# Development and evaluation of a low-cost passive wearable exoskeleton system for improving safety and health performance of construction workers: A pilot study

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**Abstract –**

**Construction workers have an increased risk of having muscle fatigue and musculoskeletal injuries, among other non-fatal workplace injuries. As a result, this project aimed to develop and evaluate a low-cost passive wearable exoskeleton system for improving construction workers' safety and health performance, mainly by mitigating the risk of developing musculoskeletal pain and fatigue. Surface electromyography (sEMG) was used to evaluate muscle activity in the Thoracic Erector Spinae (TES) and Lumbar Erector Spinae (LES) at the L3 and T12 vertebrae level, respectively, during repetitive handling tasks. In addition, both subjective (e.g., rating of the fatigue scale) and objective fatigue indicators (e.g., heart rate, skin temperature) were employed to assess fatigue. Exoskeleton use was associated with a 30% decrease in LES muscle activation compared to baseline. The application of an exoskeleton had a similar effect on the TES, decreasing muscle activity by 12%. When using an exoskeleton, a participant's neck kinematics were reduced by 23%, their low back kinematics by 11%, their hip kinematics by 5%, and their knee kinematics by 36%. Exoskeleton use was associated with a 13% decrease in heart rate and a 67% decrease in perceived fatigue. Nonetheless, skin temperature was raised by around 2% while using an exoskeleton compared to when not using one. Our preliminary findings suggest that the passive exoskeleton system could be an effective ergonomic intervention tool for assisting construction workers engaged in manual repetitive handling activities.**

**Keywords –**

**Construction safety; Exoskeleton device; Fatigue; Musculoskeletal injury**

## 1 Introduction

Both developed and emerging economies rely heavily on the construction industry [1]. In many countries around the world, the construction industry contributes between 9 and 15% of GDP [2]. Despite its immense economic contribution, the construction industry is widely seen as a high-risk sector with poor safety, health, and productivity performance around the world. More than 700 people are killed and over 200,000 are injured while working every year in the United States, according to the Bureau of Labor Statistics (BLS) [3]. The annual cost of construction injuries exceeds $48 billion, having a significant impact on the success of projects, profit margins, and the financial sustainability of construction companies [4]. Exposure to frequent motions, vibration, force, and awkward working positions are all recognized to contribute to or worsen the increased risk of fatigue and injury among construction workers [5].

Several engineering, ergonomic, and management interventions have been used in previous studies to reduce the risk of musculoskeletal injuries, such as: (1) reducing the weight of lifting loads (e.g., concrete blocks); (2) increasing the initial lifting height [6,7]; (3) team working, but not alone [8]; (4) estimating the normative duration of lifting before subjective fatigue [9]; and (5) education and awareness [10]. In theory, these interventions should have a positive impact on worker productivity and safety, but in practice, the dynamic and unpredictable nature of construction sites makes implementation difficult. In addition, many construction activities are still carried out by personnel in laborious, repetitive tasks. Other potential ergonomic measures may be necessary to reduce the high incidence of these risk factors among construction workers.

Researchers are increasingly interested in developing human-robot collaboration to alleviate the burden of monotonous and repetitive tasks on human employees. [11]. As a human-robot collaboration idea, wearable exoskeletons are one of the most promising for construction-related jobs such as repetitive lifts and lowering. When worn, an exoskeleton is a mechanical support device that helps sustain the user's weight by applying torque. Worker fatigue, productivity, and risk management can all be improved using exoskeletons. This technology can be used for both return-to-work and prevention activities. In addition to allowing a worker to execute a task with less effort and thus less danger of damage, certain exoskeleton technologies provide workers with feedback to ensure safe actions [12]. Return-to-work programs and productivity could both benefit from the use of these tools. For example, a shoulder support exoskeleton that holds the weight of the arm could allow a worker to remain in an awkward position for a longer period with substantially less effort [13]. An exoskeleton, on the other hand, has the potential to improve the quality and productivity of workers as well as reduce the risk of injury [14].

Exoskeletons can be described based on 1) whether they are powered or not (passive or active), 2) which body parts they cover (e.g., entire body, upper limb, lower limb, and body extension), and 3) the materials used to make them (e.g., rigid, or soft). Exoskeleton suits have become increasingly popular in the construction industry because of technological advancements in both wearable and robotic technology. A previous study has investigated the feasibility of exoskeleton for construction workers and highlighted the necessity to evaluate their short- and long-term effects on safety and health, user acceptability, and productivity [15]. Therefore, it is important to understand the interplay between exoskeleton systems, workers, and tasks to make the most use of these technologies, and past research suggests that the benefits of exoskeleton suits may differ based on the kinds of construction works [16]. When it comes to exoskeletons, as with any new technology, we need to be aware of both the positive and negative aspects of this technology and address them before implementing it in the construction industry. Exoskeleton research has just begun to surface, shedding light on their effects. Some studies have shown that wearing an exoskeleton when stooping reduces spinal muscle use significantly [17,18]. The exoskeleton reduced the load on the back by minimizing muscular usage, which may assist in reducing fatigue and maybe preventing an accident [19]. However, this new technique has only a small amount of research.

To analyze the advantages of exoskeletons in the construction sector, it is best to use wearable sensor technology, which is accurate, unobtrusive, and provides a plethora of data for the study. Construction workers will benefit greatly from the comparative data that these studies may supply. For example, wearable sensing technology can collect data on the effects of a device on a user's posture in addition to metabolic expenses [20]. Furthermore, wearable sensing technology can capture dynamic data and then use that data to quantify the differences in the way the worker is moving with or without the devices [21]. Worker safety and health can benefit greatly from the development of exoskeleton technology, which incorporates wearable sensors. As a result, sensors like these are critical to the advancement and use of exoskeleton technology in the construction industry. In the construction industry, wearable sensors will enable the expansion of exoskeleton devices, which could lead to safer and more productive work. When it comes to exoskeleton technology, there is still plenty to learn, both pros and cons. Workplace health and safety relies on wearable sensors because they may give professionals access to data on a wide range of topics, from exoskeletons and their return-to-work and injury prevention applications to a wide range of other worker health solutions.

Research gap: Despite the obvious promise of exoskeleton devices, additional research is required to determine the positive and negative effects of exoskeletons and to address them prior to implementing and using this technology in the construction industry. There are no clear criteria available to evaluate the effects of exoskeletons on construction workers. Many standard ergonomic assessment approaches are mostly based on static models of work and do not take the potential implications of an exoskeleton into account. Although wearable sensing technology is the greatest method for evaluating the benefits of exoskeletons in the construction sector, no research studies have examined the application of this technology to quantify the effects of exoskeletons on construction workers.

## 2 Research Methodology

### 2.1. Design considerations

Low back injuries are widely recognized as the most common WMSDs. Construction workers mostly develop low back injuries mainly due to risk factors such as awkward postures and repetitive motions that are associated with workplace activities (e.g., repetitive lifting, carrying, lowering). To mitigate these injuries, there is a necessity to develop an ergonomic intervention (e.g., a robotic wearable passive exoskeleton system) that can assist the trunk and waist movements (i.e., lumbar flexion/extension, lateral bending, axial rotation) in the direction of anti-gravity. Unlike a robotic human-powered amplifier based on end-effector inputs [22] and an electric motor-assisted device to aid with trunk flexion and extension [23], the passive wearable exoskeleton system is a non-motorized device that helps individuals with lifting activities. This wearable technology borrows ideas from human muscles by using elastic components that can be interpreted as external muscular force generators. Generally, the proposed robotic passive wearable exoskeleton system was configured to transmit assistive torque or forces to a user's lower extremities (i.e., thigh and leg) through actuators and springs allocated at both hip joints.

### 2.2. Structure of the robotic passive wearable exoskeleton system

As shown in **Figure 1**, a robotic exoskeleton system that is both passive and wearable has been designed. At the shoulders, trunk, and thighs, this novel passive wearable exoskeleton system was articulated to synchronize with hip rotation. System components include a shoulder, trunk, and two leg pieces for each leg joined by Velcro straps in four parts. In order to release elastic energy during repetitive movements, two springs were linked from the shoulder to the hip region [24]. Additional benefits include load transfers from the spine to the legs, which enhances the user's capacity to do tasks that are both ergonomic and physical. This exoskeleton may be attached to the user's body using straps without any assistance from a professional. In choosing the harnesses and cuffs, we looked for ones that are lightweight, flexible, and less likely to cause internal joint damage from incorrect alignment. The proposed design and structural development of the robotic passive wearable exoskeleton system aims to make the mechanical structure as basic as feasible, specifically to mitigate risk factors for WMSDs during manual repetitive handling duties, which is why it is crucial to remark (i.e., lifting, lowering, and carrying activities).

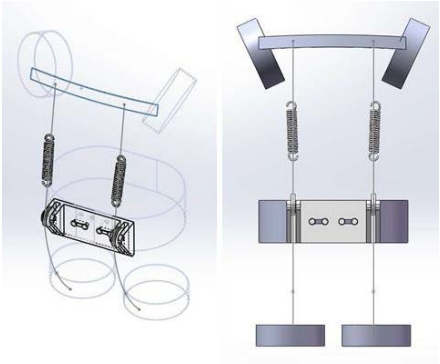


**Figure 1**. A prototype design of the proposed robotic passive wearable exoskeleton system.

### 2.3. Experimental design and procedures

The current project implements a design for a randomized crossover research that required only one testing session. Ten healthy university male student participants were selected to take part in the experimental endeavor. If the participants did not have a history of mechanical pain or injury to their upper extremities, lower extremities, or back, then they were allowed permission to take part in the activity. Each participant received an explanation of the in-depth procedures of the experiment, which covered the research objectives, the protocol, and any potential dangers. Participants provided demographic information and written consent after being informed about the study, following a process approved by the Human Subject Ethics Panel of Hong Kong Polytechnic University (reference number: HSEARS20220819005).

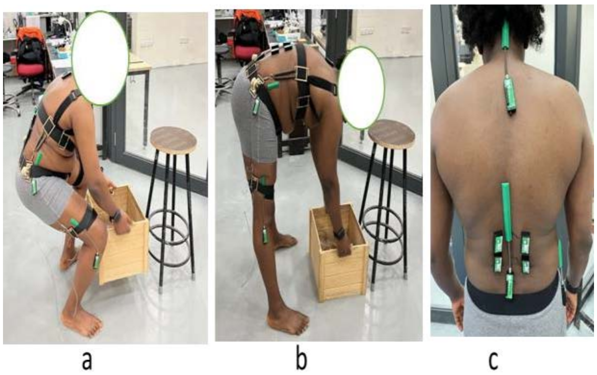
The lifting postures (stooping versus squatting) and systems (with vs. without passive exoskeleton) were the independent variables in this study. The muscle activity (i.e., right, and left sEMG: Lumbar Erector Spinae (LES) at L3 vertebrae level, Thoracic Erector Spinae (TES) at T12 vertebrae level), joint kinematics (neck, low back, hip, and knee kinematics), and physical fatigue (e.g., heart rate, HR; skin temperature, ST; and the perceived fatigue score) were the dependent variables in this study. During the performance of the lifting task, EMG data were gathered from these muscles on both sides utilizing Biometrics Ltd Data LITE, a wireless surface EMG sensor system. On the other hand, twin-Axis Electrogoniometer, which can measure angles in up to two planes of movement, was utilized to evaluate the kinematics of the neck, low back, hip, and knee regions. These movements include flexion/extension, and lateral bending. Physical fatigue indicators such as HR and ST were captured using a wearable sensor (i.e., Empatica E4). Perceived fatigue level was assessed using the rating-of fatigue scale. **Figure 2** indicates a range of wearable sensors used for the data collection in this study.

DataLITE Explore EMG Sensor Electrogoniometer Empatica E4

**Figure 2.** Wearable sensors used for data collection.

The principal experimental task in this study was manual, repetitive handling. In this exercise, participants are instructed to stoop or squat to pick up a heavy box (i.e., 15 kg), carry it along a predetermined route, and then drop the box at a given destination using their stooping or squatting position. The experimental procedures are depicted in Figure 3, which depicts the laboratory setting. Following the training, every participant conducted ten iterations of the experiment, one for each of the conditions that were randomly assigned. To lessen the amount of fatigue experienced by the participants, there was a five-minute break in between each of the consecutive experimental trials.

After the trial, participants were told to do two sets of Maximum Voluntary Contractions (MVCs) against physical resistance for each muscle. The participants were instructed to lay prone with their torsos hanging over the side of a table during the MVC trials for the TES and LES muscles. This was carried out in preparation for the trials currently under way. The participants were then instructed to manually resist the researcher by stretching their trunk upward and twisting to the left and right. After each trial, there were a rest period of two minutes, and during that time, each muscle was contracted to its fullest extent for five seconds [25]. The MVCs trials are performed to attain the maximal amplitude of surface electromyographic (sEMG) activity for the aim of normalizing the sEMG signals and, as a result, permitting comparisons of muscle activity between various muscles, lifting positions, and systems.



a b c

**Figure 3.** Laboratory experimental setup: (a) Squat Lifting; (b) Stoop Lifting; (c) Placement of EMG and Electrogoniometer sensors

### 2.4. Data processing and analyses: surface electromyography (sEMG), Electrogoniometer, and HR sensors

The positioning of the sEMG electrodes and Electrogoniometer sensors is shown in Figure 3. It is planned to conduct research on both the right and left sides of the two muscles (TES, LES,). This was executed with a biomechanical perspective. DataLITE Wireless sEMG sensors (LE230) (UK Biometrics Ltd) were attached bilaterally to each muscle to record electrical activity. The distance between the electrodes is 20 millimeters, while the diameter of the electrode is 15 millimeters. All surface electromyography (sEMG) data are going to have their raw electrocardiography signals sampled at a frequency of 2000 Hz with a common-mode rejection ratio of 100 decibels. Using a moving window of 1000 milliseconds that passes across the sEMG signals recorded during the two MVCs, we determined the sEMG signal that has the highest root mean square (RMS) value for each muscle. The sEMG signal with the highest RMS value for each muscle was the one used for normalization.

Each trial of the experiment underwent a visual examination for artifact effects. In the following step, a band-pass filter operating between 20 and 500 Hz was applied to each single sEMG signal. To get rid of power-line interference, we utilized a notch filter with its center frequency set to 50 Hz. To provide an accurate estimation of the RMS sEMG signals, the rectified and processed sEMG signals, in conjunction with an average constant window of 1,000 milliseconds, were utilized. The collected sEMG signals were utilized to derive the mean root-mean-square value of the EMG activity. The highest percent MVC sEMG is shown as a percentage of the maximum percent RMS during MVC, which was used to normalize the obtained data. Because of its sensitivity to transient changes in body loading, the highest amplitude, also known as the maximum percent of the maximum velocity component, was chosen for this study as a useful indicator of human exoskeleton interaction across brief time periods. Its amplitude is also useful as a long-term indicator of human exoskeleton interaction [25]. The Biometrics DataLITE Explore Wireless dongle served as the bridge between the sensors and the PC software, allowing for the transfer of raw data.

Four Electrogoniometer sensors, manufactured by Biometrics Ltd, were affixed to the spinous processes at the T1, S1, lateral to hip, and lateral to knee for measuring cervical, low back, hip, and knee motion, respectively (**Figure 3**). The rate of sampling was set at 1000 samples per second. To convert Goniometer readings into engineering units usable by the Biometrics Ltd. program, we employed unfiltered ASCII encoding. Sub-sampling was established, and 100 data points were sampled for each activity. The final step was to determine the average of the subsamples. Using the Biometrics ltd. data acquisition software, all the data were recorded, and subsamples were taken.

### 2.5. Assessment of fatigue

Participants were given the Rating-of-Fatigue Scale with 11 possible responses, from 0 (no fatigue) to 10 (total exhaustion), to rate their level of perceived exertion [26]. Each subject's level of exertion during the experimental sessions with and without an exoskeleton was measured using this scale. Additionally, a wearable sensor (i.e., Empatica E4) was used to monitor HR and ST continuously during each task.

### 2.6. Statistical analyses

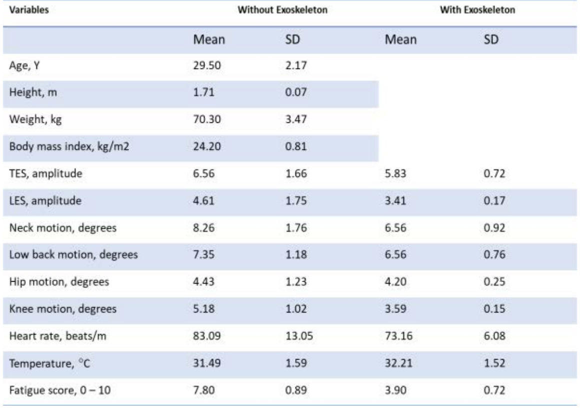
To ensure that the data were normally distributed, we ran the Shapiro-Wilk test. Then, a two-factor (2 x 2) mixed-model repeated-measures analysis of variance (ANOVA) was used to assess the differences in muscle activity between subjects who lifted in a stoop versus a squat position (within-subject factors) and who lifted with or without an exoskeleton system (between-subject factors). A two-way (2 x 2) repeated-measures ANOVA was also used to examine the correlation between the number of repetitions performed and the amount of fatigue experienced by the participants. Post hoc comparisons between pairs were calculated using the Bonferroni adjustment. The analyses were performed in SPSS 27.0 (Statistical Program for the Social Sciences) (IBM, USA). Statistical significance was determined at the $p$ 0.05 level.

## 3. Results

### 3.1. Descriptive statistics

**Table 1** details descriptive statistics. The LES muscle activity with the use of exoskeleton showed a reduction of about 30% as compared to without exoskeleton. Similarly, TES muscle activity was reduced by 12% with the use of exoskeleton as compared to without exoskeleton. The reduction of the neck, low back, hip, and knee kinematics were 23%, 11%, 5%, and 36%, respectively, with the use of exoskeleton as compared to without exoskeleton. HR and fatigue scores were reduced by nearly 13% and 67%, respectively, with the use of exoskeleton as compared to without exoskeleton. However, ST was slightly increased by about 2% with the use of exoskeleton as compared to without exoskeleton.

**Table 1**. Descriptive statistics



| Variables | Without Exoskeleton | | With Exoskeleton | |
|---|---|---|---|---|
| | Mean | SD | Mean | SD |
| Age, Y | 29.50 | 2.17 | | |
| Height, m | 1.71 | 0.07 | | |
| Weight, kg | 70.30 | 3.47 | | |
| Body mass index, kg/m2 | 24.20 | 0.81 | | |
| TES, amplitude | 6.56 | 1.66 | 5.83 | 0.72 |
| LES, amplitude | 4.61 | 1.75 | 3.41 | 0.17 |
| Neck motion, degrees | 8.26 | 1.76 | 6.56 | 0.92 |
| Low back motion, degrees | 7.35 | 1.18 | 6.56 | 0.76 |
| Hip motion, degrees | 4.43 | 1.23 | 4.20 | 0.25 |
| Knee motion, degrees | 5.18 | 1.02 | 3.59 | 0.15 |
| Heart rate, beats/m | 83.09 | 13.05 | 73.16 | 6.08 |
| Temperature, °C | 31.49 | 1.59 | 32.21 | 1.52 |
| Fatigue score, 0 – 10 | 7.80 | 0.89 | 3.90 | 0.72 |

### 3.2. Effects of exoskeleton system lifting posture on muscle activity

Muscle activity in ANOVA data is shown in Table 2. All muscles examined showed significant changes in sEMG activity when comparing the primary effects of lifting posture ($p < 0.05$) and system ($p < 0.05$). Furthermore, sEMG activity for the LES muscle significantly interacted with lifting posture and systems. However, there was no interaction effect of lifting posture and system was observed for TES muscle.

**Table 2**. Summary of ANOVA results for muscle activity

| Independent Variables | LES | | TES | |
|---|---|---|---|---|
| | F | p | F | p |
| **Main effect** | | | | |
| System | 13.43 | 0.001 | 4.46 | 0.042 |
| Posture | 10.71 | 0.002 | 14.98 | 0.001 |
| **Interaction** | | | | |
| System * Posture | 8.28 | 0.007 | 0.77 | 0.385 |

3.3. Effects of exoskeleton system and lifting posture on joint kinematics

Findings of ANOVA on joint kinematics are reported in **Table 3**. When examining the primary effects of lifting posture and system, there were statistically significant changes in the kinematics of the neck and low back. Knee kinematics for the exoskeleton showed substantial alterations due to the lifting posture, while hip kinematics did not. For low back kinematics, a notable interaction impact between lifting posture and exoskeleton use was observed. However, no system-lifting posture interaction effect was found for any of the other kinematics we looked at.

**Table 3**. Summary of ANOVA results for joint kinematics

| Independent Variables | Neck motion | | Low back motion | | Hip motion | | Knee motion | |
|---|---|---|---|---|---|---|---|---|
| | F | p | F | p | F | p | F | p |
| **Main effect** | | | | | | | | |
| System | 20.38 | 0.001 | 7.85 | 0.008 | 0.712 | 0.404 | 50.43 | 0.001 |
| Posture | 16.97 | 0.001 | 11.40 | 0.002 | 5.36 | 0.026 | 1.88 | 0.179 |
| **Interaction** | | | | | | | | |
| System * Posture | .038 | 0.846 | 4.16 | 0.049 | 0.871 | 0.357 | 2.38 | 0.131 |

3.2. Fatigue assessment

The HR, ST, and subjective fatigue scores are shown in Table 4 along with the analysis of variance (F ratios and p-values). The major effects of lifting posture and exoskeleton used were statistically significant for HR and subjective fatigue scores. However, changes in ST were unrelated to both lifting posture and exoskeleton used. There was an interaction effect between lifting posture and exoskeleton used for changes in HR and ST, not for subjective fatigue scores.

**Table 4.** Summary of ANOVA results for fatigue assessment

| Independent Variables | HR | | ST | | Fatigue | |
|---|---|---|---|---|---|---|
| | F | p | F | p | F | p |
| **Main effect** | | | | | | |
| System | 14.38 | 0.001 | 2.45 | 0.126 | 536.82 | 0.001 |
| Posture | 7.43 | 0.010 | 2.86 | 0.103 | 50.80 | 0.001 |
| **Interaction** | | | | | | |
| System * Posture | 13.95 | 0.001 | 4.16 | 0.049 | 1.42 | 0.243 |

## 4. Discussion

The purpose of this research is to evaluate the effects of a passive exoskeleton system on muscle activation, joint kinematics, and fatigue ratings while performing laboratory simulations of manual repetitive handling tasks. The findings were as follows: (1) there was a statistically significant difference between the effects of lifting posture and the exoskeleton system on sEMG activity of the muscles studied; (2) there was a statistically significant difference between the effects of lifting posture and the kinematics of all regions studied except for the knee region; (3) there was a statistically significant difference between the effects of the exoskeleton and the kinematics of all regions studied except for the hip region; and (4) there was a statistically significant difference between the effects of lifting posture and using an exoskeleton on HR and subjective fatigue scores, except for ST.

4.1. Effects of exoskeleton system and lifting posture on muscle activity

Both TES and LES muscles tested showed a statistically significant ($p < 0.05$) increase in muscle activity (sEMG activity) while lifting using stoop posture, regardless of whether an exoskeleton system was used. Most notably, the results showed that sEMG activity in TES and LES was considerably ($p < 0.05$) lower while utilizing the exoskeleton system as opposed to not using it for manual repetitive handling tasks. In general, these results showed that people who utilized the passive exoskeleton system had less sEMG activity and, hence, a lower risk of developing WMSDs. Exoskeleton systems have been shown to lower LES muscle activation during manual repetitive handling tasks [27-30]. Like current findings, Bosch et al. [29] found that participants using an exoskeleton system saw a 35%-38% decrease in maximal voluntary contractions (MVC) during a simulated assembly work simulation involving a protracted forward bending task. The LES muscle's activity was found to be significantly reduced by 12-15% MVC in an evaluation conducted by Huysamen et al. [27]. Cardoso et al. [31] found that while performing trunk bending duties in the furniture production industry, the wearer's back muscles were less active by between 0.8% and 3.8% while wearing a passive exoskeleton system. These results provide support for the hypothesis that the passive exoskeleton system may help reduce the risk of WMSDs among construction workers by mitigating the effects of internal muscle activity and spinal strains.

### 4.2. Effect of exoskeleton system on joint kinematics

In the current study, evaluation of spinal and peripheral joint kinematics shows that using a passive back exoskeleton changes joint kinematics. In a similar vein, prior research suggests that donning a passive back support exoskeleton modifies joint kinematics [32]. Similarly, Sadler et al. [33] compared the kinematic changes between lifting with and without a back-support passive exoskeleton. According to their research, employing the back-support passive exoskeleton significantly reduces trunk flexion during the whole lift cycle. Another study using a passive exoskeleton also demonstrated an increase in peak lumbar flexion, however this time it was limited to lifts from the ankle level and not the knee level [34]. Moreover, the range of motion was not affected by either exoskeleton in a second study that examined two passive exoskeletons [35]. Furthermore, the kinematics of lifting while wearing a passive exoskeleton was investigated in a separate study [36]. Joint angles in the knee, hip, low back, and upper back did not change noticeably when wearing the exoskeleton. Increases in ankle flexion, decreases in lumbar and thoracic (mid back) flexion, and equal hip flexion were seen in people wearing a passive exoskeleton compared to those not wearing the exoskeleton [37].

### 4.3. Effect of exoskeleton system on fatigue

Both objective fatigue indicators such as HR and subjective fatigue scores were significantly reduced during lifting tasks while using a passive exoskeleton system.

This study confirms the findings of previous studies showing that using an exoskeleton system considerably reduces the perception of effort during physical activity [28, 38]. Yet, another study found that RPE significantly increased by 0.75 points following exoskeleton-assisted physical task performance [39]. Nevertheless, no research has been done to determine what the minimally clinically important difference (MCID) in exertion level is when utilizing the Borg CR 10 for a lifting task. Consequently, the 0.75 RPE change in their study is debatable in terms of its clinical importance. The results of this study show that compared to when no exoskeleton was used, HR decreased by about 13% when using an exoskeleton. While one study observed a 10% reduction in HR when utilizing a back-supported passive exoskeleton for a lifting task [38], another found an increase of 7% [40]. Yet, contrary research has found little evidence that utilizing an exoskeleton significantly alters HR while carrying out a task [41]. These conflicting findings suggest that it is not possible to draw any firm conclusions about the effect of exoskeleton use on HR, across a variety of tasks and exoskeletons.

### 4.4. Limitations

Like with any research, the current study was subject to some limitations. First, measurements were conducted in a laboratory setting. The subjects selected for this study were university students who lacked experience with manual materials handling; as a result, the group employed was not exactly representative of construction industry workers. In addition, individuals were not trained on the tested exoskeleton for an extended period, and task performance was not assessed in this study. It is unknown if participants would become significantly more/less comfortable with the exoskeleton or would perform significantly more/less consistently with longer use. Even though all subjects were instructed on how to do the task prior to data collection, two distinct postures were used. In a real-world construction setting, however, other postures are anticipated.

## 5. Conclusions and recommendations

Preliminary results suggest that using the passive exoskeleton system decreased sEMG activity. In addition, when using the exoskeleton system, participants showed increased spinal and peripheral joint kinematics. Finally, participants reported less fatigue during the tasks while using the exoskeleton system, as measured by HR and subjective fatigue scores. The key findings of this study are that (1) the passive exoskeleton system has promising applications as an ergonomic intervention tool to aid construction workers while conducting manual repetitive handling activities; (2) findings have provided evidence that the system is not only practical but also portable, convenient, and user-friendly; and (3) this research may help safety managers select the best passive exoskeleton for use in the construction industry by shedding light on the effects of exoskeleton use on muscle activation, kinematics, and physical exertion. Despite these advantages, more studies are required to determine how this passive exoskeleton system affects other peripheral and spinal muscles (e.g., abdominals, glutei etc.), physiological metrics (e.g., respiratory rate, oxygen consumption, etc.), and labor task performance across a variety of construction trades. Additionally, it would be interesting for future research to investigate the feasibility of using passive exoskeleton devices to improve the health and efficiency of construction workers.

**Declaration of Competing Interest.** No authors have reported any financial or other conflicts of interest that could be considered as influencing the work provided in this paper.

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