach. For example, participants in the first task (Task 1) might lift the gondola to different heights to dump the material. The path was provided, but they did not have to exactly follow the path. Some participants in the second task (Task 2) chose to install blocks from one section after another, while some chose to install blocks from the floor up to the soffit. All these actions were uncontrolled and represented how workers actually perform tasks in the fields. Below are more details.

3.1. Tasks

Task 1 was to push and empty a construction gondola on a platform (Figure 2). The platform was 14 ft long, 57 in. wide, and 63 in. above ground level, and a ramp was made of two 16 ft × 57 in. sections with an average incline of 8.7 degrees. The construction gondola weighed 63.5 kg when empty and 120 kg when filled. In this task, one BSE (HeroWear Apex) was tested. The HeroWear Apex is an elastic lower-back EXO with a manual on/off switch providing adjustable locking for the neutral length of the elastic bands.

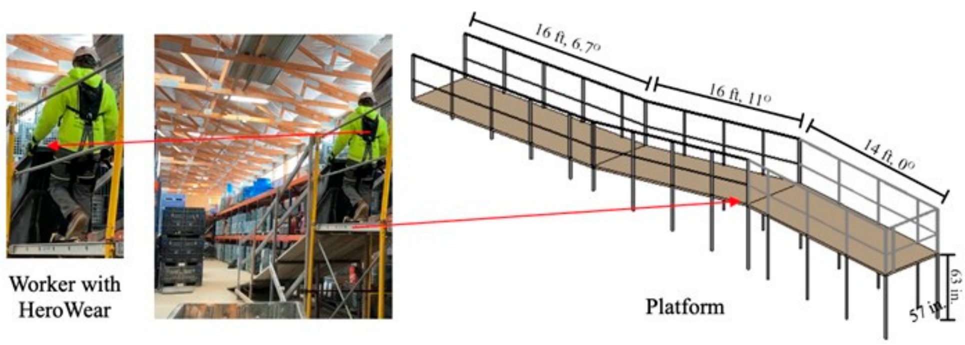


Figure 2. Pushing/emptying a construction gondola on a platform.

Task 2 was to install and remove wooden blocks between metal studs (Figure 3). A metal stud wall was constructed with 7 studs roughly 8 ft (2.4 m) by 8 ft (2.4 m) with a roughly 2 ft (0.6 m) soffit. The wooden blocks to install or remove had dimensions of

2 × 6 × 16 in. with a mass of 0.91 kg. In this task, two ASEs (i.e., Hilti EXO-01 and Ekso EVO) were tested. Both ASEs have a nonlinear torque profile that provides maximum torque when the upper arm is held near a right angle to the body.

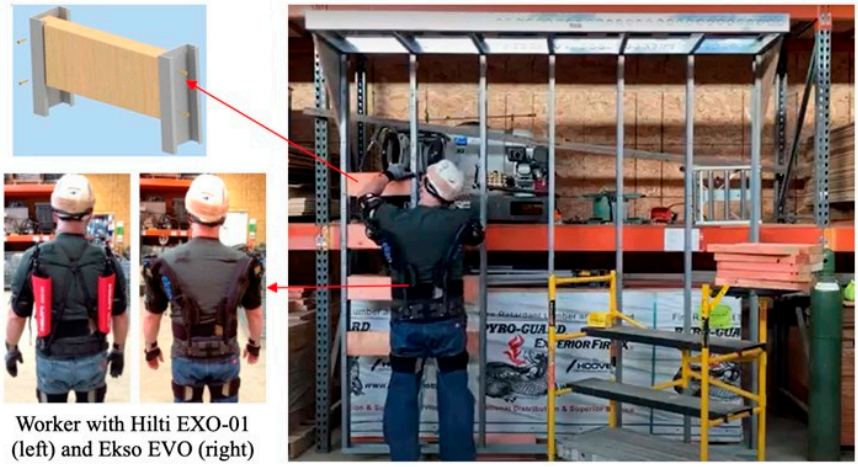


Figure 3. Installing/removing wooden blocks between metal studs.

The BSE and ASEs selected here were mainly due to their affordable price and availability in the market. They were recommended to our industrial partner and received the approval of their safety director. Moreover, the test participants were allowed to use the EXOs based on their preference, considering that the focus of this research was to identify potential usability problems of existing EXOs when they are used in construction environments.

3.2. Participants

Four male workers participated in Task 1 and three of them participated in Task 2. They were all professional construction workers. Their ages and years of experience in their current jobs are listed in Table 1. They all signed the informed consent documents according to procedures approved by the University of Wisconsin Minimal Risk Research IRB (protocol 2021-1608).

Table 1. Information of participants.

Participant	Age	Weight	Height	Years in Current Job	Task Attendance	
					1	2
001	25	190	6′ 3″	6	X	X
002	61	230	5′ 9″	10	X	X
003	56	195	6′ 2″	35	X	X
004	38	225	5′ 10″	4	X	

It is worth noting that the main objective of this pilot study was to gain insight into the primary usability problems of passive EXO products when they are used in construction workplaces, and not on deriving any statistically significant conclusions about the impacts of wearing EXOs on construction workers. Research from the human factors literature shows that the majority of usability problems can be detected with three to five participants in a test and running additional participants during the same test is unlikely to reveal new insights [37,38]. For this reason, we believe that the number of test participants in this pilot study is adequate to meet the pilot study objective.

The recruited workers were measured to confirm that the EXOs were fit and worn appropriately. For the HeroWear Apex, the fitting involved the selection of the proper shoulder harness and thigh strap size and the correct elastic band length with the appropriate band strength. In this study, the normal strength band was used (labeled "Strong" by the manufacturer). For the Hilti EXO-01, the fitting ensured that the shoulder mechanism was aligned properly with the body including waistband tightness and height of the support pillars along the back. Here, the elastic band system was set to engage one band (rather than two) at the maximum moment arm setting. For the Ekso EVO, the fitting involved the selection of the waistband size, vertical dorsal pillar height, and armband size. In addition, the EVO provides interchangeable spring cartridges for nominal lifted loads of 5 lb., 7 lb., 10 lb., 12 lb., and 15 lb. In this study, one worker (Participant #002) opted to use the 10 lb. cartridge while the others used the 7 lb. cartridge.

3.3. Procedure for Gondola Pushing and Dumping

In Task 1, the participants followed a specific path of movement (Figure 4). They started with a loaded gondola at the start/endpoint and pushed it up the ramp to the raised platform. There, they dumped the contents of the gondola into a new, empty one sitting on the ground below. Then, the participants pushed the empty gondola down the ramp, turned around the start/end point, and moved to exchange for the newly loaded one. The loaded gondola was finally pushed back to the start/end point to finish one cycle. The length of the whole path is approximately 125 m. The participants were requested to perform the cycle 10 to 15 times.

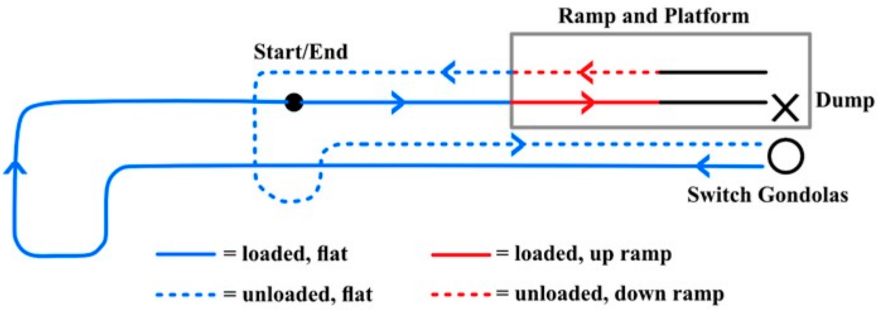


Figure 4. Movement path in Task 1.

Before the experimental procedure, each participant was equipped with an XSens motion capture suit and a Polar H10 heart rate sensor. The XSens motion capture system was calibrated using the Neutral pose calibration within the XSens software. The participants completed the task without the EXO (NoExo) first and then with the HeroWear Apex. Participants were provided a break period (approximately 15–20 min) to rest between NoExo vs. HeroWear Apex conditions. During the break, the XSens motion capture system was recalibrated. The participants were measured and fitted with the EXO, and they initiated the task when they were ready to continue. The participants were instructed on how to activate the locking mechanism of the HeroWear Apex, but it was left to them to decide whether and when to activate or deactivate it during the experimental procedure. The task completion time under each condition was recorded. At the end of the tests, the participants were surveyed with questions about the benefits and limitations of using the HeroWear Apex.

3.4. Procedure for Wooden Block Installation and Removal

In Task 2, each participant was requested to install 18 blocks in total and then remove them for each of the three test conditions, i.e., first without the EXO (NoExo), then with the Ekso EVO and finally with Hilti EXO-01. Nine blocks were installed in each of the two wall sections framed by steel studs from the floor to the soffit, six blocks in the wall, and three in the soffit. The participants were told the approximate locations on the studs to install the blocks. However, no instructions were provided to the participants on what order they should follow. The task took between 25 and 31 min.

As in Task 1, each participant was equipped with an XSens motion capture suit and a Polar H10 heart rate sensor before the experimental procedure. The participants completed the task first without the EXO (No Exo), then with the Ekso EVO and finally with Hilti EXO-01. Participants were provided a break period (approximately 12 min) to rest between

NoExo vs. Ekso EVO vs. Hilti EXO-01 conditions. During the break, the XSens motion capture system was recalibrated. The participants were measured and fitted with the EXO, and they initiated the task when they were ready to continue. The task completion time under each condition was recorded. At the end of the tests, the participants were surveyed with questions about the benefits and limitations of using the Ekso EVO and Hilti EXO-01.

3.5. Analysis

The heart rate data and the task completion time were directly input into Excel for analysis. The IMU motion capture data was processed by XSens MVN Analyze Pro software, Version 2020.2.0, to calculate joint angles. Within the XSens software, the joint angles are defined using the International Society of Biomechanics (ISB) standards except for the shoulder. Shoulder angles are reported as the relative orientation between the "shoulder" segment (approximately the clavicle and scapula) and the upper arm (humerus), using a ZXY (flexion/extension, abduction/adduction, and axial rotation, respectively) Euler angle sequence defined by XSens [39].

In Task 1, the focus was placed on analyzing the sagittal pelvis tilt angle as an estimate of trunk lean. The data were partitioned into four phases of interest (i.e., loaded gondola up-ramp, unloaded gondola down-ramp, unloaded gondola on flat ground, and loaded gondola on flat ground; see Figure 3) under No Exo vs. HeroWear Apex conditions. In addition, the normalized histograms (i.e., probability density histograms) of pelvis tilt angle were created, and the mean, standard deviation, inter-quartile range (IQR), and 5–95% range of motion (ROM) were calculated.

In Task 2, the shoulder angle data were analyzed between No Exo vs. Ekso EVO vs. Hilti EXO-01 conditions. The focus was placed on the flexion/extension and abduction/adduction angles for the left (block-holding) and right (tool-holding) shoulders. In addiiton, the probability density histograms of these angles were created, and the mean, standard deviation, IQR, and 5–95% ROM were calculated.

The angles were chosen in line with the portion of the body that each EXO targeted. The Herowear Apex targets lower back support, and therefore the pelvis tilt angle was chosen since it shows the relationship between the lower back and the legs. Both the Ekso EVO and Hilti EXO-01 are designed to lift the upper arms against gravity; this motion is either flexion (arm lifted in front of the body) or abduction (arm lifted toward the side).

The IQR and 5–95% ranges for the flexion/extension and abduction/adduction angles are important in identifying how naturally the EXOs integrate with the body. The 5–95% metric was chosen to indicate if there was a physical restriction on the range of motion due to the EXOs, while limiting susceptibility to potential outlier data or behaviors. The IQR was chosen to show the range of angles that the workers favor during the activity, and if the EXOs lead to them preferring a narrower or wider band of angles.

4. Results

4.1. Effects of the EXO Use on Pelvis Tilt Angles

Table 2 illustrates the effects of the HeroWear Apex on the pelvis tilt angles of the participants when pushing the loaded gondola uphill. Their probability density histograms are illustrated in Figure 5. During the uphill pushing of the gondolas, three of four participants reduced their mean forward pelvis tilt angle when using the HeroWear Apex as indicated in Table 1. The probability density histograms of the pelvis tilt angle for Participants #1 and #3 shifted to the left significantly. The reduction suggests an upright posture and low exertion of the hip and lower back muscles, consistent with the intended effect of the HeroWear Apex.

Table 2. Pelvis tilt (deg) for pushing the loaded gondola uphill.

Participant #	Pelvis Tilt (Mean; deg)		IQR (25–75%; deg)		ROM (5–95%; deg)	
	No Exo	HeroWear Apex	No Exo	HeroWear Apex	No Exo	HeroWear Apex
001	50.0	46.3	5.7	5.4	16.0	13.6
002	43.8	42.7	8.2	7.2	23.7	22.5
003	41.4	33.4	4.1	4.3	10.1	10.5
004	26.7	37.8	7.4	5.7	15.4	13.2
MEAN	40.5	40.1	6.3	5.6	16.3	15.0
SD	9.9	5.6	1.8	1.2	5.6	5.2

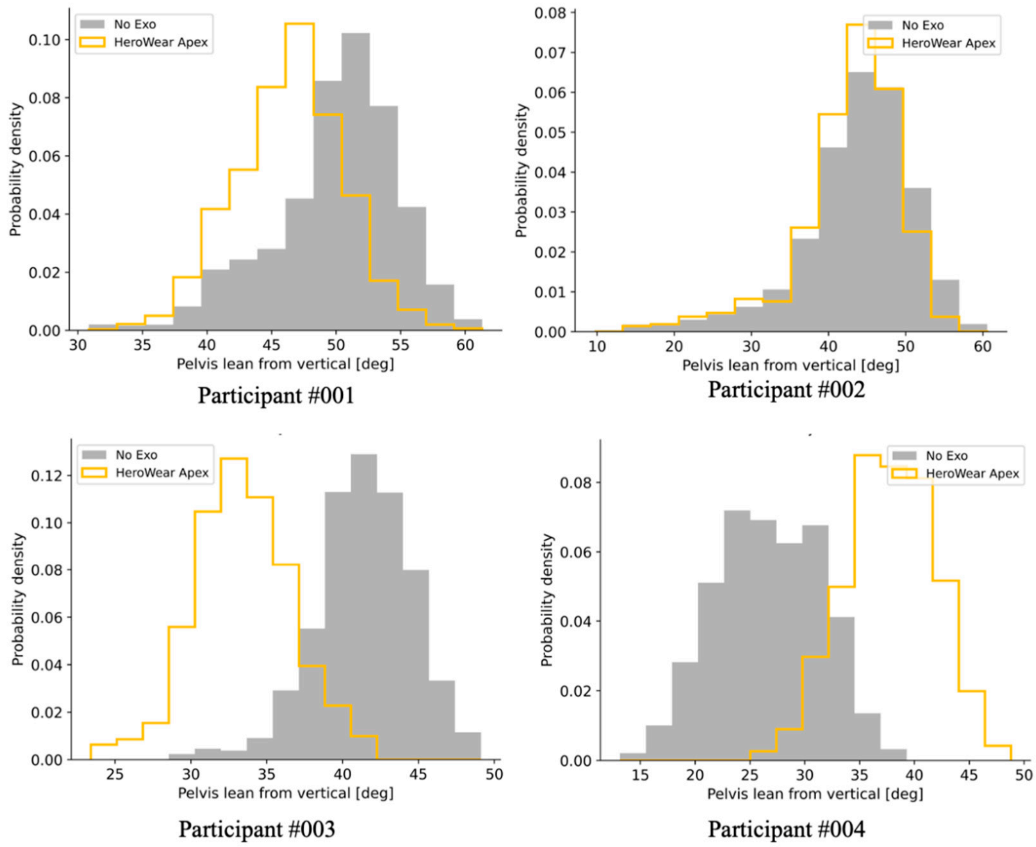


Figure 5. Histograms of pelvis lean from vertical for pushing the loaded gondola uphill.

Table 3 and Figure 6 illustrate the effects of the HeroWear Apex on the pelvis tilt angles of the participants when pushing the unloaded gondola downhill. During the downhill pushing of the gondolas, the participants showed reduced forward pelvis tilt with the HeroWear Apex again. Participant #003 even leaned to negative angles (leaning back). The basic mechanics of lowering a heavy gondola downhill require the body to lean back more, but the additional backward angle with the HeroWear Apex suggests that it may "pull" the hip into extension.

Table 3. Pelvis tilt (deg) for pushing the unloaded gondola downhill.

Participant #	Pelvis Tilt (Mean; deg)		IQR (25–75%; deg)		ROM (5–95%; deg)	
	No Exo	HeroWear Apex	No Exo	HeroWear Apex	No Exo	HeroWear Apex
001	4.1	1.0	5.0	5.2	12.5	13.6
002	23.3	20.3	4.6	6.6	11.3	15.6
003	−1.2	−8.3	4.0	4.4	19.1	11.5
004	1.6	16.2	6.7	4.9	21.5	12.0
MEAN	7.0	7.3	5.1	5.3	16.1	13.2
SD	11.1	13.3	1.2	0.9	5.0	1.9

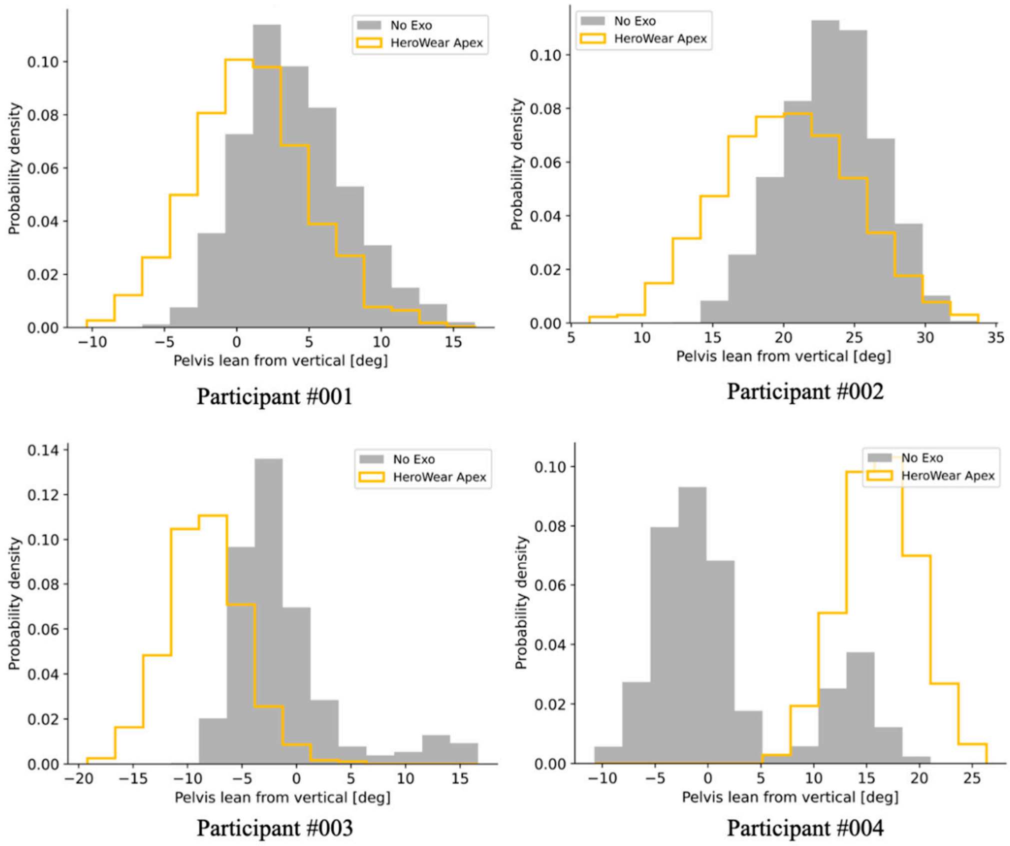


Figure 6. Histograms of pelvis lean from vertical for pushing the unloaded gondola downhill.

Tables 4 and 5 and Figures 7 and 8 show the effects of the HeroWear Apex on the pelvis tilt angles of the participants when pushing the loaded (Table 4, Figure 7) and unloaded (Table 5, Figure 8) gondolas on level ground. Both cases are difficult to interpret. The pelvis tilt angles for the two participants increased, but decreased for the other two. Typically, level-ground pushing requires much less power from the human than uphill and downhill pushing, so the HeroWear Apex should not be as necessary.

Table 4. Pelvis tilt (deg) for pushing the loaded gondola at level ground.

Participant #	Pelvis Tilt (Mean; deg)		IQR (25–75%; deg)		ROM (5–95%; deg)	
	No Exo	HeroWear Apex	No Exo	HeroWear Apex	No Exo	HeroWear Apex
001	27.4	26.8	6.6	6.5	16.6	15.6
002	25.4	27.6	6.7	6.5	14.9	17.6
003	16.6	11.1	3.6	4.6	8.9	11.4
004	9.3	22.7	5.6	3.8	17.4	10.2
MEAN	19.7	22.1	5.6	5.3	14.5	13.7
SD	8.4	7.6	1.4	1.4	3.8	3.5

Table 5. Pelvis tilt (deg) for pushing the unloaded gondola at level ground.

Participant #	Pelvis Tilt (Mean; deg)		IQR (25–75%; deg)		ROM (5–95%; deg)	
	No Exo	HeroWear Apex	No Exo	HeroWear Apex	No Exo	HeroWear Apex
001	17.5	16.8	5.6	6.8	12.8	14.6
002	19.5	20.7	4.4	6.5	12.2	15.9
003	10.9	6.1	3.3	3.5	8.4	8.6
004	7.1	20.3	7.4	3.8	19.6	9.7
MEAN	13.8	16.0	5.2	5.2	13.3	12.2
SD	5.8	6.8	1.8	1.7	4.7	3.6

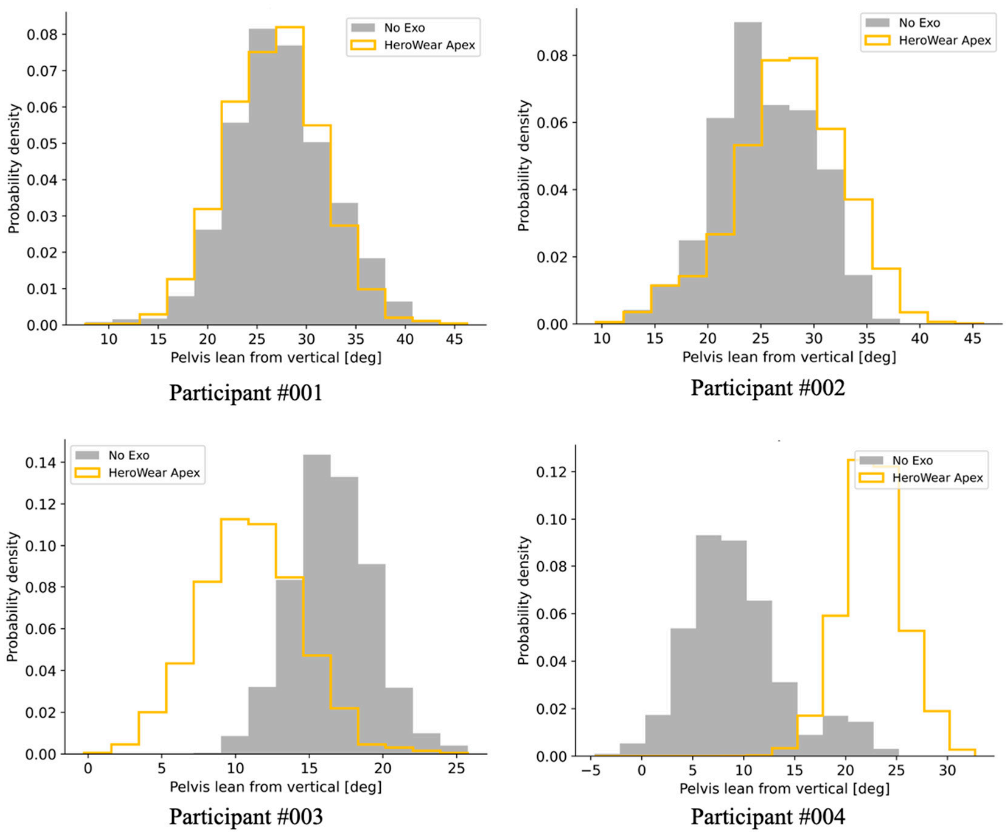


Figure 7. Histograms of pelvis lean from vertical for pushing the loaded gondola at level ground.

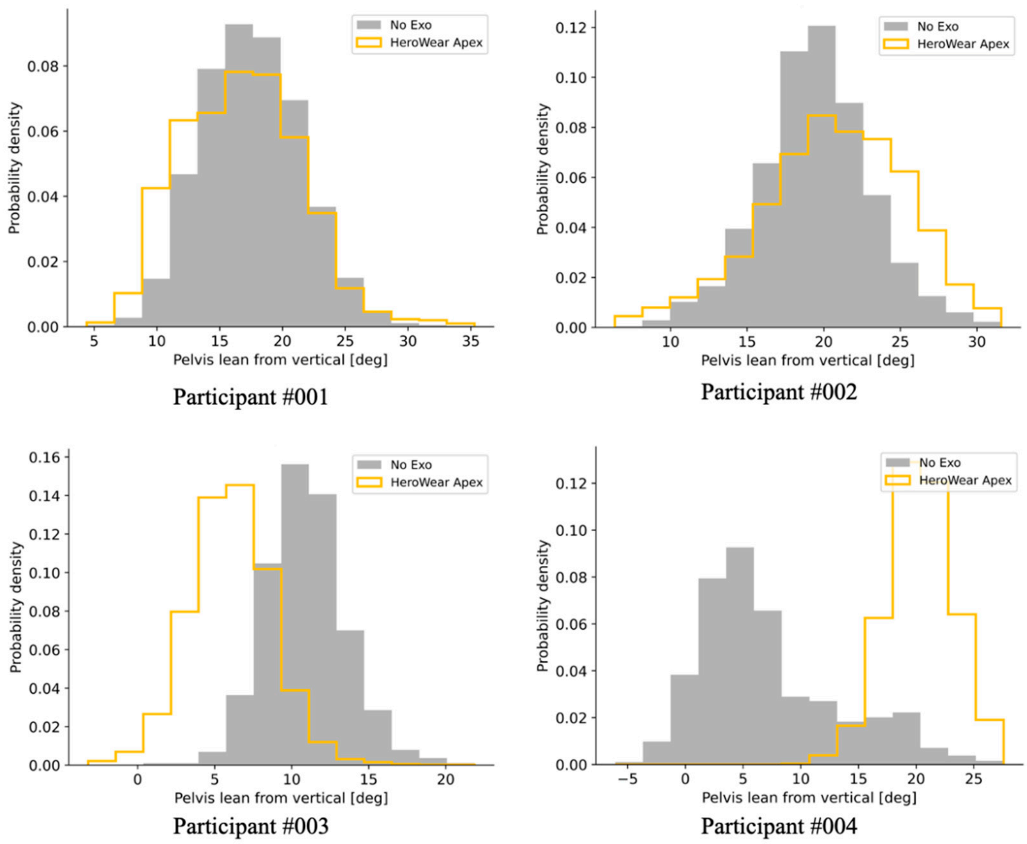


Figure 8. Histograms of pelvis lean from vertical for pushing the unloaded gondola at level ground.

4.2. *Effects of the EXO Use on Flexion/Extension and Abduction/Adduction Angles*

Tables 6 and 7 and Figures 9 and 10 compiled the effects of the Hilti EXO-01 and Ekso EVO on the flexion (raising the arm to the front) and extension (pushing the elbow to the back body) of the shoulders. Both devices led to a reduced 5–95% ROM in shoulder flexion/extension on the right shoulder. The main cause of this change was a substantial increase in the fifth percentile flexion angle, indicating that the lowest end of the distribution was cut off or shifted. This suggests that close-to-the-body motions are more affected by the ASEs than motions in the middle or upper end of the shoulder flexion range.

Table 6. Flexion/extension (deg) of the right shoulder.

Participant #	Flexion (+) (Mean; deg)			IQR (25–75%; deg)			ROM (5–95%; deg)		
	No Exo	Hilti EXO-01	Ekso Evo	No Exo	Hilti EXO-01	Ekso Evo	No Exo	Hilti EXO-01	Ekso Evo
001	24.0	28.1	22.9	74.6	60.4	30.1	109.4	95.5	75.1
002	45.8	38.8	43.1	48.2	54.4	40.7	119.3	114.3	114.5
003	29.1	35.6	35.9	40.7	48.5	34.8	108.0	99.6	90.9
MEAN	33.0	34.2	34.0	54.5	54.4	35.2	112.2	103.1	93.5
SD	11.4	5.5	10.2	17.8	6.0	5.3	6.2	9.9	19.8

Table 7. Flexion/extension (deg) of the left shoulder.

Participant #	Flexion (+) (Mean; deg)			IQR (25–75%; deg)			ROM (5–95%; deg)		
	No Exo	Hilti EXO-01	Ekso Evo	No Exo	Hilti EXO-01	Ekso Evo	No Exo	Hilti EXO-01	Ekso Evo
001	39.8	44.4	31.9	71.0	57.9	43.5	103.4	105.5	96.4
002	53.0	48.8	52.0	56.4	62.3	58.3	90.2	99.1	114.2
003	45.4	35.5	41.5	39.6	48.9	39.5	100.0	92.4	74.4
MEAN	46.1	42.9	41.8	55.7	56.4	47.1	97.9	99.0	95.0
SD	6.6	6.8	10.1	15.7	6.8	9.9	6.9	6.6	19.9

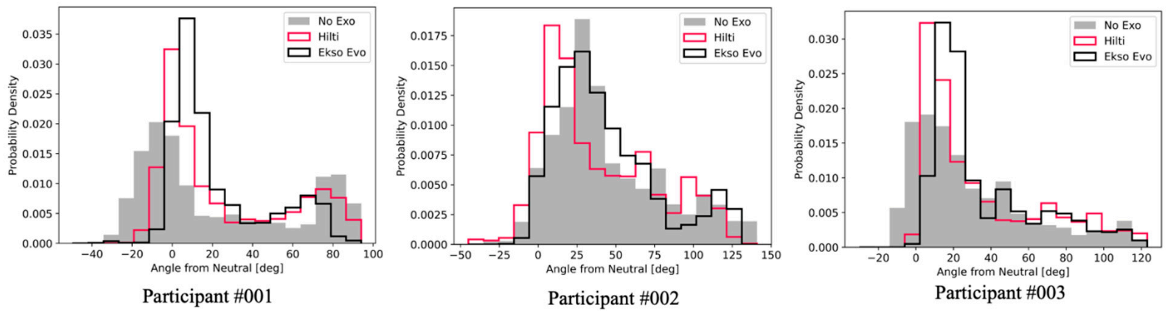


Figure 9. Histograms of flexion/extension of the right shoulder for block installation.

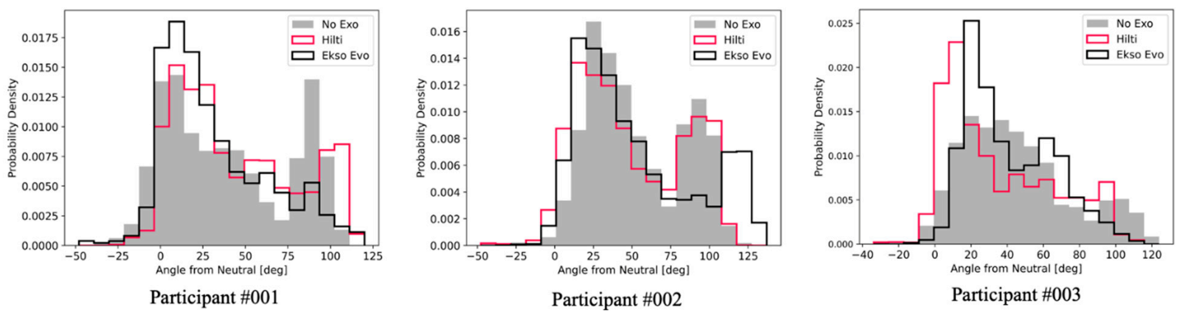


Figure 10. Histograms of flexion/extension of the left shoulder for block installation.

Tables 8 and 9 and Figures 11 and 12 compiled the effects of both devices on the abduction (lifting the arm to the side) and adduction (putting the arm down or across the body) of the left and right shoulders. The main finding is that the Ekso EVO caused an increase in the mean shoulder abduction angle. This is understood to be because its spring force tended to make the participants lift their arms away from neutral even when they had no specific intention to do so. The Hilti EXO-01 may reduce the right (tool arm) shoulder abduction 5–95% ROM. This finding appears to be subtle, but it may be related to the reduced across-body movements of the upper arm.

Table 8. Abduction/adduction (deg) of the right shoulder.

Participant #	Flexion (+) (Mean; deg)			IQR (25–75%; deg)			ROM (5–95%; deg)		
	No Exo	Hilti EXO-01	Ekso Evo	No Exo	Hilti EXO-01	Ekso Evo	No Exo	Hilti EXO-01	Ekso Evo
001	15.4	17.3	21.3	9.2	7.7	7.1	28.4	22.3	21.9
002	27.1	29.1	32.7	14.1	14.1	15.1	42.9	38.1	38.0
003	21.2	16.9	23.4	8.6	8.1	11.9	27.3	25.6	30.7
MEAN	21.2	21.1	25.8	10.6	10.0	11.4	32.9	28.7	30.2
SD	5.9	6.9	6.1	3.0	3.6	4.0	8.7	8.3	8.1

Table 9. Abduction/adduction (deg) of the left shoulder.

Participant #	Flexion (+) (Mean; deg)			IQR (25–75%; deg)			ROM (5–95%; deg)		
	No Exo	Hilti EXO-01	Ekso Evo	No Exo	Hilti EXO-01	Ekso Evo	No Exo	Hilti EXO-01	Ekso Evo
001	13.1	15.8	27.2	14.7	14.3	14.6	40.9	37.4	41.5
002	17.2	28.3	34.9	14.9	17.3	22.6	37.3	38.5	48.0
003	23.2	24.3	32.4	16.0	24.2	18.3	39.6	55.5	46.1
MEAN	17.8	22.8	31.5	15.2	18.6	18.5	39.3	43.8	45.2
SD	5.1	6.4	3.9	0.7	5.1	4.0	1.8	10.1	3.3

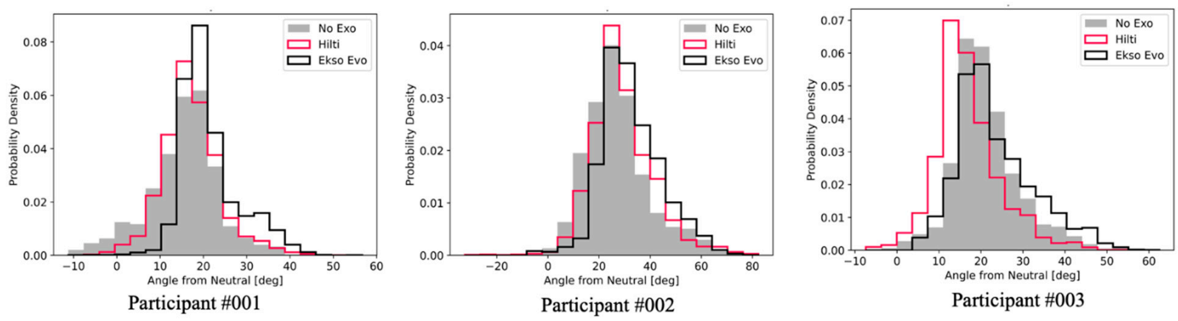


Figure 11. Histograms of abduction/adduction of the right shoulder for block installation.

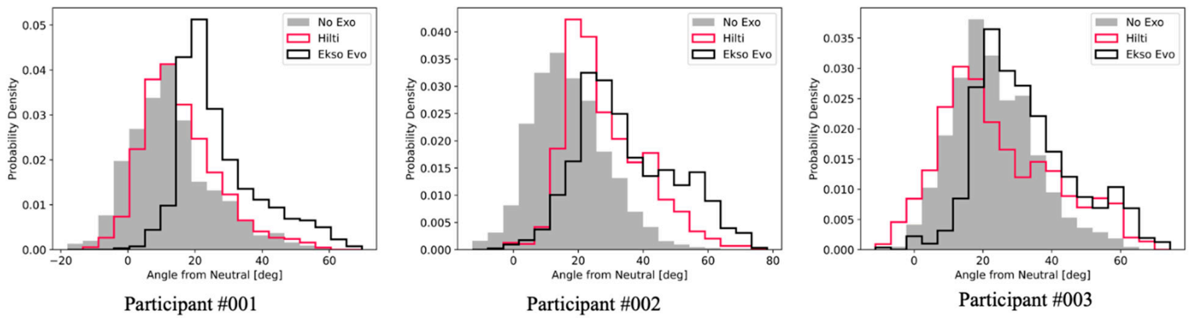


Figure 12. Histograms of abduction/adduction of the left shoulder for block installation.

4.3. Effects of the EXO Use on Task Completion Time and Heart Rates

Figure 13 illustrates the time required for completing the tasks of pushing/emptying gondolas and installing/removing wooden blocks with and without EXOs, respectively. It can be seen that wearing the EXOs could help reduce the task completion time in both tasks, although the reduction is small. Figures 14 and 15 show the distribution of the heart rates for individual participants when completing the tasks with and without EXOs.

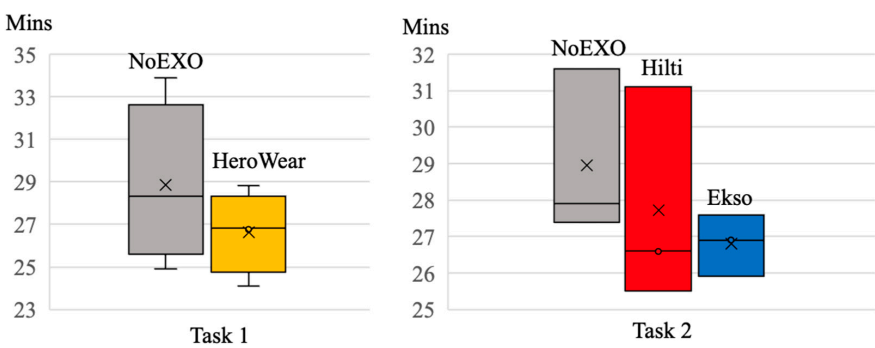


Figure 13. Completion time for Task 1 (**Left**) and Task 2 (**Right**).

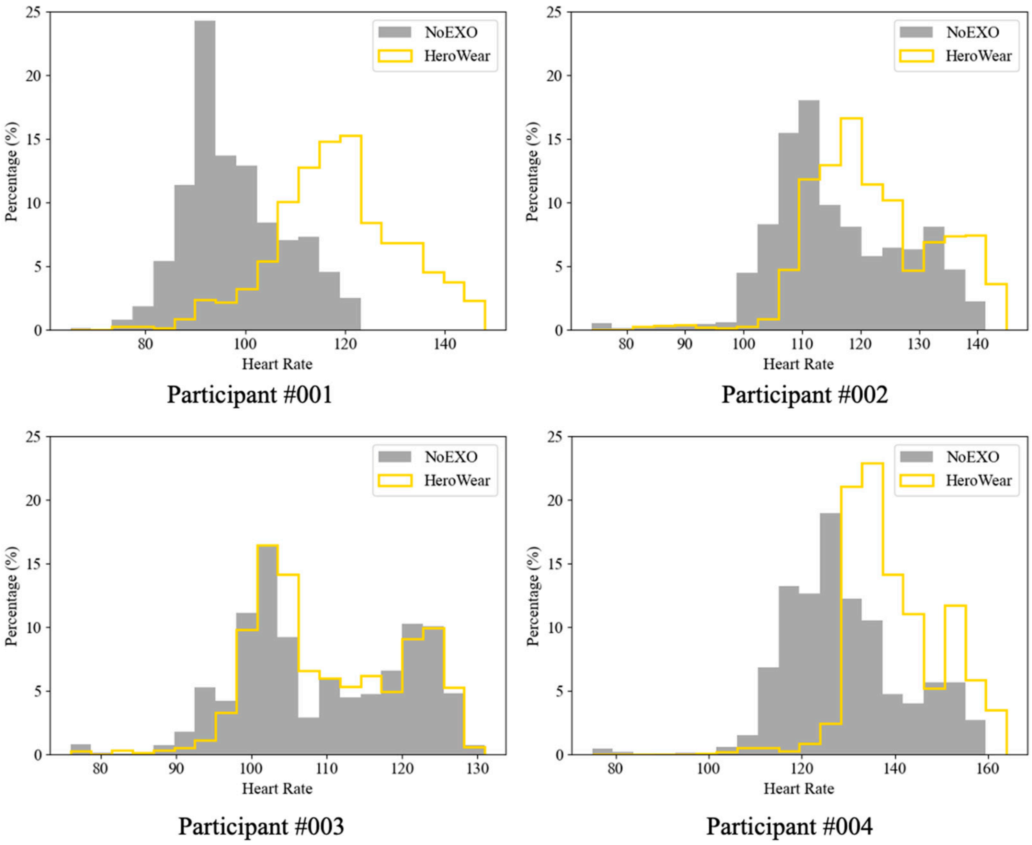


Figure 14. Distribution of the heart rates for individual participants during Task 1.

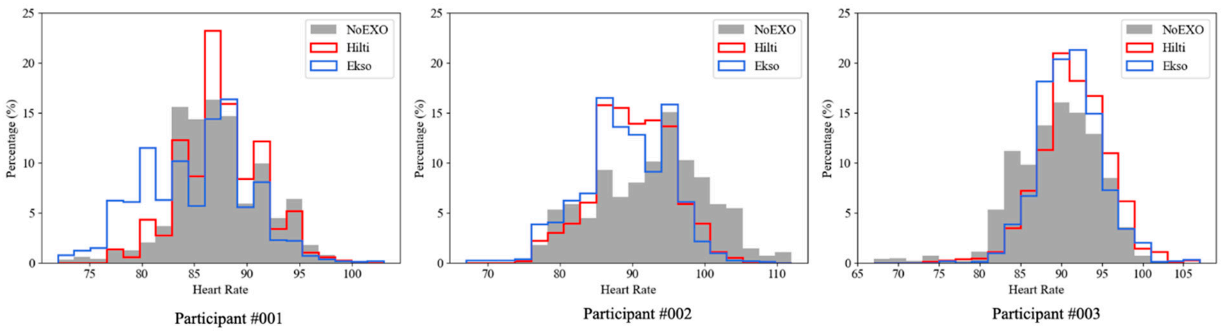
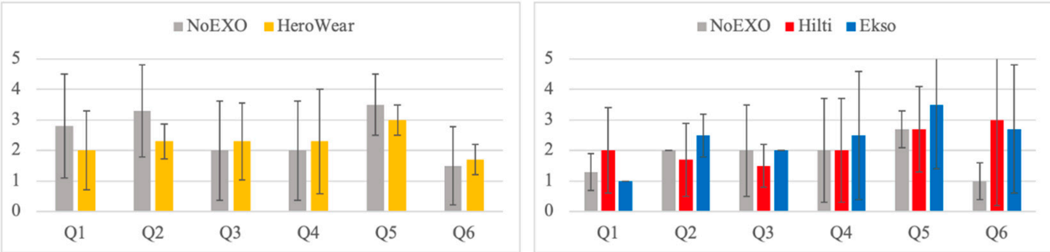


Figure 15. Distribution of the heart rates for individual participants during Task 2.

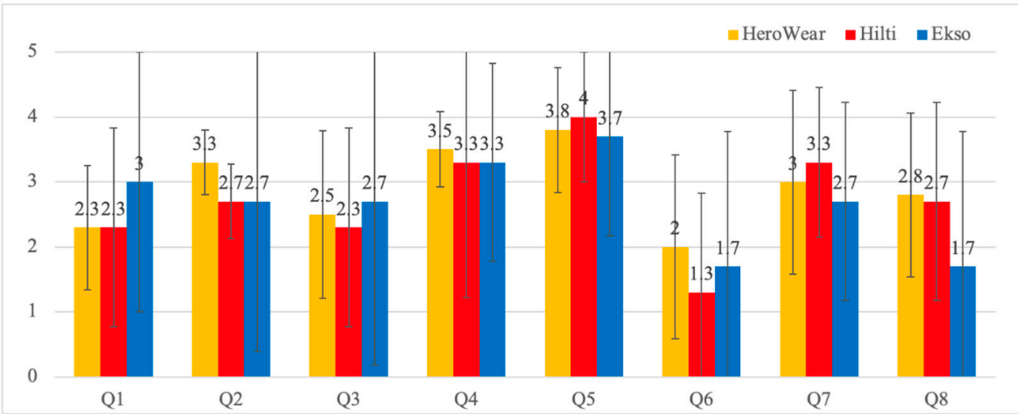
4.4. Opinions on the EXO Use

All the participants were surveyed to gather their opinions regarding EXO use. The survey comprised two parts. The first part is about their perceived task loads with and without EXO use. Here, the NASA Task Load Index [40] was adopted and the average ratings of the participants plus the standard deviations are shown in Figure 16. The second part of the survey is related to the participants' ratings on EXO usefulness, comfort, etc., as shown in Figure 17.



Q1:	Mental Demand: How mentally demanding was the task? (0 – very low, 5 - very high)
Q2:	Physical Demand: How physically demanding was the task? (0 – very low, 5 - very high)
Q3:	Temporal Demand: How hurried or rushed was the pace of the task? (0 – very low, 5 - very high)
Q4:	Performance: How successful were you in accomplishing what you were asked to do? (0 – very low, 5 - very high)
Q5:	Effort: How hard did you have to work to accomplish your level of performance? (0 – very low, 5 - very high)
Q6:	Frustration: How insecure, discouraged, irritated, stressed, or annoyed were you? (0 – very low, 5 - very high)

Figure 16. Perceived Task Loads with/without EXOs.



Q1	On a scale from 0 to 5, I found that to put on the EXO included (0 – No effort, 5 – extreme effort).
Q2	On a scale from 0 to 5, I found that the EXO was (0 – Uncomfortable, 5 – Very comfortable).
Q3	While initially wearing the EXO, I found that my movements were (0 – Not obstructed, 5 – Obstructed)
Q4	The EXO provided ergonomic (efficient and comfortable) support during the test (0 – N/A, 1 – Strongly disagree, 5 – Strongly agree).
Q5	It was easy to adapt/learn how to use the EXO during the test (0 – N/A, 1 – Strongly disagree, 5 – Strongly agree).
Q6	The EXO was compatible with my tools, PPE, etc. (0 – N/A, 1 – Strongly disagree, 5 – Strongly agree).
Q7	Overall, I was satisfied with the EXO (0 – N/A, 1 – Strongly disagree, 5 – Strongly agree).
Q8	I intend to continue to use the EXO (0 – N/A, 1 – Strongly disagree, 5 – Strongly agree).

Figure 17. Perceived EXO usefulness, comfortability, and satisfaction.

4.5. Discussion

Overall, our results are aligned with the findings from previous studies (e.g., [39–41]) that the use of EXOs would reduce the natural ROMs of test participants. In our results, the restrictions on the workers' ROMs were noted in all conditions (i.e., pushing the loaded gondola up, the unloaded gondola down, and the loaded or unloaded gondola at level ground) when HeroWear Apex was used. Hilti EXO-01 and Ekso EVO restricted the workers' ROMs on their right shoulders, but not on the left ones.

It is worth noting that not all participants responded to the EXOs the same way, which is common in human-subjects research studying the behavior and performance of test subjects (e.g., [42,43]). For example, Participant #004 in Task 1 showed the opposite change direction of his pelvis tilt angles in comparison to the others. It is partly because the participant had a noticeably hunched back when pushing the gondola without the HeroWear Apex, as shown in Figure 18. The wearing of the HeroWear Apex led him to work with a straight back and bend at the hip rather than hunching over. As a result, his pelvis tilt angle increased.

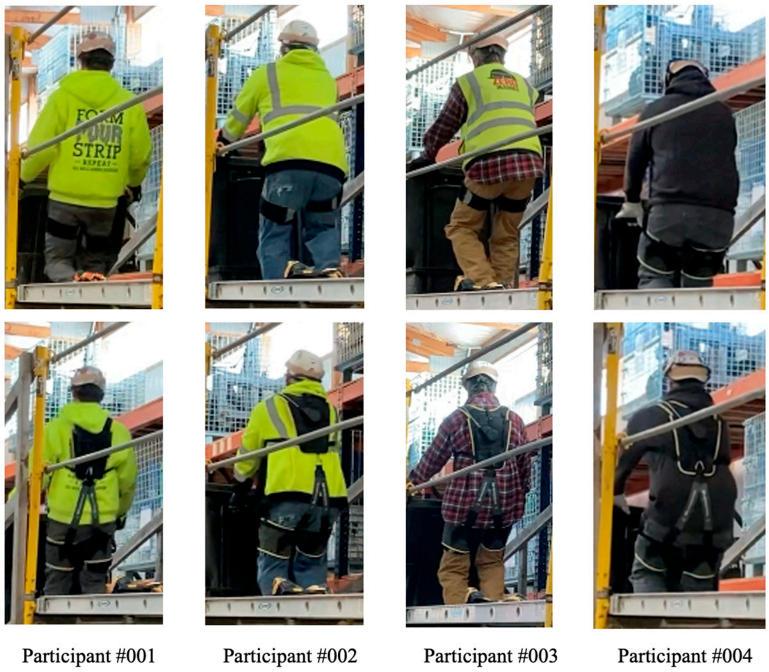


Figure 18. Participants with and without HeroWear Apex.

As for heart rates, existing studies showed that EXOs could reduce the heart rates of participants (e.g., [44,45]) or increase theirs (e.g., [46]). In this study, the wearing of EXOs increased the heart rates of the participants in Task 1, but the increase was not significant in Task 2. The heart rate increase may be due to several factors. For example, it was the first time the participants wore the EXOs during work and they might have felt nervous. In addition, the tightened straps on the legs or arms may have impacted the participants' heart rates.

The participants had opposite opinions on the EXO use, which was indicated by the high standard deviations of the ratings for several questions in the surveys (e.g., Q4 and Q6 in Figure 16 and Q1, Q7, and Q8 in Figure 17). Some liked the EXOs because of the support provided. For example, they said the HeroWear Apex helped them keep their backs aligned and less stressed, and more loads were off the back when emptying the gondolas. Both Hilti EXO-001 and Ekso EVO helped take the load off their arms while working overhead. On the other hand, others disliked the EXOs due to the imposed movement restraints, as well as the pain, soreness, and discomfort produced by the tightened straps on legs or arms when wearing the EXOs.

5. Conclusions and Future Work

This paper presented a pilot study for investigating workers' responses to the use of three passive EXOs (i.e., HeroWear Apex, Hilti EXO-01, and Ekso Evo) for two tasks: pushing/emptying gondolas and installing/removing wooden blocks in a construction workplace. The study quantitatively compared the difference in the workers' joint motions, heart rates, task completion time, and the perceived task loads with and without the EXOs. In addition, workers' opinions on EXO use in practice were collected. It was noted that the use of EXOs reduced the natural ROMs of the workers, but not all workers responded to the EXOs the same way. Furthermore, it was found that wearing the EXOs increased the participants' heart rates in Task 1, but the increase was not significant in Task 2. All three EXOs helped the workers reduce task completion time and the workers had conflicting opinions regarding EXO use. The findings and results from this study provide a fundamental understanding of how EXOs might impact construction workers when they are used in practice.

There are still several limitations that we plan to address in the future. First, the number of participants is limited and all of them are male. The augmentation of the physical capability provided by EXOs is expected to encourage more women to pursue a career in construction fields, given that men currently form the overwhelming majority of the construction workforce [41], and women have generally not considered jobs in construction by assuming that they lack the physical attributes needed to perform tasks in the field [42,43]. In future research, we aim to increase the diversity of study participants by including female workers and left-handed workers in field tests. In addition, this pilot study was conducted in a construction prep yard, which was the daily workplace of the construction workers participating in this study. The workplace is less controlled than a laboratory, but it is not as cluttered and dynamic as a construction site. It is unclear whether the cluttered and dynamic environments of construction sites would impact the usefulness and ease of use of EXOs. Therefore, more tests on active construction sites are needed to complement the findings and results from this study.

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